

Primitive Accumulation and Capital Expansion in Public Knowledge Production Across Generative Levels

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Abstract

This paper develops a provisional political-economic and epistemic framework for investigating the initial formation, historically specific primitive accumulation, and recursive expansion of knowledge-producing capital across generative levels. The inquiry distinguishes inherited knowledge resources, feasible productive capabilities, effective control of generative conditions, and the capitalization of particular positions within evolving relations of production. It examines meta-knowledge, research methods, standards, infrastructures, applications, and generated outputs as model-relative positions in partially ordered and reciprocally revisable dependency structures. The consequences of accumulation are proposed to depend on effective dependencies, feasible substitutions, governance arrangements, and the distribution of authority to maintain or transform production conditions. Capital formation and expansion are compared across capitalist enterprises, public institutions, cooperatives, knowledge commons, and communist conceptions of collective production, while retaining the historical specificity of primitive accumulation through separation and dispossession. The analysis distinguishes heterogeneous value creation, recognition, appropriation, circulation, and reinvestment, and investigates how these processes affect the continuing reproduction of knowledge-producing capabilities. Ownership, access, practical autonomy, epistemic authority, and institutional power are considered separately. A preliminary relational formalism represents typed productive dependencies, feasible activities, differentiated rights, plural valuations, and substitution-sensitive counterfactual dependency; its mathematical implications are explicitly distinguished from empirical findings and normative judgments. Documentary illustrations address publishing, shared software, scientific standards, artificial intelligence, and cultural archives. The discussion proposes revisable public generativity as one provisional ethical criterion concerning opportunities to create, maintain, understand, and transform shared productive conditions under contestable governance. The paper concludes by identifying the historical, measurement, causal, and comparative evidence required to assess concentrated control and possible extraction at different generative levels. Its contribution is an open research framework rather than a universal hierarchy of knowledge or an empirical law of capital expansion.

Keywords: primitive accumulation; knowledge capital; public knowledge production; generative levels; structural dependency; heterogeneous value circulation; knowledge commons; power.

Discussion Paper Note

The manuscript investigates primitive accumulation and capital expansion in public knowledge production across generative levels. It uses a relational and historically situated account of productive conditions, heterogeneous values, institutional control, and generative dependencies. Its economic vocabulary is treated as a set of analytical proposals requiring historical specification and empirical testing, particularly when extended across capitalist, public, commons-based, and communist institutional conceptions.

The central distinction concerns the broad initial formation of knowledge-producing conditions and the historically specific meaning of primitive accumulation associated with dispossession and the separation of producers from means of production. The manuscript also separates accumulation of productive capabilities from claims concerning appropriation, extraction, or exploitation. The term *generative levels* denotes a model-relative dependency description, open to feedback, revision, and historical transformation, without claiming that knowledge development follows a universal hierarchy or an unexamined time order.

The manuscript contains first drafts of Sections 1–17 and Appendices A–I, including terminology, political-economic background, dependency structures, relational two-complex models, value-circulation constructs, differentiated rights, counterexamples, institutional illustrations, and an empirical research design. Targeted source-to-claim assessments have been recorded for the 93 cited bibliography entries, at evidence levels ranging from original full text to publisher and institutional summaries. These assessments do not amount to full passage-by-passage verification. The mathematical constructions remain preliminary, their implications depend on stated assumptions, and the illustrative cases do not establish new causal or empirical findings. This version incorporates an internal consistency and editorial consolidation review; independent specialist scrutiny, comprehensive source checking where warranted, and author approval remain necessary before publication.

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The terms *capital*, *commons*, *communism*, *extraction*, and *exploitation* can carry distinct historical, disciplinary, and political meanings. Uses of the present conceptual framework should specify the institutional arrangements examined, distinguish normative assessment from empirical description, and retain the possibility of correction or contestation by affected contributors and communities.

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Notices

Publication status. Independent preliminary theoretical discussion paper, version 2.6, 24 October 2026. The main text (Sections 1–17) and Appendices A–I are drafted. References have individual verification records; the manuscript has not undergone peer review or a final scholarly consistency audit.

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Research independence. This conceptual manuscript contains no original human-participant data or institutional case findings. It does not imply affiliation with or endorsement by any institution.

1 Introduction

The present study examines the formation, accumulation, and expansion of productive knowledge capital within historically constituted relations of public knowledge production. Its principal objective is to explain how the same broad process of accumulating conditions for further knowledge creation may operate under heterogeneous institutional arrangements, while yielding substantially different configurations of ownership, productive agency, value circulation, and power. The investigation proceeds through an analytical distinction between initial capital formation and historically specific processes of primitive accumulation; an account of knowledge production across interacting generative levels; and a relational analysis of the appropriation, circulation, and reproduction of heterogeneous forms of value. The method is primarily conceptual and comparative, informed by political economy, knowledge-commons scholarship, science studies, and an exploratory representation of generative dependencies. Historical cases and formal constructions will be developed in later sections. The present Introduction specifies the research object, establishes the principal distinctions, formulates the hypotheses guiding the inquiry, and identifies the limits of the proposed approach.

A knowledge-producing system can acquire resources and capabilities that extend its opportunities for further inquiry. A collection of manuscripts can become an organized archive; shared procedures can become reusable methods; a community's tacit practices can be made teachable; a research apparatus can become part of a maintained infrastructure; and a theory can supply concepts with which new objects of study are articulated. In each case, the relevant development involves more than a quantitative increase in recorded information. Knowledge, skill, material resources, coordination practices, and institutions become connected in ways that support activities beyond the immediate circumstances of their formation. Such accumulated conditions may be sustained, modified, inherited, transferred, or recombined. Under some arrangements, they also become objects of appropriation and control. The term *productive knowledge capital* will provisionally designate these historically assembled, relatively durable conditions insofar as they can be mobilized to support further knowledge production. The proposed term is deliberately relational: its analytical application depends on a specified production system, actors, accessible capabilities, and the processes through which productive conditions are reproduced.

The description of a resource as *capital* requires theoretical care. In a Marxian analysis, capital denotes a historically specific social relation implicated in the valorization of value and the organization of wage labour; it does not simply name a useful stock of tools or knowledge. The present manuscript engages with that historically specific conception while investigating a broader class of capital-like accumulation processes within knowledge production. It consequently distinguishes *knowledge-capital formation*, used provisionally for the organization of durable productive conditions, from *capitalist relations of accumulation*, which require their own historically and institutionally determinate criteria. The broader usage is an analytical proposal whose benefits and costs require examination. Its explanatory value will depend on whether it helps identify recursive production processes and relations of control without erasing differences among political-economic traditions.

This distinction is particularly important for the term *primitive accumulation*. Marx's discussion of so-called primitive accumulation treats the historical separation of producers from their means of production as constitutive of capitalist production relations [61]. The separation, together with the conversion of social means of production into capital and the formation of a labour force dependent on wages, carries explanatory content that a generic account of initial wealth formation would obscure. In knowledge production, a university establishing a publicly accessible archive, a cooperative maintaining research software, and a corporation acquiring exclusive rights over a collectively developed infrastructure may each be involved in the formation or reconfiguration of productive capacities. Their institutional relations cannot be assumed equivalent. A historically specific analysis of primitive accumulation should investigate whether and how separation, enclosure, dispossession, or subordinating dependence occurs. A broader analysis of *initial knowledge-capital formation* can examine cases in which durable productive capabilities arise through public expenditure, collective labour, voluntary contribution, reciprocal exchange, or shared stewardship. The possibility of drawing connections between the two categories is

an object of inquiry, rather than a license to identify them in advance.

The reference point of an “initial” formation likewise depends on the historical boundary of the inquiry. A newly established laboratory may combine publicly funded education, inherited theoretical knowledge, instruments developed in other institutions, local material contributions, and the practical judgment of its members. At the laboratory level, this composition may constitute an identifiable formation of productive conditions. At the level of the broader knowledge system, its constituent resources are products of interwoven histories of prior production. An inquiry into initial capital formation therefore needs to specify the system whose formation is being described, the relations inherited from other systems, and the social processes through which these conditions become usable. The present framework makes no assumption of an absolute original stock of knowledge or a universally privileged starting point. Initiality concerns a specified relational boundary and a documented formation process.

The institutional range of the question is equally significant. Knowledge production can occur in capitalist firms, universities, public research organizations, professional associations, libraries, open-source projects, cooperative enterprises, community workshops, and other forms of collective practice. The history of open science itself invites institutional rather than purely technical explanation; David’s historical account, for example, examines the emergence of open-science institutions in relation to changing social and economic circumstances [23]. Scholarship on knowledge commons treats shared knowledge as an object of governance and collective-action problems, including questions of access, conservation, enclosure, and continuing maintenance [40]. Ostrom’s analysis of institutional self-governance similarly demonstrates the relevance of participant-created rules and continuing collective action, while drawing on resource settings whose properties must be distinguished from those of informational goods [70]. Benkler’s account of commons-based peer production provides another point of departure for studying knowledge production coordinated outside conventional managerial hierarchies [8]. These traditions support an investigation in which durable productive capability can develop under different governance structures, without presupposing a single relation of ownership or a single mode of value appropriation.

Conceptual precision also matters when considering capitalist, commons-based, and communist forms of knowledge production. *Capitalism* refers here, when deployed as a political-economic category, to historically specific relations whose interpretation depends on the chosen theoretical account. *Commons-based production* denotes arrangements in which shared resources and rules of access, contribution, maintenance, and governance play a constitutive role. A commons can coexist with markets, public administration, private property, and diverse regimes of labour. *Communism* names a distinct family of political-economic theories and institutional conceptions concerning collective production, property, and the organization of social life; its historical expressions and theoretical meanings require explicit specification. These categories therefore overlap in some possible institutional practices yet remain analytically distinguishable. The manuscript will examine communist conceptions of collective knowledge production alongside commons arrangements without treating their labels as institutional synonyms or their normative aspirations as established empirical outcomes.

A shared analytic question arises across this diversity: how does a knowledge-producing arrangement acquire and maintain the conditions of further production? An institution may accumulate trained participants, methods, equipment, working relationships, archival resources, conceptual vocabularies, trusted practices, and organizational means of coordination. The availability of these conditions may increase the number or range of activities that participants can carry out, improve the dependability of existing practices, or enable conceptual transformations that redefine the relevant activities themselves. Under some conditions, such developments increase productive capacity without a corresponding concentration of exclusive rights. Under others, the expanding activity of many participants may be accompanied by growing control in the hands of a relatively small set of actors. Accumulation and concentration thus require separate descriptions. The former concerns changes in productive capability and the conditions that support it; the latter concerns the distribution and exercise of effective control over those conditions.

The central theoretical extension proposed here concerns *generative levels*. Knowledge-producing conditions can occupy different positions within a network of dependencies among productive activities. A localized application may draw upon methods, data, interpretive practices, standards, mathematical

formalisms, and institutional arrangements. A research method may support multiple applications; a conceptual framework may shape the formulation and evaluation of multiple methods; and common infrastructures may enable otherwise separate lines of inquiry. The study proposes that accumulation at such different positions can have different effects on the expansion, accessibility, and control of subsequent knowledge production. One application may yield a bounded stream of products or services. A widely used methodological platform may support many programs of investigation. A change in the standards through which evidence is admitted, data are classified, or contributions are recognized may influence the formation and validation of knowledge across several domains. The comparison directs attention to the *generative reach* of accumulated conditions rather than the numerical volume of knowledge associated with a particular actor.

The term *level* has a limited and revisable role. A generative grammar offers one useful analogy: some rules contribute to a large family of derivations, while other operations appear close to particular outputs. Yet actual knowledge production commonly involves reciprocal causation, partially ordered requirements, competing methods, lateral transfers, and revisions initiated by applications. A practical innovation may reveal the inadequacy of an inherited theory; a new instrument may alter the possible objects of inquiry; institutional reform may reorganize standards by which earlier achievements are interpreted. There is consequently no commitment to a universal tree with meta-knowledge at an immutable root and applications at passive leaves. Levels are relative to a particular generative model and research question. The same resource can be foundational for one activity, peripheral for another, and transformed through interactions that cross its provisional assigned level. The relevant model must permit nested dependencies, cycles in processes of revision, plural representations, and historically shifting boundaries.

These qualifications sharpen the proposed research hypothesis. The effect of knowledge-capital accumulation is conditioned by the location of accumulated resources and rules within a specified generative structure, the range of activities supported by them, the feasibility of substitutes or alternative paths, and the actors' capacities to control their availability or transformation. In a model where a single foundational method is a necessary input to numerous dependent activities, exclusive control over that method may create a broad channel for appropriating resources or influencing decisions. If alternative methods are available, or if affected contributors can redesign shared infrastructure, the effective reach of the same formal position may be considerably narrower. By contrast, an application-level resource can constitute a powerful bottleneck if many critical activities rely on it and replacement is difficult. Generative depth alone consequently provides an incomplete predictor of structural influence. The joint analysis of dependency, substitutability, institutional control, and practices of appropriation is essential to the proposed account.

A further distinction concerns the object over which a person or institution exercises rights or power. A research output may have a legal owner, a steward, a set of licensees, and a community of practitioners whose capacity to interpret or transform it depends on additional resources. Equipment may be owned by an institution but scheduled by an administrative office. A repository may be openly readable while contributions remain subject to a narrow approval process. A methodological standard may be publicly documented, yet its maintenance or certification concentrated in a particular body. Participants may acquire expertise through collective work even where the resulting data or intellectual property is held elsewhere. These examples distinguish legal title, access, use, modification, exclusion, governance, attribution, and effective productive agency. They also show why *ownership of productive capacity* requires caution: human skill, autonomy, tacit judgment, and social relations cannot be represented exhaustively as alienable property. The manuscript will therefore analyze rights over resources and outputs alongside the institutional capacities to mobilize or constrain human and collective productive activity.

Table 1 identifies the principal objects of this inquiry. The distinctions are analytical and may intersect in particular cases. In subsequent sections, they will provide a framework for comparing the institutional organization of production with the historical development of generative dependencies.

The distribution of benefits from collective knowledge production provides another part of the research problem. The concept of *value* can refer to several differently constituted objects, including monetary revenue, scientific or interpretive significance, recognized contribution, strengthened capac-

Table 1: Analytical objects and relations in multilevel knowledge-capital formation

Object or relation	Principal analytical concern
Knowledge resources and outputs	Availability, attribution, legal rights, stewardship, reuse, and transformation.
Productive conditions	Infrastructure, material supports, labour arrangements, rules, and access to necessary inputs.
Productive capabilities	Skills, coordination, practical autonomy, and capacity to initiate or sustain knowledge-generating activities.
Generative dependencies	Downstream reach, alternatives, cross-level transformation, and historical reconfiguration.
Heterogeneous value circulation	Creation, recognition, conversion, appropriation, distribution, and reinvestment of different value forms.
Power and institutional control	Authority to set rules, govern participation, restrict access, alter evaluation, and shape reproduction.

ities, professional reputation, cultural meaning, social trust, and institutional influence. Some of these forms can be priced within a market; others require different descriptive or evaluative practices. Treating them as interchangeable units would obscure important aspects of knowledge production. Even where economic valuation is possible, the generation of value may depend on practices whose contributions are difficult to isolate or assign to an individual producer. Work that maintains archives, validates evidence, trains newcomers, corrects records, or sustains collaborative trust may alter productive conditions without producing a readily marketable output. An account of capital expansion must therefore investigate how heterogeneous values are created and recognized, and under what arrangements they can be converted into further productive capacities.

The term *circulation* extends the analysis beyond a one-time allocation of outputs. Knowledge may be reused, interpreted, taught, transformed, or incorporated into additional productive structures. Revenue may finance renewed research or be distributed to claimants who did not participate in production. Recognition may attract collaborators, institutional support, and opportunities to influence future standards. Data generated through publicly supported activities may become inputs to proprietary tools, while the tools themselves may create new public benefits and dependencies. The direction, conditions, and accessibility of these movements matter. A beneficial return to a contributor need not take the same form as the original contribution; a distributed collective can likewise maintain productive conditions through arrangements other than monetary transfer. The analysis consequently treats circulation as a pattern of transformations among heterogeneous, historically interpreted value forms rather than a conserved scalar flow. Relations of contribution, recognition, appropriation, and reinvestment may overlap and may change during the process being studied.

The generative-justice literature offers an important dialogue for these questions. Eglash’s account emphasizes unalienated circulation of forms of value and discusses distributed modes of participation, including peer production and community-based practice [26]. The present investigation draws from the distinction between value circulation that sustains generative conditions and arrangements through which value becomes separated from its contributors. It proposes to examine such patterns across levels of knowledge production, with particular attention to institutional and epistemic mediation. This extension raises questions about the identification of a contributor in highly distributed research, the recognition of maintenance and interpretive labour, the conversion of public contributions into private advantages, and the conditions under which those advantages contribute to or diminish the continued capacities of other participants. These questions require case-specific attention to legal rights, consent, obligations, alternatives, governance, and the historical conditions of contribution.

Power enters the analysis at several points. Control over funds, infrastructure, and access can alter which knowledge-producing activities are feasible. Authority over procedures and methodological standards can affect how knowledge claims are generated, tested, recognized, and communicated. Control over archives, platforms, or evaluative institutions may shape the practical visibility of contributions and

the routes through which they can be used. At a further level, actors can exercise influence over the institutional arrangements that assign ownership, authorize conversion of value, and determine whether contributors may challenge decisions affecting their work. In these respects, power concerns the configuration of possibilities available to participants as well as the distribution of benefits from accomplished activity. The power relations of a knowledge system may reinforce particular patterns of accumulation, but the existence and operation of such mechanisms require evidence rather than inference from organizational scale alone.

Science studies has already examined important forms of cumulative advantage. Merton's account of the Matthew effect considers the unequal allocation of scientific recognition and its relationship to the communication of research [64]. This literature helps distinguish differential recognition from underlying contributions and suggests routes through which recognized standing may influence further opportunities. The present paper extends the analytical question to generative dependency structures: the opportunity to reproduce advantage may depend partly on which methods, infrastructures, concepts, and governance mechanisms are controlled, how widely they are required, and how benefits obtained at one level can be mobilized at others. Such cross-level effects remain hypotheses to be assessed through theoretical examination and empirical research. The existence of cumulative advantage in a recognition system does not by itself demonstrate extraction or dependence across every generative level.

The distinction between *appropriation* and *extraction* also requires explicit development. Appropriation may describe the allocation or taking of resources and benefits according to particular legal and institutional rules, and it can take forms compatible with collective stewardship or negotiated exchange. Extraction, as used provisionally in the present framework, refers to a more specific arrangement in which actors are positioned to obtain value generated through the activities of others while exercising asymmetrical control over the conditions of those activities, potentially restricting the contributors' capacity to participate in their continued reproduction or transformation. This working description identifies objects of analysis without settling in advance a general theory of exploitation. Exploitation judgments may additionally depend on the selected political-economic tradition, the nature of labour relations, historical claims to productive resources, the quality of consent, the distribution of costs and risks, and the normative standards under which the arrangement is evaluated. Even severe asymmetries require examination of their operative mechanisms. Conversely, formally open access to a product may coexist with concentrated control over the infrastructure needed to use it productively.

Academic publishing illustrates why these categories are already part of an established scholarly conversation. Peekhaus explicitly applies primitive accumulation and alienation to enclosure effects associated with capitalist control of academic journal publishing [76]. That analysis provides a concrete predecessor to the present inquiry and establishes that extending primitive-accumulation arguments to knowledge-producing institutions is not itself a novel move. The proposed contribution concerns a more differentiated account of where capital accumulates within generative dependencies and how value, effective control, and productive capacity circulate across those dependencies. The application of this proposal to contemporary scholarly publishing would require evidence about particular contractual arrangements, platform infrastructures, legal rights, institutional practices, and alternatives. The current paper does not infer the presence of extractive relations in a named institution from a general description of its organizational form.

The possibility of deep-level extraction merits careful examination. A productive condition situated close to a widely shared epistemic or methodological basis can participate in many otherwise distinct activities. Exclusive or asymmetric control over that condition may give its controller influence over downstream access, recognition, financing, or technical choices. If benefits obtained through such influence support further consolidation of the controlled condition, a recursive process of capital expansion and institutional dependence may emerge. The influence can be compounded when the controlled object is difficult to replace and when those affected have limited authority to revise the relevant standards or infrastructure. The potential consequences extend beyond the immediate appropriation of an output: the arrangement may reshape which activities can be undertaken, which forms of evidence remain legible, and which productive relationships can be maintained. Such possibilities motivate investigation of

generative-depth asymmetry, an expression used here for the model-dependent distribution of influence associated with the position of controlled productive conditions in a generative dependency structure.

The analysis must also make room for counterexamples and alternative institutional trajectories. A generally useful foundational theory may remain freely accessible, with multiple independently maintained implementations and no single practical gatekeeper. An application-specific service may become an indispensable component for a large number of activities, giving its controller considerable structural leverage despite a relatively localized conceptual role. Collective management of infrastructure may strengthen public capabilities while nevertheless imposing participation costs, unequal demands for maintenance work, or exclusionary practices. A privately maintained platform may support important public knowledge production while reserving certain decision rights. These cases show that generative level, legal ownership, institutional form, and practical dependency require distinct measurements. The framework aims to clarify such combinations and their consequences, including circumstances under which apparently similar levels of accumulation produce contrasting outcomes.

The converse process is equally important: accumulating knowledge capital may expand the ability of a community to reproduce and revise the conditions of knowledge production. Common repositories, teachable methods, shared instruments, cooperative maintenance, publicly contestable standards, and accessible opportunities for participation can make subsequent production possible for actors who did not contribute to the original investment. Such arrangements can yield distributed benefits and preserve possibilities for independent experimentation or institutional change. Their reproduction nonetheless involves costs, unequal commitments, and decisions about scarce resources. Publicness is therefore treated as a matter of effective access, participation, control, and sustained capability rather than merely a label attached to a resource. A resource may be legally public yet inaccessible in practice; an institutionally shared infrastructure may remain vulnerable to an unrecognized dependence on a specialized group of maintainers. Attention to these practical conditions allows the inquiry to compare commons-based, public, cooperative, and other collective formations without presuming that they are free of power asymmetries.

The relationship between capital expansion and generative transformation adds a further conceptual difficulty. A knowledge-producing system can acquire capabilities that support a greater range of activities within existing rules; it can also develop capacities to revise its rules, standards, categories, and means of participation. The latter transformation changes the basis on which earlier and later capacities are compared. A growth measure defined over a fixed output vocabulary may consequently fail to register newly available forms of inquiry or may misinterpret the disappearance of obsolete activities as a simple loss. Any formal account must specify its representation of productive activities, the scope of admissible comparison, and the observations needed to evaluate changes. The paper will explore models based on partial orders and networks of generative dependency, while allowing those networks and their interpretations to evolve. These constructions are methodological instruments and carry no claim to reveal a complete ontology of historical knowledge creation.

Historical ordering requires similar care. The terms *accumulation*, *expansion*, *inheritance*, and *reproduction* refer to relations whose ordering must be specified by the research design. A legal chronology, a sequence of recorded contributions, a causal ordering of required conditions, and a participant's own account of institutional change may provide different and partially incompatible ways of identifying historical development. A privileged universal temporal coordinate is unnecessary for the initial conceptual argument. In subsequent formal sections, the relevant history will be represented through documented or posited relations of continuation, dependency, or transformation, with the distinction between observed history and admissible but unobserved development maintained explicitly. Differences in empirical timescales between technologies, institutions, and conceptual practices will likewise require local interpretation rather than an assumed common rhythm of change.

The breadth of the inquiry creates a risk of excessive generalization. Knowledge production encompasses practices in natural sciences, mathematics, engineering, medicine, social sciences, humanities, education, public inquiry, journalism, and cultural interpretation. The standards governing evidence, authority, authorship, reproducibility, responsibility, and value vary across these domains. Scientific

validation is not interchangeable with historical interpretation, and formal representability does not establish epistemic legitimacy. The present framework therefore treats public knowledge production as a comparative field of institutional and generative relations while preserving the situated norms of particular practices. It seeks transferable analytical questions, with local answers dependent on the production system examined. Empirical research will be needed to assess which concepts support fruitful comparisons and which require domain-specific revision.

The paper's principal research questions can now be stated in connected form. First, through which historical processes do durable knowledge-producing conditions take shape, and when does their formation involve primitive accumulation in the historically specific sense of separation or dispossession? Second, how can the accumulation of such conditions support recursive expansion of productive capacities under distinct institutional configurations? Third, how do generative position, dependency, and substitutability condition the reach of accumulated knowledge capital? Fourth, how are resources, produced outputs, skills, decision rights, and opportunities to revise generative conditions allocated among different participants? Fifth, through which mechanisms are heterogeneous forms of value created, recognized, converted, circulated, appropriated, and reinvested? Sixth, how does power shape these processes, and under what circumstances do asymmetric relations become structurally extractive or undermine the continued productive capacities of contributors? Finally, how might public, commons-based, cooperative, and other collective arrangements reproduce and transform shared generative conditions, and what criteria are appropriate for examining their ethical and justice-related implications?

The proposed contribution has four components. The first is a vocabulary that separates the historical specificity of primitive accumulation from a broader problem of initial knowledge-capital formation, and separates changes in productive capability from changes in ownership or control. The second is a generative-level analysis relating the consequences of accumulated conditions to their position, reach, and replaceability within historically evolving dependency structures. The third is an account of heterogeneous value circulation that traces contributions, appropriation, conversion, reinvestment, and the maintenance or alteration of productive capacities. The fourth is a comparative approach to power and governance in which institutional labels are subjected to empirical description and relations of extraction are assessed by identifiable mechanisms. Each component is preliminary. Its usefulness should be evaluated against established political-economic concepts, alternative institutional theories, and the results of subsequent empirical investigation.

The manuscript proceeds in five linked stages. Sections 2–4 establish the political-economic vocabulary and a model-relative account of generative levels. Sections 5–8 examine the historical formation, recursive expansion, institutional organization, and differentiated control of productive knowledge capital. Sections 9–12 address heterogeneous value creation and circulation, power, and conditions under which appropriative arrangements warrant investigation as potentially extractive. Section 13 gives a preliminary relational formalism; Sections 14–16 assess documentary illustrations, ethical implications, and research limits. Section 17 provides a synthesis. Appendices A–I document the terminology, political-economic background, formal representations, counterexamples, institutional models, and empirical research design. This architecture separates historical explanation, conditional mathematical results, empirical identification, and normative judgment while making their points of contact explicit.

The investigation begins from an open proposition: the accumulation and expansion of knowledge-producing conditions may enlarge shared possibilities of inquiry, concentrate opportunities for appropriation, or combine both tendencies within the same historical configuration. Differences among these outcomes depend on the evolving relations through which productive conditions are formed, controlled, used, and renewed. Their study therefore calls for attention to the generative position of accumulated resources, the heterogeneity of circulating value, and the power relations through which participants gain or lose the capacity to participate in the further creation of knowledge.

2 Political-Economic and Epistemic Foundations

The purpose of this section is to establish the intellectual foundations for a comparative account of knowledge-capital formation and expansion. The immediate task is to identify what can be carried into a multilevel analysis from classical political economy, accounts of scientific organization and cumulative advantage, the economics of information, commons scholarship, generative justice, and studies of epistemic infrastructure. The discussion is interpretive and comparative: it reconstructs analytical contributions and identifies the assumptions under which they may be combined, while preserving disagreements about the meaning of capital, value, property, and productive agency. Six subsections treat the historical formation of capital, accumulation and reproduction, collective knowledge production, commons governance, heterogeneous value circulation, and epistemic power. The distinctions developed here provide conceptual orientation for the definitions in Section 3 and the generative-dependency analysis in Section 4.

2.1 Primitive Accumulation and the Historical Formation of Capital

The expression *primitive accumulation* acquires much of its theoretical significance from Marx's analysis of the historical constitution of capitalist production. Marx addresses a problem that arises when an already operating system of capitalist accumulation is treated as though its conditions could be explained by the same processes that the system itself presupposes. The accumulation of capital presupposes capitalist production and the availability of labour power within determinate relations of property. An account of the system's emergence therefore requires inquiry into the historical formation of those relations. In *Capital*, the investigation of so-called primitive accumulation centres on the separation of producers from their means of production and the transformation of these conditions into means for commanding labour [61]. Violence, legal compulsion, enclosure, and the restructuring of property relations enter this historical account as mechanisms with explanatory significance. Primitive accumulation in this sense cannot be reduced to the existence of a first quantity of wealth or to the fact that a productive system needs resources in order to begin operating.

The meaning of *capital* itself is implicated in this interpretation. A piece of equipment, an archive, or a fund may serve as a condition of production under different social relations. For Marxian political economy, its functioning as capital has to be understood within a determinate relation of production and valorization. Such a reading cautions against assigning capitalist properties to a resource simply because it is durable, useful, or capable of supporting further activity. The present inquiry nonetheless has reasons to investigate a broader phenomenon: scientific, artistic, educational, and technical communities assemble capacities whose continued use can enlarge the range of knowledge production, including in arrangements where commodity exchange and private appropriation are limited. The manuscript therefore maintains two vocabularies with different analytical tasks. *Initial knowledge-capital formation* provisionally names the assembly of relatively durable productive conditions within a specified knowledge-producing system. *Primitive accumulation*, in its historically specific sense, concerns transformations of social relations, especially separation, dispossession, and enclosure, involved in establishing capitalist forms of production.

The relationship between these concepts is an object of historical inquiry. Consider a hypothetical group that collectively builds a repository of research materials and establishes rules for its continued maintenance. The resulting repository could constitute an initial formation of productive conditions relative to that group. If access to a previously shared repository were subsequently made contingent on exclusive contractual arrangements, and contributors became dependent on a controller of the repository for the use of their own work, a different process would enter the analysis. Its relation to enclosure or primitive accumulation would depend on the precise history of control, the degree of effective separation, and the economic relations thereby produced. An institution's expansion of holdings is insufficient evidence of dispossession; conversely, the absence of a physical seizure does not settle whether meaningful access or productive autonomy has been curtailed.

The notion of *initial* formation also requires a scale of analysis. A university laboratory may begin

with equipment, trained personnel, inherited theories, public funding, and established research conventions. These conditions are initial relative to the newly constituted laboratory but products of long and heterogeneous histories when considered at the level of a scientific field, an educational system, or a wider social formation. The analyst should therefore specify a system boundary, the relevant inherited conditions, and the transformation by which those conditions become collectively productive. A universal historical origin is unnecessary to make a local formation process intelligible. This approach also prevents a conceptual slide from an accumulation that is *initial for the chosen case* to an accumulation that is *primitive in Marx's historically specific sense*.

Research on academic publishing demonstrates why the distinction is consequential. Peekhaus explicitly applies primitive accumulation and alienation to the enclosure of scholarly communication, examining capitalist control over the academic publishing environment and the tensions it creates for the professoriate [76]. That application gives an existing political-economic interpretation of knowledge enclosure with which the present research must engage. A further inquiry into generative levels would have to establish, case by case, whether control concerns a collection of outputs, the means through which outputs are circulated, or deeper conditions governing what work becomes visible, creditable, or reusable. The extension proposed here is an analytical differentiation of the positions and dependencies implicated in such processes. It does not purport to derive a new historical account from the mere use of a generative metaphor.

2.2 Capital Accumulation, Reproduction, and Expansion

Accumulation has a reproductive dimension. Marx's discussion of simple reproduction and enlarged reproduction treats repeated production as a process that also reproduces the social relations through which production takes place; the accumulation of capital can thereby enlarge both the productive scale and the relations of dependence characteristic of capitalist production [61]. For an inquiry into knowledge production, this connection is particularly useful: a repeated activity can reproduce equipment and research skills, but it can also reproduce intellectual-property arrangements, accepted evaluation standards, organizational hierarchies, and the social distribution of opportunities to conduct further work. Expansion of activity and reproduction of the institutional conditions of that activity are related questions, though they need not have identical outcomes.

It is helpful to distinguish *resource accumulation*, *capability accumulation*, and *relational reproduction*. Resource accumulation concerns the acquisition, conservation, and aggregation of materials that may be mobilized in knowledge-producing activity: recorded information, instruments, financial means, computing facilities, and reference collections. Capability accumulation concerns changes in what participants, individually or collectively, can actually accomplish using such resources. Relational reproduction concerns the continuing arrangements through which resources and capabilities become available, coordinated, evaluated, and controlled. These distinctions are analytical and their boundaries may overlap. A maintained repository, for example, comprises stored materials, routines of curation, contributor skills, and governance arrangements whose conjunction makes the repository productive. An increase in storage capacity does not by itself demonstrate a corresponding increase in usable collective research capability.

The classical political-economic problem of appropriation becomes more complicated when knowledge-related resources are considered. Information and codified knowledge may support repeated use by multiple parties, while their generation, interpretation, verification, and maintenance involve labour and material costs. Arrow's economic treatment of invention provides a foundational point of reference for tensions between the production of information and private incentives to appropriate its returns [3]. This literature is helpful for understanding why knowledge may have effects outside an individual producer's immediate transaction. Its conceptual vocabulary, however, should not exhaust the social relations of inquiry. Research capability can depend on access to facilities, acquired interpretive judgement, trustworthy communities, and institutional permission, even when a document is freely readable.

The accumulation of influence and recognition also deserves independent analysis. Merton's accounts of the Matthew effect examine the unequal allocation of recognition and cumulative advantage in scientific communication and reward systems [64, 65]. These studies suggest that an initial advantage in visibility or recognition may condition subsequent opportunities to obtain resources and further recognition. The direction and strength of such feedback must be established for a particular institutional setting. A researcher or group may accumulate credit without exclusive ownership of an underlying idea; another actor may control costly facilities while possessing limited epistemic authority. Reputational accumulation, legal appropriation, and command over productive conditions therefore need to be represented as distinguishable dimensions, even when empirical cases display mutually reinforcing relations among them.

Bourdieu's analysis of economic, cultural, and social forms of capital provides a related but distinct vocabulary. The different forms of capital have field-dependent efficacy and can, under specified conditions, be converted into one another [11]. For the present purpose, this approach encourages attention to how educational credentials, recognized expertise, networks of cooperation, and financial resources mediate one another within knowledge production. It also raises a conceptual difficulty: a framework that uses the term *capital* for both capitalist social relations and a broad set of social capacities risks conflating distinct theories. The present paper will treat these conceptual traditions as partially translatable analytical approaches, identify the particular relation invoked in each use, and reserve strong claims of equivalence for arguments that establish them. In particular, the proposed category of *productive knowledge capital* is a working construct whose explanatory merits require comparison with alternatives such as productive capacity, social infrastructure, and institutional resources.

Capital expansion, accordingly, should be investigated through at least three separately observable changes: enlargement of a productive system's accessible capabilities; alteration of rights and effective control over the conditions of production; and changes in the mechanisms of value creation, distribution, and reinvestment. These changes can align, diverge, or occur on different historically specified sequences. A public research infrastructure may gain new participants and uses while preserving distributed governance. A separate infrastructure may experience rising output together with increasingly centralized decisions about data access and standard-setting. A valid comparative study should be able to describe each trajectory without deriving an assessment of control from output growth alone. The potential for accumulated advantages to affect the very conditions of further accumulation will become especially important once generative dependencies are introduced.

2.3 Knowledge, Intellectual Capital, and Collective Production

Knowledge production involves collective coordination across persons, material arrangements, symbolic practices, and historical inheritances. Theoretical work, experimental investigation, mathematical proof, historical interpretation, public documentation, educational practice, and software development have different criteria for successful outcomes. Their productive conditions nonetheless frequently include accumulated materials, methods, interpretive competencies, forms of cooperation, and mechanisms for evaluating and transmitting results. The expression *public knowledge production* is used provisionally for a field of activity in which knowledge-creating relations, their outputs, or their conditions have consequences for a wider set of contributors, users, and publics. More exact boundary criteria will be formulated in Section 3. The term does not imply that the relevant practices are uniformly open or subject to a single epistemic method.

Polanyi's account of the scientific community presents independent research decisions and mutual adjustment as simultaneous features of organized inquiry [77]. His argument for self-coordination is an institutional and normative account of scientific organization, rather than an empirical finding that decentralization is invariably more efficient. Researchers can pursue problems according to situated judgement while taking account of what others have established, disputed, or made available. Such coordination does not require the detailed central direction of every intellectual act. At the same time, the model's emphasis on scientific communities needs qualification when extended to other domains or

when examining systematic exclusions from participation. The organization of enquiry includes standards of competence, authorization, language, and credibility, all of which may distribute opportunities unevenly. The present analysis therefore regards intellectual independence and collective coordination as institutional achievements whose enabling conditions and exclusions require empirical study.

The emergence of open science also has a political-economic history. David's historical analysis situates the emergence of early modern European open-science institutions amid patronage, reputational incentives, and informational asymmetries [23]. The account concerns a historically situated institutional formation; extending its mechanisms to contemporary research infrastructure requires a separate comparison of incentives and governing relations. This historical perspective is significant because openness cannot be inferred solely from the technical reproducibility of information. Disclosure practices require incentives, conventions, institutions, and continuing expectations about legitimate circulation. An archive that anyone may read can still depend on restricted preservation equipment, a limited number of curators, a specialised language, or professional criteria that constrain meaningful use. Public access is thus a property of an institutional and practical relationship rather than an isolated property of a digital file.

Benkler's analysis of commons-based peer production offers a complementary account of large-scale coordination through distributed contributions and shared informational resources [8, 9]. The contribution to the present inquiry is an account of production that can be organized through social cooperation without equating coordination with the internal hierarchy of a corporation. Yet the conditions of successful peer production remain case-dependent. Contributors may differ in the time, technical competence, computing capacity, and social support they can provide. Maintenance may depend on a concentrated group even when code or documentation is openly licensed. Governance may rely on informal authority, technical gatekeeping, or the ability to review and integrate contributions. A model of collective accumulation should therefore trace the capacities that participants can mobilize and the rules under which those capacities are coordinated, rather than infer distributed control from distributed authorship.

The social production of knowledge also gives rise to multiple attribution questions. An output may be credited to an individual author while relying on instruments, datasets, conceptual systems, editorial procedures, unpaid maintenance, and educational investments assembled by many others. Attribution of authorship and the identification of causal contributions serve different purposes and operate with different evidentiary standards. Legal rights in a resulting work, recognition of intellectual contribution, the right to decide how a repository is maintained, and the ability to conduct further inquiry need not coincide. A single property vocabulary can obscure this heterogeneity. The manuscript will therefore distinguish ownership in the legal sense, rights of access and modification, effective productive command, institutional governance, and the recognition of contributions.

An additional difficulty arises when knowledge systems provide conditions for the creation of *new kinds* of knowledge. A statistical method may be repeatedly applied to familiar data, while a novel research language may reorganize the questions an institution can formulate. Both developments can be productive, but a fixed output count measures them differently. The generative-level approach will attempt to represent this distinction through changing dependencies among methods, interpretive rules, infrastructural components, and particular applications. At this stage the claim is methodological: identifying the location of a resource within a proposed dependency structure may help describe its potential consequences for later inquiry. It does not establish the value of that resource, the uniqueness of the dependency structure, or the existence of a universal hierarchy of disciplines.

2.4 Knowledge Commons and Commoning

The knowledge-commons literature provides an institutional framework for understanding shared resources as the objects of ongoing governance. Hess and Ostrom's edited volume investigates knowledge as a commons, bringing questions of access, institutional arrangements, collective action, and threats to shared knowledge resources into a common field of analysis [40]. Ostrom's research on common-pool resource governance analyses participant-devised and monitored rules, institutional endurance, and insti-

tutional failure in particular resource settings [70]. These studies provide comparative governance questions, while their empirical conclusions require qualification when applied to informational resources. The physical and economic properties of common-pool resources differ from many informational goods, so the transfer to knowledge production requires attention to the resource characteristics of the specific case.

A useful starting distinction concerns the *resource*, the *community of practice*, and the *governance arrangements* that connect them. A scientific data collection, for example, may be legally available under permissive reuse terms while practical access depends on technical infrastructure, documentation, and specialized interpretation. The people maintaining a repository may exercise consequential authority over standards and version histories despite the public legal status of the underlying data. Conversely, a repository managed by a public agency can permit extensive external reuse while offering little participation in its internal governance. A commons analysis therefore has to consider the enforceable rights, practical capacities, maintenance responsibilities, and channels for contesting rules. Each dimension may have a distinct institutional configuration.

Commoning highlights the practices through which shared productive conditions are constituted and sustained. Repeated acts of curation, teaching, dispute resolution, preservation, software maintenance, and cooperative financing can reproduce a commons across changes in membership and technology. Such labour is itself an object of political-economic inquiry. A commons whose users receive broad access may still place concentrated burdens on volunteer maintainers. If those burdens are not replenished through adequate time, resources, or collective support, the infrastructure can become fragile despite apparently successful dissemination. The relation between public benefit and the reproduction of the conditions that generate it should consequently be examined as an institutional mechanism, including the possibility of inequitable labour allocation within a shared system.

Commons governance and communism occupy different conceptual registers. The former identifies arrangements for collectively managing particular resources and practices; the latter refers to a family of political-economic theories and institutional programmes concerning production, property, and social organization. A commons can exist inside a predominantly capitalist economy, supported by public grants, private donations, volunteer work, or cooperative revenue. Communist conceptions of knowledge production may involve broader collective relations of property and planning, yet those conceptions require specification before being compared with observed commons institutions. Publicly owned resources, state-managed infrastructures, democratically governed cooperatives, and peer-production projects likewise need not have equivalent relations of participation or control. The comparative programme in this paper therefore treats institutional labels as descriptors requiring further specification, especially where claims concern freedom from extraction or equitable reinvestment.

A second distinction concerns the relationship between *accessibility* and *generative participation*. Access to a finished document can enlarge opportunities for use without giving readers authority to alter research standards, determine the repository's priorities, or direct its resources. Access to source code can permit independent modification while governance over a dominant deployment remains centralized. A shared infrastructure may allow participation in its design but impose substantial technical costs on those seeking to use it. These differences bear directly on capital expansion across generative levels: the capacity to reuse an application-level output and the capacity to revise a widely depended-upon methodology may have different implications for subsequent knowledge production. The institutional study of commons consequently supplies variables for analyzing distributed generative capability, not an automatic determination that common ownership produces a specific outcome.

Frishmann's account of infrastructure as a shared resource clarifies why these questions extend beyond information as such [34]. Infrastructure may support a broad range of downstream productive and social activities, including uses that the initial provider did not plan. The terms of access, the social value of shared use, and the evolution of dependent systems are therefore relevant to choices about governance. This account connects commons scholarship with the paper's proposed study of generative levels: a component's importance may derive from the heterogeneous practices that depend on it, while the practical reach of those dependencies is shaped by substitutability, interoperability, resources, and institutions.

Treating infrastructural openness as a potential condition for downstream generativity remains a hypothesis to assess in particular settings, especially where open access coexists with concentration elsewhere in the production system.

2.5 Generative Justice and Heterogeneous Value Circulation

The accumulation of knowledge-producing conditions also involves the creation, recognition, appropriation, and circulation of heterogeneous forms of value. Eglash's account of generative justice places particular emphasis on the return of value to its generators and on the maintenance of capacities for continued value generation [26]. This perspective is relevant to knowledge production because contributions may generate benefits in several domains while remaining dependent on the continued availability of shared productive conditions. An open educational resource may create learning opportunities; a research instrument may expand an institution's capacity for observation; an interpretation may transform public understanding; and a standard may support cooperation among otherwise separate organizations. These activities may also be connected to monetary returns, credentials, professional recognition, or institutional power. Their effects cannot be represented adequately by assuming a single naturally commensurable substance called *value*.

The present manuscript proposes an operational distinction among *value creation*, *value recognition*, *value appropriation*, and *value recirculation*. Creation concerns changes experienced as valuable under criteria appropriate to the activity and relevant evaluators. Recognition concerns the institutional processes through which such changes become visible and are attributed importance. Appropriation concerns claims, entitlements, or effective capacities to capture or direct some resulting benefits. Recirculation concerns the subsequent use, transfer, maintenance, and conversion of resources and capabilities in ways that affect conditions for further activity. These are analytical roles within a research design, not stages of a universally fixed temporal sequence. A claim to ownership may influence what is produced, while established evaluative criteria may determine which contributions can be recognized in the first place. The associated relations can be mutually constitutive and historically revised.

The heterogeneity of value introduces questions of conversion and representation. Financial revenues can be reinvested in shared computing infrastructure. Public recognition can support further fundraising. The maintenance of a multilingual archive can improve access to knowledge and create new opportunities for participation without producing a readily measurable monetary return. A training programme can increase the practical capacities of participants, whose activity may subsequently improve a collective knowledge resource. Conversely, recognition concentrated on highly visible contributors may coexist with poorly acknowledged maintenance labour. Bourdieu's discussion of conversions between different forms of capital helps identify social mechanisms through which some conversions become possible and acquire institutional legitimacy [11]. Such conversions have costs, constraints, and evaluative conventions; treating them as exchanges between fixed equivalents would lose much of the phenomena of interest.

Questions of *circulation* should therefore include the topology of participating relations, the mechanisms enabling transfers or conversions, and the arrangements through which benefits are reinvested or withheld. A system may circulate knowledge openly while concentrating payments, access to infrastructure, or authority over future standards. Another system may distribute monetary benefits relatively evenly while permitting a small body to decide which kinds of inquiry are supported. For this reason, circulation of an output and circulation of the capacity to generate further outputs should be tracked separately. The relevant observations may include rules for allocating revenue, documented access privileges, contributor recognition, rights to fork or modify a system, maintenance costs, and procedures through which participants revise institutional arrangements. These measures require local interpretation and could conflict; the objective is an intelligible account of their relation, rather than a premature composite score.

Extraction adds a further issue. Unequal benefits can arise under many kinds of coordination and may result from explicit agreements, differentiated responsibilities, or contingent successes. To iden-

tify a structurally extractive relation, the analysis must specify the mechanism through which an actor acquires or retains value created through the contributions of others, together with the conditions under which those contributors can sustain or contest their participation. Restricted alternatives, unilateral control over essential interfaces, inequitable terms of access, and durable constraints on the reuse of collectively produced resources may be relevant indicators. Their presence, significance, and consequences require case-specific evidence. An inquiry into justice also needs explicit normative criteria; empirical asymmetry alone cannot settle how benefits ought to be distributed. Generative justice provides one family of normative considerations, while questions of authorship, democratic participation, institutional responsibility, and productive autonomy may require additional arguments.

An important consequence for the present research is that accumulation under commons-based or public arrangements should be investigated with the same conceptual care as accumulation within firms. Publicly supported knowledge production may generate expanded shared capacity while harbouring unequal unpaid maintenance commitments, exclusionary credential systems, or centralized authority. Commercial arrangements may generate substantial downstream capabilities while establishing contractual dependencies that enable the concentration of returns. Neither observation supplies a comprehensive judgment about a political-economic system. Comparative explanation should identify the concrete value paths, the rights and capabilities of relevant contributors, and the effects on continued knowledge production. The potential recursivity of extraction and public value return will be studied more directly in Sections 10–12.

2.6 Epistemic Infrastructures, Institutional Power, and Knowledge Production

The final foundation concerns the institutions and material-symbolic infrastructures through which knowledge becomes recordable, comparable, credible, and actionable. Star and Ruhleder’s study of collaborative information infrastructure shows how access and use are shaped by organizational, practical, and communicative conditions beyond the availability of software as a technical artefact [85]. Bowker and Star’s study of classification systems documents the consequential role of categories and standards in organizing both information infrastructures and social practices [12]. Together, these contributions indicate why an inquiry into knowledge capital needs to consider the rules and interfaces through which outputs are articulated, interpreted, and linked to other activities. An epistemic infrastructure may be productive precisely because it becomes incorporated into many otherwise distinct practices.

Institutional power can operate through several mechanisms. Legal ownership may grant rights to exclude or license use. Administrative authority may control budgets, eligibility criteria, and access to facilities. Technical control may govern software interfaces, data formats, computational capacity, or changes to standards. Epistemic authority may influence what counts as admissible evidence, recognizable expertise, or a legitimate research question. Each mechanism may affect the production and circulation of value. Their empirical distribution may be fragmented: a library can hold copies of a resource while an external supplier controls its indexing service; a scientific community can establish a method while funding agencies influence its uses; or a public institution can set access policy while a private contractor maintains essential computing facilities. The analysis must determine the exercise of control rather than infer it from a broad ownership label alone.

The proposed notion of *generative levels* introduces a structural consideration into this study of power. A generative level denotes a position within an analytically specified structure of productive dependencies. One resource may support a relatively narrow application, while another forms part of widely shared conditions for validation, representation, coordination, or further invention. A classification standard or foundational computational method can thus have broad downstream reach under particular conditions. Its importance depends on the actual activities that rely on it, the availability of substitutes, the possibility of independent reimplementations, and the resources needed to change practices. The deeper position of a component in an illustrative tree is insufficient evidence of greater power or social importance. Dependencies may involve multiple jointly required conditions, mutually reinforcing components, recursive revisions, and paths through which applications transform established methodologies.

Table 2: Analytical contributions and scope conditions of selected theoretical traditions.

Tradition	Contribution to the present inquiry	Key interpretive boundary
Marxian political economy	Historically constituted capital relations, separation, appropriation, and social reproduction	Primitive accumulation retains its specific relation to dispossession and capitalist formation
Knowledge and innovation economics	Information characteristics, incentives, and downstream effects of shared knowledge	Market valuation does not exhaust epistemic or social value
Sociology of science and capital	Recognition, cumulative advantage, and conversion among resources and statuses	Prestige, property, and productive command require separate identification
Commons and peer-production studies	Rules of access, collective maintenance, distributed contribution, and governance	Commons, public ownership, and communist conceptions are analytically distinct
Generative justice	Heterogeneous benefits, value return, and continued capacity for generation	Normative criteria need specification alongside empirical circulation mechanisms
Infrastructure and classification studies	Situated conditions of access, standard-setting, and epistemic mediation	Broad downstream influence depends on concrete dependencies and alternatives

This qualification is especially important for the question of extraction. Exclusive control of a resource used by many downstream producers could enable the controller to impose conditions of access, influence evaluation, or appropriate a share of resulting returns. Yet broad use also may arise from widespread voluntary adoption of an openly revisable standard. A tightly specialized application can become a crucial bottleneck even when its conceptual position appears close to a generative “leaf.” The mechanism of control therefore has to be related to effective dependency and feasible alternatives, rather than the nominal generality of the resource. This perspective provides a way to investigate whether appropriation at some generative positions has more persistent consequences for collective knowledge production without assuming that a foundational level is intrinsically more extractive.

A further source of power lies in shaping the distribution of visibility. Classification systems, search interfaces, citation conventions, professional credentials, and evaluation procedures influence whose outputs can enter a knowledge system and how these outputs are evaluated. Merton’s analysis of cumulative recognition offers one possible feedback mechanism in scientific contexts, while infrastructure studies suggest that recognition is mediated through technical and institutional arrangements [64, 12]. Such effects can influence the perceived value of contributions as well as opportunities to accumulate further resources. Nevertheless, a particular ranking or standard should be interpreted within the domain of evidence and its institutional purpose; the existence of an evaluative framework does not by itself establish unjust exclusion or intentional domination. The empirical question concerns its design, implementation, contestability, and consequences for knowledge-producing capabilities.

Table 2 summarizes the contributions and limits of the theoretical strands reviewed in this section. Its columns identify analytical resources for subsequent inquiry rather than a reduction of distinct theories to an identical vocabulary.

The foundations surveyed in this section jointly motivate a relational research agenda while retaining significant differences in their core concepts. Marxian accumulation analysis foregrounds historically specific relations of capital and labour; commons research foregrounds institutionally governed sharing; generative justice introduces questions of value return and the reproduction of creative capacities; and epistemic infrastructure studies trace the organizational conditions through which knowledge is classified and used. The proposed multilevel framework will examine their intersections through specified production systems and documented relations among resources, capabilities, control, and value. Such an investigation can yield comparative hypotheses about how accumulation changes the conditions of further knowledge production, but it must remain answerable to competing conceptual interpretations and empirical counterexamples. Section 3 therefore turns to the precise analytical categories needed for the subsequent formal and institutional comparisons.

3 Conceptual Foundations of Knowledge Capital

This section specifies the analytical vocabulary through which the paper investigates knowledge-capital formation and expansion. Its objective is to make a comparative inquiry possible without presuming that a socially useful knowledge resource is automatically capital in a historically specific political-economic sense, or that public accessibility determines the organization of production. The discussion first identifies the boundaries of public knowledge production, then distinguishes resources, productive capacities, and generative conditions. It subsequently defines initial capital formation, primitive accumulation, expansion, appropriation, and extraction, before establishing a relational account of their historical constitution. The mode of argument is conceptual and methodological: the categories are proposed as instruments for interpreting concrete institutional histories and for constructing hypotheses in later sections. Candidate observations are identified where appropriate, while the formal dependencies among generative levels are reserved for the later formal analysis and for the generative-level framework in Section 4.

3.1 Public Knowledge Production and Its Institutional Boundaries

Knowledge production designates activities through which persons and organized collectivities develop, investigate, articulate, test, contest, interpret, preserve, transform, and transmit claims, practices, or representations that can enter further processes of inquiry. The term covers diverse epistemic enterprises whose methods of warrant differ. A mathematical argument, an experimental measurement, an archival interpretation, a field observation, and a software model each involve forms of production, but their epistemic achievements cannot be assessed by a single invariant criterion. The present definition therefore identifies a family of organized activities and their enabling relations; it does not settle their truth conditions, cultural significance, or normative standing. Education, curation, translation, and maintenance belong within the research field when their activities causally sustain or transform knowledge-producing capacities, even where they yield few conventionally countable publications.

The word *public* requires several distinct specifications. One sense concerns *public accessibility*: results, materials, or methods can be inspected and used by an identified audience under particular terms. A second concerns *public participation*: the governance or production process admits contributions from a wider population, potentially subject to qualifications, procedures, and resource limitations. A third concerns *public support*: resources, labour, or institutions are financed or otherwise sustained through public arrangements. A fourth concerns *public consequence*: a knowledge-producing process shapes the opportunities, collective understandings, institutions, or material conditions of persons beyond its immediate producers. These dimensions may overlap, but none entails the others. A publicly financed project may distribute its outputs under restrictive conditions. A privately maintained open repository may attract public contributions. A specialized professional infrastructure may have extensive public consequences even when meaningful access requires considerable training and equipment.

For purposes of this manuscript, *public knowledge production* refers to a historically situated field of knowledge-producing activities whose outputs, productive conditions, contributions, or consequences are materially implicated in relations with an identifiable public or collectively affected constituency. This is a deliberately broad research domain, not a declaration that its institutions are normatively public-spirited. Analysis should specify which public dimension is salient and who is included or excluded by it. The relevant public can consist of a research community, a linguistic community, a civic association, users of a technical standard, or a wider population dependent upon a knowledge-intensive service. Publics may overlap, diverge in their interests, and change through the very practices under examination. The legal designation of a public institution supplies evidence about one aspect of its organization; it does not replace investigation of substantive accessibility, governance, and effects.

A *knowledge-producing system* is the provisional unit within which resources, practices, activities, and governance relations are traced. It may be a laboratory, publishing network, open-source project, archival consortium, research field, or broader institutional ecology. System boundaries are analytical choices justified by the explanatory question and the available observations. The same resource can

be internal to one research system and inherited from another. A scientific database, for example, may be an output of a curatorial collaboration, an input to several disciplinary communities, and an instrument through which an administrative organization exercises access control. The analyst should identify boundary-crossing contributions, dependencies, and claims rather than treat the system boundary as a wall around self-sufficient production.

The distinctions between public accessibility, coordinated production, and governance have precedents in scholarship on knowledge commons and peer production. Hess and Ostrom examine knowledge as a shared resource whose management raises questions of collective action and institutional design; Benkler examines production coordinated through distributed contributions and social relations [40, 8]. The present inquiry uses these contributions to motivate separate attention to the accessibility of outputs, the distribution of labour, the rights to modify common resources, and control over the conditions of further production. The normative significance of public knowledge production must be examined alongside its social organization, including the costs and exclusions that may accompany ostensibly open institutions.

3.2 Knowledge Resources, Productive Capacities, and Generative Conditions

A *knowledge resource* is a relatively identifiable object, arrangement, record, or practice that may be mobilized within a knowledge-producing activity. Examples include a documented result, a corpus, a trained model, a research instrument, a method specification, a manuscript collection, or a procedure for preserving and retrieving observations. A resource may be embodied in people, material artefacts, institutional relations, or combinations of these. Describing a resource does not yet establish that it is accessible, reliable, sufficient for productive use, or capitalized. Its possible uses depend upon interpreters, complementary resources, governance conditions, and the aims of inquiry. A digital collection whose contents are publicly downloadable may have limited practical usability for contributors lacking the language, expertise, computing capacity, or time needed to work with it.

A *productive capacity* is the context-dependent ability of an actor or coordinated set of actors to carry out specified knowledge-producing activities under a stated collection of conditions. Capacity is therefore relational: it involves capabilities, permissions, access, organizational coordination, and opportunities for action. The competence of a researcher to perform a statistical analysis differs from the operational ability of a laboratory to sustain an experimental programme. The latter may require trained personnel, instruments, stable funding, documentation, a viable maintenance organization, and procedures for reviewing findings. Neither the ownership of an instrument nor formal permission to access a dataset is by itself sufficient evidence of the relevant operational capacity. Candidate observations include demonstrable procedures, maintained services, reproducible workflows, successful collaborations, and documented opportunities to undertake classes of inquiry; such observations require interpretation in their local context.

A *generative condition* is an enabling or constraining relation that helps determine which kinds of knowledge-producing transformations are feasible for an actor or collective. A condition may consist of a resource, a practice, a rule, a social relation, or their conjunction. Research funding may support the acquisition of an instrument, while legal access conditions determine the tasks for which the instrument can be used; the conjunction matters for actual production. Standards of evidence and categories of admissible explanation can also function as generative conditions because they shape what investigations an institution can recognize and sustain. The expression does not imply an ultimate ontological substrate. The identification of generative conditions is an explanatory hypothesis, relative to a specified system, population of activities, and historical configuration.

It follows that a resource, a capacity, and a generative condition are different analytical roles rather than mutually exclusive classes of things. A method is a resource when it is stored as an accessible specification; part of a productive capacity when investigators can competently apply and adapt it; and a generative condition when further activities rely on it in a specified setting. The same method may also become a generated output after being revised through application. Such role changes matter for

Table 3: Analytical roles in the constitution of productive knowledge capital.

Analytical role	Specification	Candidate evidence or question
Knowledge resource	Identifiable material, symbolic, embodied, or institutional element available for possible use	Records, instruments, methods, repositories, maintenance histories
Productive capacity	Situated ability of actors to perform specified activities under enabling conditions	Competence, operational continuity, demonstrated workflows, accessible complements
Generative condition	Enabling or constraining relation shaping feasible transformations	Dependencies, permissions, standards, coordination and substitution possibilities
Productive knowledge capital	Accumulated and maintainable configuration supporting further knowledge production	Reproducible combinations of resources, capacities, governance and continuing use
Capitalist capital relation	Historically specific organization of control, labour and valorization	Property and employment relations, appropriation, contractual and financial claims

multilevel accumulation. They enable a theory to represent the movement between generated knowledge and the conditions of further generation without fixing an immutable division between foundational and applied knowledge. They also expose why a measure such as repository size captures only a portion of the knowledge-capital phenomenon.

The working expression *productive knowledge capital* refers in this manuscript to a relatively durable and reproducible configuration of resources and relations that can be mobilized to sustain, extend, or transform knowledge-producing capacities across an identified history. Durability is relative: an arrangement must be reproducible or maintainable across relevant activities or episodes, rather than permanent. The word *capital* in this proposed construct identifies accumulated productive potential and the possibility of further productive deployment. It does not independently establish capitalist valorization, market exchangeability, property ownership, or a measurable capital stock. These further attributes require their own evidence. The distinction remains necessary because Marxian capital designates historically determinate relations of production and valorization, rather than a generic name for all useful productive conditions [61]. A Marxian reading may therefore reject the broader capital vocabulary in particular cases while accepting the underlying descriptions of productive capacities. The manuscript retains this disagreement as a substantive boundary of its comparative terminology.

Table 3 collects the working distinctions and indicates the kinds of evidence relevant to their investigation. The table identifies questions for research design rather than proposing a fixed measurement scheme across disciplines.

A further distinction concerns *generativity*, understood provisionally as the potential of a situated configuration to support a specified repertoire of further transformations. Productive capacity concerns what actors can undertake under existing conditions; generativity highlights the structure and variability of possible further productions, including the potential transformation of productive conditions themselves. The repertoire may include established operations, novel combinations, and revisions to the methods by which production is organized. An observed expansion in output volume is only one possible manifestation of this broader phenomenon. Investigation should distinguish documented productive activity from inferred possibilities and from transformations that are merely imaginable to an external analyst.

3.3 Initial Capital Formation and Primitive Accumulation

Initial knowledge-capital formation names the assembly of an identifiable and maintainable configuration of productive conditions relative to a specified system boundary and starting configuration. The word *initial* marks the beginning of a particular explanatory sequence, such as the formation of a research organization, a shared technical facility, or a repository maintenance collective. It does not denote the first appearance of knowledge in a universal chronology. Initial conditions are frequently inherited from other histories: training was provided elsewhere, methods were developed by earlier contributors, infras-

849 tructure draws on public investment, and legal or epistemic conventions precede the institution under
850 study. An adequate account identifies what is newly assembled, what is inherited, and what remains
851 dependent upon external organizations.

852 An initial configuration can form through savings and investment, donated labour, public provision,
853 cooperative coordination, redistribution of equipment, social transmission of techniques, or the incor-
854 poration of existing outputs into further practice. These pathways need not share the same relations of
855 authority or appropriation. A commons-based technical project, for example, may accumulate maintain-
856 able source code, review competence, community trust, and documentation through voluntary contribu-
857 tions. A university may assemble a new research facility through public appropriations and collaborative
858 agreements. A firm may acquire comparable assets through market contracts and financial investment.
859 In each case an investigator can examine the growth of a capacity for future production, while separately
860 documenting the institutional conditions under which its resources and benefits are controlled.

861 The historically specific Marxian account of *primitive accumulation* addresses an additional and
862 sharper problem: the formation of capitalist social relations through processes such as the separation
863 of producers from their means of production [61]. This sense requires investigation of dispossession,
864 enclosure, coercion, legal transformation, or comparable mechanisms establishing dependence upon
865 controllers of productive conditions. Consequently, the presence of a newly assembled knowledge in-
866 frastructure provides evidence for initial capital formation, while a claim of primitive accumulation in
867 the Marxian sense requires analysis of the associated transformation of social relations. The two pro-
868 cesses may coincide, and some institutional histories may exhibit initial formation without the specific
869 dispossessive transformation described by Marx. A comparative terminology should preserve both pos-
870 sibilities.

871 A further issue is whether forms of *ongoing enclosure* can reproduce conditions resembling primitive
872 accumulation within already established knowledge systems. Research on academic publishing offers
873 one theoretically relevant line of inquiry: Peekhaus relates the enclosure of scholarly publishing to prim-
874 itive accumulation and alienation [76]. The empirical burden remains local. Investigators would need
875 to establish an earlier configuration of productive rights or capabilities, identify the mechanism of their
876 restriction or transfer, and examine whether contributors have become meaningfully dependent on the
877 new arrangement. A paywall, by itself, establishes a restriction on access under certain terms; its relation
878 to the historical separation of producers or the extraction of value requires additional institutional and
879 historical evidence. The broader vocabularies of enclosure and dependency may be applicable where the
880 historically specific category of primitive accumulation would be premature.

881 The accumulation process also depends upon its *reference scale*. A facility's founding resources
882 can be new for a department while continuing a decades-long field-wide accumulation of techniques. A
883 method developed within one community can later serve as an enabling condition in another, changing the
884 location and meaning of the relevant initial configuration. Publicly shared resources can permit multiple
885 systems to form productive capacities without requiring exclusive transfer of the underlying knowledge.
886 Conversely, their use may depend upon scarce complements, such as specialized instruments or costly
887 computing resources, and those complements can become sites of unequal control. The analysis should
888 therefore specify the original contributors, the institutions enabling access, and the reproducibility of
889 productive arrangements as they circulate between systems.

890 The distinction between formation and primitive accumulation matters for comparisons among
891 capitalist, commons-based, public, cooperative, and communist conceptions of knowledge production.
892 Broad productive accumulation can be investigated in each configuration, but the social meaning of that
893 accumulation depends upon relations of property, labour, governance, and value. Commons governance
894 and communism designate different bodies of institutional practice and political-economic theory; a
895 repository governed by contributors does not by itself instantiate communist production. In Marxian
896 terminology, it is also coherent to contend that a collectively maintained productive facility constitutes a
897 growing productive capacity without functioning as capital in the specific capitalist sense. The present
898 paper will make its intended sense of *capital* explicit whenever its distinction affects an inference.

3.4 Capital Accumulation, Capitalization, and Expansion

Accumulation describes changes through which a knowledge-producing system acquires or consolidates maintainable resources, competencies, infrastructural arrangements, and other conditions for further production. A collection of archived studies may grow, but the productive relevance of the additions depends on their quality, accessibility, intelligibility, and complementarity with existing practices. A system may accumulate technical artifacts while losing indispensable maintenance expertise; measured output growth and effective productive capacity can consequently diverge. The choice of indicators should reflect the productive function under investigation. For example, counts of reusable methods, continuity of community maintenance, successful integrations, or diversity of supported research tasks may be informative in different settings, subject to the reliability of each indicator.

Capital expansion, in the paper's broader working vocabulary, occurs when an accumulated configuration supports the enlargement, diversification, intensification, or reconstitution of knowledge-producing capacity. *Enlargement* concerns the range or scale of activities that can be undertaken; *diversification* concerns the emergence of qualitatively different activities; *intensification* concerns changes in throughput or reliability under relevant constraints; and *reconstitution* concerns transformations of the conditions under which further activities become possible. These aspects need not advance together. A technical standard may make a research procedure faster and more interoperable while narrowing the permissible forms of evidence. A shared repository may support many new users while the group able to revise its architecture remains small. The degree to which such changes constitute an improvement for the relevant public calls for a further evaluative account.

Capitalization is analytically distinct from accumulation and expansion. In a strict financial usage, capitalization concerns processes through which expected future returns are represented in capital values or tradable claims. More broadly within a knowledge-producing institution, the term may designate the organization of controllable resources, rights, or revenue channels so that an actor can appropriate returns associated with productive activity. These usages should be distinguished whenever applied to a case. Accumulating an openly usable dataset creates a potentially productive resource; establishing a proprietary entitlement over access to an essential interface may create a mechanism of capitalization; expanding the dataset's usefulness to more research areas may constitute a change in generative capacity. All three can occur together, but the evidence required to establish each differs.

The relevant changes can also diverge across participants. An institution may enlarge its collection of research outputs while concentrating the ability to index, license, or commercially analyze those outputs. Contributors may retain rights to individual articles but encounter limited avenues for influencing platform-level arrangements. Another institution may expand productive capabilities by sharing maintenance burdens, documentation, and decision rights with a wider range of participants. These examples establish comparison questions rather than general conclusions about particular kinds of institutions. Growth in revenue, publications, computing power, or user counts supplies only partial evidence about the capacities, dependencies, and value relations involved.

The expression *recursive expansion* draws attention to a further possibility: the products of one knowledge-producing process may enter the enabling conditions of other processes, including processes that transform the rules by which new knowledge is produced. A shared method can support further results, and some of those results can become reasons to revise the method. A collective's ability to maintain a repository may generate educational resources that enlarge the group of potential maintainers; the additional maintainers may then revise the governance and architecture of the repository. An exclusive infrastructure may also use revenues or data obtained from dependent activities to strengthen its infrastructural advantages. The existence and direction of such feedback depend on evidence about actual dependencies, reinvestment, participation, and alternatives. They should not be inferred solely from the abstract reproducibility of digital information.

This account avoids treating value growth as equivalent to capital expansion. Monetary returns are important in many settings, but heterogeneous social, epistemic, and institutional contributions resist straightforward summation. A new interpretive category may broaden participation and change the kinds of questions that can be posed, while producing no immediately observable market income. A

monetized service may generate substantial revenue while leaving contributors' independent productive capacity unchanged or diminished. Accounts of information economics and infrastructure help explain why public availability and the benefits of complementary use are important, while generative justice directs attention to the return of value to continuing productive capacities [3, 34, 26]. Their theoretical implications are examined within the limits of the particular arrangements in which value and capacity are assessed.

3.5 Ownership, Appropriation, Extraction, and Exploitation

The relations through which knowledge production is organized include legal entitlements, operational permissions, decision-making powers, practical capacities, expectations of recognition, and claims upon economic returns. A general statement that an actor *owns the knowledge* often obscures the object and scope of control. An actor may hold copyright in a text while another hosts its principal distribution channel; readers may lawfully access the text but lack rights to modify its associated software; a research collective may share code under an open licence while a separate organization controls the only practical infrastructure needed to reproduce an expensive analysis. A satisfactory analysis identifies the rights-bearing actors, the governed objects, the relevant jurisdiction or institutional rules, and the gap that may exist between formal rights and effective capability.

Work on jural relations and bundles of property rights supplies conceptual tools for such an inquiry. Hohfeld differentiates claims, privileges, powers, and immunities, helping to distinguish a right to use an object from authority to alter the legal position of other persons [43]. Schlager and Ostrom distinguish access and withdrawal from management, exclusion, and alienation within an analysis of resource-governance positions [82]. These are sources of analytical differentiation, rather than ready-made legal definitions for intellectual property, employment, or scientific governance. Research on knowledge infrastructures must additionally examine contractual licences, confidentiality, standard-setting, contribution policies, technical interoperability, and the costs of exercising formally permitted rights. Legal ownership and effective control can have different extensions.

For the purposes of this paper, *appropriation* refers to an identifiable actor's acquisition or retention of resources, benefits, claims, or effective powers associated with a production process. It may occur through remuneration, licensing, attribution, institutional assignment, contractual exchange, public redistribution, or other mechanisms. The term is descriptive at this level: appropriation can take mutually agreed, collectively authorized, coercive, and contested forms. *Extraction* identifies a more specific proposed mechanism in which an actor recurrently captures benefits made possible by the contributions or dependence of others through an asymmetrically controlled arrangement, with consequences for the allocation or reproduction of productive conditions. This working definition remains open to normative contestation and empirical refinement. A claim of extraction should therefore specify the production relationship, the asserted benefit, the mechanism of control, the affected contributors, and relevant counterfactual arrangements. Asymmetry of outcomes alone is insufficient to establish such a mechanism.

Exploitation carries additional theoretical and normative burdens. In a Marxian analysis it has a determinate relation to production, labour, surplus value, and class relations; other ethical and political-economic traditions employ different accounts of unfair advantage, vulnerability, or unequal reciprocity. The present paper will identify the framework under which exploitation is alleged rather than use the term as a universal synonym for unequal payment or concentrated benefit. At some sites of public knowledge production, unpaid contribution may be voluntary and socially valuable while also supplying advantages to organizations better positioned to monetize complementary services. Whether the arrangement is exploitative depends on the relations of contribution, authority, consent, benefit, dependency, and reproduction, interpreted within the stated theoretical framework. Similar care is required when examining academic prestige, access fees, patent licences, or the unpaid maintenance of shared knowledge infrastructure.

Human productive capabilities introduce a categorical limitation on an ownership vocabulary. Knowledge and skill embodied in persons, their autonomy in inquiry, and their practical ability to par-

Table 4: Distinct rights, powers, and capabilities in knowledge production.

Dimension	Principal object	Investigative question
Legal entitlement	Works, data rights, licences, contracts, property claims	Which claims and permissions are enforceable, against whom, and under what conditions?
Operational access	Facilities, records, interfaces, complementary tools	Who can actually make use of the resource at sustainable cost?
Governance and revision	Rules, standards, admission and review procedures	Who can amend, contest, or replace the rules of production?
Productive autonomy	Competence, coordination, time and material support	Which activities can participants independently or collectively undertake?
Recognition and valuation	Attribution, ranking, certification, legitimacy	Who influences visibility and criteria of acknowledged contribution?
Appropriation and return	Income, credit, data, capacity, reinvestment	Who receives the resulting benefits and shapes their further circulation?

participate in collective decisions are not equivalent to transferable property in an instrument or a dataset. A contract may regulate the use of labour or the assignment of some resulting intellectual property; it does not thereby convert a person's capacities into an owned object in the same sense as equipment. Consequently, the paper distinguishes ownership of outputs, control over the facilities and rules through which capacities are exercised, and the practical autonomy of knowledge producers. An institution may possess formal ownership of an archive while researchers retain interpretive competence; conversely, researchers may possess expertise while lacking access to necessary instruments or permissions. These differences affect the possibilities of both accumulation and separation from productive conditions.

A particularly consequential field of control concerns *generative rules*: conventions, technical standards, protocols, classifications, methods of validation, and other arrangements that organize subsequent inquiry. Governance of such rules may support compatibility and trust, while also supplying means of gatekeeping, selective recognition, or dependency. The relevant questions are who may propose revisions, who may veto changes, who bears the cost of migration, and whether alternative arrangements remain practically available. An apparently open standard may have costly proprietary complements, whereas a centrally maintained standard may permit broadly participatory revision and low-cost substitution. The influence of a rule therefore depends on its position in a concrete network of practices as well as the powers attached to its governance.

Table 4 identifies separable dimensions of control. The questions are designed to prevent the inference that a single title of ownership explains access, productive command, or power over future rules.

The evaluation of extractive arrangements also depends on heterogeneous value circulation. Outputs, monetary benefits, recognition, skilled participation, infrastructural reliability, and institutional legitimacy may circulate through different mechanisms. Some can be transferred, while others are generated, transformed, or eroded through participation itself. A contribution to a software commons may yield reusable code, collective know-how, status, and opportunities for paid employment without producing a conserved scalar quantity of value. Control over a widely used infrastructure may allow some benefits to be captured while other benefits circulate openly. The analytically important questions concern the paths of contribution and return, the conversion among value forms, and whether the conditions for continued generation become more broadly available, concentrated, or fragile. The detailed treatment of these processes belongs to Sections 9–12.

3.6 Relational and Historical Constitution of Knowledge Capital

The categories introduced in this section acquire their meaning through specified relations and histories. The same knowledge resource may be an output for one collective, a necessary input for another, a shared object of governance for a third, and a source of licensed returns for a fourth. Its status as productive cap-

ital is therefore dependent on the relations through which actors can maintain and mobilize it. Likewise, a technique's location in a generative structure cannot be identified from its title or apparent abstraction alone. A method may function as a foundational condition for one class of inquiry while appearing as a specialized application in another. Generative positions are comparative constructs requiring an identified domain of activities and evidence about which dependencies are operative.

The relational character of productive capacity also means that power cannot be inferred directly from possession. Possessing an archival collection may confer little effective leverage when equivalent materials are available elsewhere, interoperable copies can be created at modest cost, and decisions are contestable. Governance of a modest technical component may create substantial leverage when a wide variety of other practices rely on it, migration is expensive, and access terms can be unilaterally modified. These are mechanisms to investigate, not consequences guaranteed by a nominal level in a hierarchy. The later multilevel analysis will therefore distinguish relative generative position, the scope of effective dependency, practical substitutability, governance authority, and the ability to capture or redirect circulating benefits. The possible effects of deep-level control are a conditional hypothesis about such configurations.

Historical constitution introduces an additional distinction between *transformation in a productive system* and *revision of the investigator's representation*. A classification scheme may change because participants adopt new categories, or the analyst may discover dependencies that were previously undocumented. The two processes produce different explanatory claims. Similarly, an institutional transition may change the distribution of rights without immediately changing the repertoire of feasible research activities; a new technical practice may change productive capacities while formal ownership stays constant. The inquiry should trace documented changes in practices, resources, legal entitlements, participation, and technical dependencies, while specifying when any alleged change is primarily epistemic on the part of the observer.

A relational history also requires explicit ordering conventions. In an archival study, dated events and documentary sequences may support a partial order of institutional changes. In a computational model, a sequence of revisions may be ordered by dependency or recorded version ancestry. Different observations may yield incompatible or incomplete orderings, and simultaneous processes may lack a reliable total order. The framework consequently treats historical sequence as an empirically or formally specified relation within a case. It does not presuppose a globally privileged present or equate an unrealized capacity with a future event awaiting occurrence. Possible transformations and observed realizations remain distinct objects of inquiry, with the former reconstructed under stated assumptions and the latter supported by evidence.

To facilitate comparative work, each proposed instance of knowledge-capital accumulation should be documented through a minimum analytic record: the unit of production and its boundary; the investigated resources and capabilities; the dependencies through which production is feasible; the contributors and affected publics; the distribution of ownership and practical control; the relevant mechanisms of value creation, circulation, and reinvestment; and the historically grounded changes the researcher seeks to explain. The record should also report salient alternatives, uncertainty, and the basis for claims about restriction, appropriation, or extraction. Such documentation can support case comparisons while permitting different empirical methods, including archival reconstruction, interviews, institutional analysis, quantitative observation, and carefully delimited computational representation. It should preserve discrepancies across sources and resist treating convenient numerical proxies as comprehensive measures of productive capacity or justice.

The proposed vocabulary remains provisional where it might obscure historically specific capital relations, culturally situated knowledge practices, or values resistant to commensuration. A productive arrangement may widen feasible inquiry while concentrating rule-making authority; the resulting judgment therefore depends on whose capabilities are examined and which evaluative criteria are declared. Section 4 addresses the placement of accumulated conditions within relative generative levels. Later formal constructions must establish what the additional structure explains beyond the historical and institutional description on which it depends.

4 Generative Levels of Knowledge Production

This section develops the manuscript’s account of generative levels as a way of locating knowledge-capital formation within the conditions of further knowledge production. Its objective is to distinguish the position of a resource within a generative dependency structure from the resource’s size, market valuation, institutional owner, and degree of actual control. The discussion proceeds through relative levels and dependency relations, meta-knowledge, theories and methodologies, infrastructures and institutions, application-level outputs, cross-level interaction, and historical reconfiguration. The proposed distinctions are analytical devices for comparative political economy and epistemic inquiry; their application to a particular historical setting requires evidence about the tasks, practices, and participants involved.

4.1 Generative Dependencies and Relative Levels

A knowledge-producing activity normally depends on conditions that extend beyond its immediate output. Research may employ a language of description, a system of inference, a method of observation, instruments, trained judgment, accumulated results, procedures for criticism, and institutions sustaining collaboration. Some conditions are necessary for a narrowly specified activity; others make an activity less costly, more reliable, more interpretable, or possible on a larger scale. Their relationships provide a starting point for distinguishing generative levels. In the present framework, a *generative dependency* is an empirically or interpretively specified relation through which a resource, capability, rule, or arrangement participates in making a defined class of productive activity feasible or alters its attainable forms.

Dependencies can be conjunctive, substitutable, complementary, or enabling under specific conditions. A particular experiment may jointly require a measuring device, a trained operator, an accessible sample, and an accepted procedure for interpreting observations. An alternative device might replace the first instrument while changing accuracy, expense, and required competence. A public archive may expand feasible questions without being indispensable to each subsequent paper that cites it. The common description that an underlying resource “generates” downstream knowledge therefore covers distinct mechanisms: logical or methodological presupposition, technical enablement, institutional permission, economic feasibility, pedagogical transmission, and practical coordination. A convincing account should identify which mechanism is at issue.

Generative level is defined relative to a specified ensemble of activities and the dependency relations selected for study. A resource occupies a relatively *deeper* generative position when its operation supports conditions used in producing an extensive or structurally upstream family of other resources and activities within that ensemble. A resource occupies a relatively *near-output* position when its direct role is more closely tied to a specified deliverable or task. This terminology establishes an analytical orientation rather than a universal ordering of kinds of knowledge. An apparently elementary technique can be indispensable within one domain and peripheral within another. Similarly, two theories may support disjoint productive pathways and remain incomparable in a partial ordering. The inference from a high position in a diagram to broad effective influence requires separate investigation.

Simon proposed that the architecture of complex systems can often be studied through hierarchical arrangements and varying degrees of decomposability [83]. His analysis supplies a useful methodological analogy: relations within and between components can differ in strength, and the tractability of hierarchical descriptions depends on the actual interaction pattern. The present paper uses that insight cautiously. Knowledge-producing arrangements can display cross-cutting institutional dependencies, reciprocal learning, competing standards, and transformations that reorganize the very units under investigation. A single rooted tree would suppress many of these relationships. Directed graphs, hypergraphs, overlapping complexes, or partially ordered subsets may each be appropriate for a particular question; the later formal treatment will specify which dependencies justify an order relation.

The distinction between *structural position* and *effective dependency* is essential. A normative standard can govern numerous activities yet leave robust alternatives available. An apparently narrow computational service can become a bottleneck if a research community has little practical ability to migrate

Table 5: Illustrative positions and mechanisms in knowledge-production dependencies. The ordering is analytical and task-relative; entries may overlap or change position.

Illustrative position	Generative contribution	Possible loci of effective control
Meta-knowledge and epistemic conventions	Conditions for articulating, recognizing, comparing, and validating claims	Curricular authority, classification systems, epistemic criteria
Theories and methodologies	Explanatory resources, inferential procedures, experimental and interpretive methods	Method licenses, training access, disciplinary review
Shared infrastructures and standards	Reusable technical, organizational, and procedural conditions for many activities	Platforms, interfaces, repositories, governance, maintenance
Applied procedures and outputs	Situated interventions, software, reports, products, and problem-specific results	Deployment rights, contracts, distribution, downstream use

its accumulated data and routines. Dependencies also have different modalities. A legal requirement may condition whether an institution can publish; a methodological requirement may condition whether a claim satisfies a community's evidential standards; an economic requirement may condition whether a project can be financed. These modalities shape the form of possible exclusion and the routes through which power may operate. Their differences should remain visible in the description of capital accumulated at a given level.

Table 5 offers a provisional orientation across representative analytical objects. The columns identify typical generative contributions and potential sites of control rather than asserting a fixed correspondence between a named level and an institutional regime. Overlap is expected, and the same object can play different roles in different studies.

The term *depth* accordingly provides a starting hypothesis about consequential dependency, not a direct measure of capital value, extractive potential, or social importance. The manuscript will later examine how dependency breadth, replaceability, the concentration of control, and the organization of value circulation condition those further properties. Keeping these dimensions separate allows analysis of both concentrated foundational infrastructures and narrow outputs whose control nevertheless constrains extensive downstream activity.

4.2 Meta-Knowledge and Epistemic Grammars

Meta-knowledge concerns the means by which a knowledge-producing community organizes, represents, assesses, and transforms knowledge claims and practices. It can include concepts used to describe an object of inquiry, criteria for inference and evidence, procedures for distinguishing error, rules for combining representations, and practical competences involved in recognizing an intelligible question. As a class of productive conditions, meta-knowledge matters because a change in such procedures may affect numerous activities without directly changing the subject matter or immediately visible products of those activities.

The metaphor of an *epistemic grammar* helps specify one part of this domain. In a formal grammar, rules constrain which constructions are admissible and how certain complex expressions can be composed from constituent operations. By analogy, a disciplinary or institutional epistemic grammar contains historically maintained expectations about which statements can be posed, how evidence can be assembled, and how a claim can enter a recognized sequence of examination and revision. The analogy remains partial. Social understanding involves tacit competencies, interpretation, situated judgment, contestable purposes, and embodied cooperation; it cannot be presumed to possess a uniquely enumerable collection of production rules. An epistemic grammar is therefore an explanatory reconstruction of selected practices, with explicit limits, rather than a claim that social reasoning literally instantiates a

context-free language or a mechanically executable code.

Historical studies of science caution against treating evaluative conventions as fixed. Kuhn's account of research traditions and scientific transformations challenged straightforward cumulative descriptions of knowledge growth, although his historical concept of a paradigm is distinct from the generative-level construct proposed here [53]. Daston and Galison's history of scientific objectivity further places epistemic virtues and trained practices within changing historical formations [21]. Taken together, these contributions support an investigation of evaluative standards as maintained and transformed conditions of inquiry. They do not establish the present paper's political-economic interpretation of meta-knowledge as capital; that interpretation must be argued through productive use, institutional control, and consequences for further activity.

The cumulative character of meta-knowledge can be considered in several forms. A research community may develop reusable proof techniques, conventions for documenting uncertainty, accessible methods of interpretation, or educational practices that allow newcomers to participate more effectively. Such accumulation may be publicly reproduced through teaching, translation, collaborative correction, and shared institutional memory. The relevant capital-like quality lies in an expanded capability to support further knowledge production. In a different configuration, accumulated interpretive expertise or authority over evaluation may be concentrated among actors able to determine admission to journals, educational credentials, repositories, or technical standards. A similar depth of generative position can therefore coexist with different property regimes and power relations.

The danger associated with control at this level has a specific conditional logic. If an evaluative rule is invoked across many domains, if credible alternatives are unavailable or costly to establish, and if an actor has effective authority to enforce the rule, its control may influence an extensive field of possible research. Selective recognition can alter what attracts training, resources, and further investigation. Such effects concern opportunities for knowledge production as well as the distribution of the knowledge already produced. Yet foundational scope alone does not demonstrate extraction: a jointly governed standard can coordinate distributed inquiry, and a stringent evidential criterion can protect users from unreliable claims. The pertinent question is how rule-making authority is constituted, contestable, revisable, and related to the interests and capacities of its participants.

The relationship between epistemic grammars and other levels is reciprocal. Difficulties encountered in applied investigation can expose inadequacies in accepted concepts; newly available instruments can change what counts as a reproducible observation; collective criticism can generate revised norms of disclosure. A historical reconstruction should therefore record both the ways in which meta-knowledge constrains activities and the ways in which those activities participate in reproducing or altering meta-knowledge. Treating an epistemic grammar as immutable would make its apparent generative depth an artifact of the model's assumptions.

4.3 Theoretical and Methodological Generative Structures

Theoretical and methodological structures mediate among broad epistemic conventions, concrete practices, and emerging bodies of knowledge. A theory may provide objects, relations, constraints, explanatory hypotheses, and expectations that enable further questions to be formulated. A methodology may organize sampling, observation, argument, experimentation, simulation, modeling, archival reconstruction, or qualitative interpretation. Their productive roles differ. Theoretical concepts may travel across methods; a method may be used under incompatible theoretical accounts; and a practical research tradition may integrate several approaches without resolving their conceptual differences.

Their accumulation occurs through the development of reusable procedures and trained capacities. A proof strategy can support many propositions, a statistical method can be adapted to different datasets, and an interpretive protocol can organize comparisons across historical sources. These forms of reuse generate a potential difference between the creation of a method and its later productive reach. Accumulation may be reflected in more reliable outcomes, a broader feasible research agenda, reduced coordination cost, or a capacity to revise the method after criticism. None of these changes follows from

the number of publications alone. Citation counts, adoption metrics, and market revenues each capture selected effects under particular conventions of valuation.

Methods also create dependencies through their interfaces to instruments, data, professional training, and publication norms. A computation can depend jointly on a mathematical model, software implementation, data access, and tacit choices during calibration. An archival interpretation can depend on language competence, source preservation, institutional permission, and standards of contextual analysis. It would be misleading to assign the productive capacity to a single artifact without examining this bundle. The distinction matters for capital analysis because rights in software, ownership of physical equipment, entitlement to use data, and control over professional accreditation can be separated among several actors even when they participate in one research activity.

The same methodological structure can support capitalist and commons-based accumulation. A proprietary analytics platform may expand the research capabilities of its purchasers while giving the vendor contractual and technical control over continuity of access. A publicly maintained package may distribute the capacity to inspect and modify its procedures, while depending on concentrated expert maintenance and an uncertain flow of resources. A public laboratory may combine open results with restricted physical access because of safety, scarce equipment, or confidentiality. These examples are idealized configurations, not empirical verdicts about any particular institution. Their comparison concerns effective rights, decision-making, and the ability of contributors and users to sustain productive activity.

There is also a distinction between methodological *influence* and methodological *authority*. A method may become widespread through voluntary adoption, demonstrated reliability, pedagogical convenience, or compatibility with shared infrastructure. Other methods may be marginalized through publication practices or accreditation requirements. An investigator should distinguish diffusion and dependency produced by successful coordination from constraints resulting from exclusion, coercive bargaining, or entrenched gatekeeping. Political-economic evaluation requires evidence of how these mechanisms are organized, since widespread use alone underdetermines the meaning of centrality.

Cross-level influence becomes visible when method development reshapes meta-knowledge. Innovations in measurement can change disciplinary expectations concerning evidence. New modes of textual analysis can alter what counts as a relevant comparison. A previously dominant methodology may become one among several admissible approaches, while established results are reevaluated under altered standards. Such changes indicate that generative levels have permeable boundaries. The importance of a theory or method can therefore be investigated both through the activities it enables and through its capacity to transform the standards by which further knowledge is generated and recognized.

4.4 Standards, Institutions, and Productive Infrastructures

Standards and infrastructures form a distinctive locus of capital accumulation because they couple reusable means of production with arrangements for coordination, continuity, and governance. They include laboratories, libraries, archives, computational environments, repositories, data formats, identifiers, scientific instruments, professional associations, research protocols, and institutional procedures. A standard can reduce the cost of exchange or make results comparable; an infrastructure can sustain ongoing production despite turnover among its participants. These enabling functions often become apparent when resources are unavailable, poorly maintained, or incompatible with adjacent systems.

Studies of infrastructure emphasize its relational character. Star and Ruhleder analyzed information infrastructure through the practical conditions of use and access [85]. Star's methodological reflection similarly located infrastructure within the relation among tools, practices, standards, and built environments [84]. Bowker and Star showed how classification arrangements participate in organizing institutions and possibilities of interaction [12]. These accounts substantiate treating an infrastructure as more than a durable technical object. The generative contribution of a repository, for example, depends on its curatorial work, metadata conventions, interpretive usability, legal permissions, preservation practices, and compatibility with the communities it serves.

Capital accumulation at this level can take the form of improved maintenance capability, interoper-

1263 ation, error correction, specialized personnel, organizational trust, and a larger set of feasible collabora-
1264 tions. Some of these benefits can accrue without exclusive ownership. Frischmann’s study of infrastruc-
1265 ture addresses the social value of shared resources and the importance of the conditions governing their
1266 use [34]. An open technical standard may create wide productive opportunities, while the durability
1267 of those opportunities depends on stewardship, stable financing, and procedures for revising the stan-
1268 dard. Conversely, closed technical interfaces can support coordination for participants while increasing
1269 dependence on the actor controlling compatibility, migration, or access.

1270 The form of infrastructural dependence deserves particular care. Access may be formally permit-
1271 ted while substantive use remains impractical because essential documentation, computational capacity,
1272 funding, or training is unavailable. A licence may allow reuse while shared data are locked into a for-
1273 mat that is prohibitively expensive to extract. Conversely, restricted access to sensitive materials may
1274 be compatible with broad public benefit under accountable oversight. The distribution of effective gen-
1275 erative opportunity should therefore be examined through the combination of formal rights, technical
1276 feasibility, institutional conditions, and the capabilities required for participation.

1277 Institutions also maintain criteria for what counts as a functioning infrastructure. Decisions about
1278 acceptable formats, disciplinary taxonomies, credentials, procurement, repair priorities, and permissible
1279 uses can shift the trajectories of future inquiry. These choices bring infrastructural accumulation into
1280 contact with the meta-knowledge described in Section 4.2. Classification authority, platform administra-
1281 tion, and scholarly evaluation may overlap without belonging to one unified organization. An analysis
1282 of power should trace specific decision rights and enforcement mechanisms rather than inferring com-
1283 prehensive control from a resource’s visibility or apparent centrality.

1284 The shared or public status of an infrastructure is similarly multidimensional. Public funding, public
1285 ownership, free access, permissive licensing, transparent governance, and participatory rule modification
1286 are different properties. A publicly financed dataset can be operated through a private contractor; an
1287 open-source repository can depend on a small maintainer group; a cooperative platform can employ
1288 proprietary tools for selected tasks. The generative-level approach permits comparison of these mixed
1289 configurations without collapsing institutional form into a single continuum from private to public. It also
1290 prepares a more precise examination of the distribution of production conditions and value circulation
1291 in the manuscript’s later sections.

1292 4.5 Applied Knowledge, Technologies, and Generated Outputs

1293 Applied knowledge and generated outputs are relatively close to a specified use, intervention, or deliv-
1294 erable. They can take the form of an empirical report, a public-health guideline, a software applica-
1295 tion, an educational resource, a technical design, a translated text, or a contextually grounded interpreta-
1296 tion. These outputs may have immediate instrumental value, but their generative roles are heterogeneous.
1297 Some are largely consumed in a bounded decision; others become components, datasets, examples, or
1298 training materials for a broad family of subsequent activities. Their position is therefore relative to the
1299 productive network being studied.

1300 The near-leaf analogy drawn from generative grammar can illustrate one possible mode of depen-
1301 dence: many upstream resources contribute to the construction of a specific output. The analogy breaks
1302 down when an output becomes an input to additional inquiries or changes the procedures by which out-
1303 puts are produced. A widely reused software component may be an application relative to the theoretical
1304 work that originally informed it, yet function as critical infrastructure for another community. A suc-
1305 cessful intervention may supply evidence that revises a background theory. A body of case studies may
1306 generate new classificatory concepts. Assigning a permanent low level to such artifacts would obscure
1307 precisely the recursive expansion relevant to knowledge capital.

1308 Output-level accumulation can occur through incremental refinement, adoption, localization, iter-
1309 ative testing, and collective improvement. Its benefits may include improved practical performance,
1310 expanded service coverage, new forms of participation, and transferable learning. Market transactions
1311 can finance continued development; public provision can distribute benefits independently of individ-

ual purchasing power; communities can maintain shared artifacts through reciprocal contributions. The underlying question is how the resulting productive capacities are constituted, accessed, supported, and governed, rather than whether each mode of organization fits a single preferred institutional model.

A common analytical temptation is to presume that capital control near the output level carries limited systemic consequences. Such an inference depends on the availability of alternative outputs and the possibility of substitution. A task-specific interface can become essential when substantial bodies of records, training routines, compliance procedures, and organizational commitments depend on it. A proprietary format initially designed for one use may spread widely enough to influence data portability or public access across different activities. By the same reasoning, a deep theoretical resource can be widely known while exerting little exclusionary leverage because many alternatives are usable. The relevant comparison involves realized dependencies, switching costs, and the routes by which control can be exercised.

Appropriation at this level also has differentiated consequences. Ownership of a final report, copyright in a software implementation, command over distribution channels, and the capacity to train models using a body of outputs implicate different rights and mechanisms. Economic revenues may circulate to creators and maintainers, finance broader infrastructure, or be concentrated elsewhere. Nonmonetary value may circulate through instruction, clinical practice, scholarship, and collective memory. Identifying an output's position in a generative network is only the beginning of an account of capital expansion. To understand the distribution of its consequences, one must trace the relations linking the output to productive effort, rights, institutions, and further opportunities for creation.

4.6 Cross-Level Dependencies and Recursive Interactions

The preceding distinctions support a more complex conception of generative stratification than a descending chain from abstract rules to concrete products. Knowledge production frequently involves paths that traverse several analytical levels, join previously separate branches, and return to modify the conditions that supported the activity. An archive might support the development of a new method; that method might expose shortcomings in an existing classification standard; an improved standard might enable further archiving and comparative inquiry. A technology initially developed for one task can be incorporated into general-purpose infrastructure. These relationships generate multiple possible sequences of dependency and revision, with no presumption of a single global derivation or temporal direction.

Three analytical relationships are especially relevant to the political economy of accumulation. The first is *vertical dependence*, in which an activity makes use of conditions assigned to a relatively deeper level in the chosen representation. The second is *lateral dependence*, in which resources or practices associated with comparable levels support one another without a strict ordering. The third is *reconstructive feedback*, in which experiences or outputs occasion a change in the rules, methods, or infrastructures by which further activity becomes possible. These distinctions are descriptive; an individual relation may instantiate several mechanisms depending on the research question.

Dependencies are also often jointly constituted. One result may require multiple compatible sources or coordinated contributions. Other results may be produced by alternative bundles whose relative feasibility depends on available tools and institutional arrangements. A representation based solely on pairwise links can obscure these joint requirements; a hypergraph or a relational complex may preserve them more adequately. The manuscript's later formal section will examine the conditions under which such structures can represent generative pathways, the limits of assigning levels within them, and the difference between a modeled dependency and a historically demonstrated causal mechanism.

Cross-level capital accumulation can expand a system's capacity in two distinct senses. Existing conditions can support additional outputs without substantially changing the dependency structure; alternatively, accumulated knowledge can modify the structure and thereby alter the family of feasible activities. The second possibility is central to the idea of generativity. A new method may enable research questions that were difficult to articulate under the previous methodological configuration. Shared infrastructures can generate new interactions among disciplines, while collaborative activity can reveal a need for differ-

ent governance rules. Expansion therefore involves both the enlargement of productive capability within a configuration and the potential reconstitution of conditions through which that capability is exercised.

Value circulation follows neither a necessary top-down direction nor a uniform measure. Financial resources from a specific application may subsidize basic research, while shared theories and methods may improve the quality of distributed practical work. Reputation earned through a visible output may support institutional influence over research agendas. Data generated by publicly supported activity may improve a proprietary platform, and platform revenue may or may not return to the contributors who sustained that activity. Distinct forms of value are created, interpreted, transferred, and transformed along these pathways. A schematic description of structural dependence cannot itself decide whether a circulation is equitable, extractive, or conducive to public generativity. Such judgments require additional evidence concerning contribution, appropriation, control, alternative arrangements, and the reproduction of productive conditions.

The relevance of generative depth to extraction can now be stated more precisely. A resource with broad downstream dependence may confer considerable leverage on the actor controlling indispensable access or modification rights. The leverage may increase when alternatives are difficult to construct and when resources obtained from dependent activities support continued consolidation of control. Nevertheless, depth is neither a sufficient nor a necessary condition for extraction. The same resource can be governed in ways that expand collective autonomy; a specialized output can form an acute bottleneck; and a nominal controller may lack the effective authority to enforce exclusion. These possibilities call for a comparative analysis of depth, dependence, substitutability, governance, and value circulation as separable, interacting variables.

4.7 Historical Transformation of Generative Levels

A generative-level description is indexed to a historically constituted arrangement of productive practices and to the observer's stated analytical purpose. Both matter. An altered classification can change a scholar's representation of a system while leaving its operational conditions intact. An institutional reform can change rights and governance without immediately altering the technical possibilities of production. A newly developed method can change productive capabilities while existing legal ownership persists. A more comprehensive transformation can alter several of these domains together. Historical analysis should therefore distinguish representational revision, technical change, institutional reallocation, conceptual reorganization, and changes in observed productive activity.

The continuation of a knowledge-producing system is similarly a relation to be established, rather than a universal clock imposed upon it. A historical sequence may be reconstructed through documents, preserved artifacts, policy decisions, versions of software, institutional records, and accounts of practice. Some events can be reliably ordered within a particular lineage while relations among activities in different domains remain uncertain or incomparable. A study may track how a resource acquires infrastructural significance across one documented series of changes without assuming that every relevant development can be placed on a common scale of progress. This is especially important when epistemic traditions, languages, or institutions maintain different conditions of recognition.

Historical movement across analytical levels may take several forms. A local research procedure can become a disciplinary method through formalization, teaching, and repeated adaptation. A frequently used application can become an infrastructural dependency after integration into shared workflows. A foundational concept can lose its enabling position when a new representational approach permits work around it. Standards can split into competing implementations or be integrated into a more expansive interface. A scientific field can also preserve a recognizable institutional identity while the rules that organize its evidential practices undergo substantial reconstruction. Such changes suggest that level assignment should be revisited when the dependency system itself has changed.

The political-economic significance of these transitions concerns who participates in constituting the new arrangement and who can act within it. A shared tool may become indispensable through the labor of many contributors while decisions about its technical direction become centralized. A platform may

1410 achieve greater interoperability and broader participation through common governance. Public invest-
1411 ment may increase the scale of productive infrastructure while assigning maintenance responsibilities to
1412 actors with limited decision rights. These examples show why accumulated generative capability and
1413 the allocation of control should be analyzed together while remaining conceptually distinct. A shift in
1414 generative position can change the field of feasible appropriation even if nominal ownership remains the
1415 same.

1416 Two methodological cautions follow. First, changing importance within an observed network should
1417 not automatically be interpreted as an endogenous change in the knowledge-producing system: an ex-
1418 panded archive or revised measurement protocol may expose dependencies previously unnoticed. Sec-
1419 ond, an investigator should avoid projecting an observed dependency indefinitely across possible contin-
1420 uations. Substitution, collective contestation, institutional reform, methodological invention, and chang-
1421 ing purposes can modify the conditions under which a resource exerts influence. Claims about persistent
1422 domination or extraction require evidence regarding both the durability of control and the reproduction
1423 of the underlying dependencies.

1424 The framework developed here consequently locates knowledge-capital accumulation within a
1425 changing landscape of productive opportunities, epistemic conventions, institutions, and rights. Meta-
1426 knowledge, methods, infrastructures, and outputs are analytically recognizable sites of accumulation,
1427 although their boundaries and relations remain contingent. The relative position of capital within this
1428 landscape can influence its capacity to support further production and its possible use as a source of
1429 leverage over other contributors. Subsequent sections examine how initial productive conditions form,
1430 how accumulation becomes recursively expansive, and how capitalist, public, commons-based, cooper-
1431 ative, and communist conceptions of knowledge production organize the ownership and circulation of
1432 what is generated. The central empirical challenge remains the reconstruction of actual dependency and
1433 power relations in historically specified settings.

1434 5 Initial Formation and Primitive Accumulation of Knowledge Capital

1435 The present section examines the formation of productive knowledge capital within historically con-
1436 stituted relations of knowledge, labour, infrastructure, governance, and control. Its objective is to ex-
1437 plain the origins of identifiable capacities for further knowledge production while preserving the distinct
1438 meaning of primitive accumulation in political-economic analysis. The investigation proceeds through
1439 inherited productive conditions, cooperative labour, public investment, enclosure and separation, capi-
1440 tal formation at different generative levels, and the path-dependent reconfiguration of initial conditions.
1441 The mode of argument combines conceptual reconstruction with historically informed institutional com-
1442 parison. Illustrations specify possible mechanisms and should be distinguished from empirical findings
1443 about their prevalence or consequences in particular fields.

1444 An account of initial formation requires a declared boundary around the activity being studied. A
1445 research institute may begin operations with an endowment, a building, and instruments; those assets in
1446 turn presuppose infrastructures and skills formed through other institutional histories. An open scientific
1447 software project may begin with a small codebase while employing mature programming languages, pub-
1448 licly available mathematical theory, standards, and knowledge accumulated by earlier contributors. A
1449 publishing commons may be newly established as an organization while inheriting professional conven-
1450 tions concerning authorship, evidence, peer criticism, and archiving. Within each example, an investiga-
1451 tor can locate a point at which the specified productive configuration becomes operational. That point
1452 supplies a relative analytical origin, even though the enabling conditions extend through histories beyond
1453 the chosen boundary. This distinction is consequential for evaluating whether productive capacity has
1454 been collectively created, acquired from others, appropriated through exclusion, or constituted by some
1455 combination of these processes.

1456 The broader formation of productive capital and historically specific primitive accumulation should
1457 remain distinguishable throughout this account. Marx's treatment of so-called primitive accumulation
1458 concerns the production of capitalist social relations, centrally including the separation of producers from

means of production and the historical creation of conditions for wage labour and capitalist ownership [61]. The accumulation of a library, the training of researchers, or the creation of an openly governed repository may enlarge a community's productive capacity without establishing the same relations of separation. Conversely, a change in access or control can occur without creating much new knowledge and may nevertheless alter the political-economic character of the productive arrangement. Theoretical analysis gains precision by identifying the productive asset or capacity formed, the relations through which it becomes usable, and the processes through which claims upon it are allocated.

5.1 Historical Inheritance of Knowledge and Productive Conditions

Historical inheritance constitutes a central mechanism through which knowledge production obtains its apparent starting resources. The object considered here is a configuration of accessible materials, retained capabilities, conventions, and institutions that enables a specified class of inquiry. Its inherited character does not imply that the resources are passive deposits. A published theorem must be understood, a repository maintained, a technique learned, and an experimental apparatus calibrated. Inheritance therefore consists partly of resources transmitted across participants and partly of continuing practices that make such resources meaningful and operable. The cost, accessibility, and durability of those practices contribute to the conditions under which a newly established productive arrangement can function.

Knowledge inheritance can occur through manuscripts, oral instruction, professional education, interoperable data, archives, code, laboratory routines, disciplinary criticism, and publicly supported infrastructures. A formal proof may remain accessible through publication while the expertise needed to extend it is unevenly distributed. A historical archive may formally permit consultation while practical use requires specialised languages, interpretive techniques, and institutional travel resources. A computational method may be documented in an article while large datasets, compatible software environments, and tacit calibration procedures remain difficult to reproduce. These differences suggest that an inventory of documents or stored information underrepresents the effective productive conditions that a new knowledge organization receives. The relevant inheritance includes the socially organised capacity to activate resources, examine their adequacy, and transform them in further work.

In the economics of research, difficulties of exclusive appropriation and the possibility of benefits extending beyond the initial investigator have long been relevant to arguments for public support of basic research [3, 66]. These arguments have distinct assumptions and limitations. Information can be shared without being depleted in the way many material resources are depleted, yet access, comprehension, experimentation, and complementary resources can remain rivalrous, costly, or governed by exclusionary arrangements. A mathematical insight may be reproduced at a low marginal information cost while an associated experiment depends on expensive facilities and scarce expertise. Consequently, an inherited informational resource may supply a potentially broad generative condition without making the resulting productive capacities equally available across institutions or persons.

Historical inheritance has a temporal and epistemic dimension. What is inherited depends partly on the observer's periodization and partly on the changing interpretation of earlier work. A forgotten classification can become useful when connected to a new data system; a technique previously considered adequate can become contested when an alternative validation procedure emerges. The resulting change may concern the feasibility of an activity, the institutional valuation of its products, or the reconstruction through which researchers identify older work as relevant. These possibilities should be differentiated in historical analysis. The generative-level framework introduced in Section 4 treats depth as relative to such situated dependencies. It does not establish that a resource located within an earlier generation of inquiry possesses permanent epistemic priority over a later application.

Inherited conditions are also unevenly preserved. Maintenance of libraries, repair of instruments, documentation of software, translation of archives, and transmission of practical knowledge require present effort. A resource can remain legally in the public domain while becoming practically inaccessible through physical deterioration, institutional closure, disappearing technical compatibility, or lost expertise. Conversely, deliberate preservation and training can increase the number of independent groups

able to use the same resource. A study of initial knowledge-capital formation should therefore include the institutions that conserve and reactivate inherited capacities, together with the financing and recognition of that conservation work. The public availability of a resource at one date offers an incomplete account of the conditions supporting its continuing productive use.

The attribution of initial capital deserves similar caution. If a new organization combines a publicly funded data collection, a community-developed software library, and its own labour to produce a working analytical platform, the platform may represent a genuine new productive accomplishment. Its formation nevertheless reflects distributed contributions whose origins and governance relations differ. The analytical task is to reconstruct the contributions and dependencies with enough specificity to explain which actors can subsequently use the platform, decide on its development, and benefit from its operation. A historically situated account can recognise innovation by the organizing group while also describing the collectively produced inheritance on which that innovation relies.

5.2 Labor, Cooperation, and Collective Capital Formation

Cooperation joins inherited resources to capacities exercised through shared activity. The relevant analytical object includes individual skill, reciprocal learning, coordinated procedures, and the organizational arrangements that allow contributors to undertake work that isolated action would render more difficult or infeasible. Scientific research teams, editorial collectives, software maintainers, translators, data stewards, and informal communities can each create productive conditions whose value for further inquiry exceeds the immediate set of outputs through which their cooperation becomes visible. The initial formation of such conditions is therefore a process of capability development as well as resource assembly.

Cooperative production can generate at least three analytically distinct kinds of continuing capacity. First, it may produce transferable outputs such as texts, code, datasets, schemata, or instruments. Second, it may alter participants' capabilities through training, mutual correction, shared problem-solving procedures, and the creation of practical expertise. Third, it may establish relations of coordination, trust, attribution, or collective decision that support subsequent activity. These contributions overlap, but they differ in what can be owned, copied, transferred, or maintained. Software files may be distributed under a licence; the acquired ability of contributors to understand a codebase is embodied in persons and social relations; the continuing coordination of maintenance decisions depends on governance and participation. Treating these products as a single stock obscures their different modes of accumulation.

Benkler's analysis of commons-based peer production identifies ways in which distributed participants coordinate information production outside some of the characteristic hierarchical and market arrangements of firms [8, 9]. Within the present argument, that work supports a limited institutional proposition: distributed cooperation can create persistent productive resources through arrangements whose coordination and incentive structures differ from conventional employer-directed production. Its relevance extends to the formation of shared software, educational materials, knowledge collections, and collaborative practices. It does not follow that every voluntary collaboration is effectively governed as a commons, or that a product released openly gives all contributors equal influence over infrastructure, recognition, or the conditions of continued participation.

Consider an illustrative research software collective. Contributors may first assemble an interoperable set of analytical routines from publicly documented methods. A stable release makes those routines available to a broader community. Repeated technical discussions then yield testing conventions, training documentation, contribution procedures, and a common understanding of acceptable evidence. At this point, the collective has accumulated more than source code. It has created reproducibility capacities, coordination practices, and a partially institutionalized procedure for revising its own outputs. If control over hosting, authentication, project naming, or release authorization is concentrated among a few maintainers, that concentration may help coordination while also shaping contributors' effective powers. A political-economic account should distinguish both effects and examine mechanisms of contestation, succession, and exit.

Cooperation need not involve homogeneous interests. The same project may bring together publicly

funded researchers seeking reliable methods, volunteers seeking opportunities to learn, firms seeking complementary products, and institutions seeking reputational benefits. These motivations can coexist without producing a single shared metric of value. The formation of a publicly useful knowledge asset might yield professional recognition for one contributor, skilled competence for another, usable data for a third, and revenue for an organization that provides associated services. The heterogeneous nature of these returns makes value attribution and circulation an empirical and normative issue. Collective production supplies conditions for accumulation, while the allocation of decision rights and benefits determines some of the subsequent differences between productive expansion and capital concentration.

Labour is also involved in activities conventionally regarded as ancillary to knowledge creation. Data cleaning, citation checking, error correction, documentation, accessibility work, language support, software maintenance, archival preservation, and institutional coordination can make subsequent research possible. Their productive role may be underestimated when evaluation emphasizes named discoveries or counted publications. Merton's accounts of cumulative recognition in science provide a basis for investigating how acknowledgement may become concentrated among participants whose positions already favor visibility [64, 65]. That insight should be interpreted together with institutional evidence about actual contribution and reward. Unequal recognition does not, by itself, identify which labour generated a specific output or demonstrate a particular exploitative relationship.

A further distinction concerns the reproduction of contributors. Training and continued participation require material support, time, wellbeing, linguistic accessibility, and opportunities for meaningful agency. An organization may accumulate a significant public codebase while exhausting the capacity of its volunteer maintainers. In that configuration, the stock of visible outputs grows even as its conditions of further development become fragile. Conversely, a collective may devote resources to education, documentation, and maintainability without immediately increasing its number of outputs, thereby strengthening the basis for subsequent inquiry. Both cases suggest that the formation of knowledge capital should be assessed through changes in sustainable productive capability and participation, not through an output inventory alone.

The institutional status of collectively formed capital remains open. Cooperative production can occur inside firms, publicly funded laboratories, universities, voluntary associations, and commons-based organizations. Its organisation may include compensation, unpaid participation, democratic governance, managerial direction, or contractual restrictions. The presence of cooperation therefore identifies a generative mechanism rather than a political-economic regime. Comparative research should ask which aspects of the collectively created capacity remain available to contributors, who can revise its rules, how continuity is financed, and whether participation creates durable autonomy or dependence. Such questions link the formation of shared productive assets to the later analysis of ownership and value circulation.

5.3 Public Investment and Institutional Capital Formation

Public investment and institutional provisioning can create the durable productive conditions within which a substantial range of knowledge activities become feasible. The object of analysis includes funding for research, education, information infrastructures, scientific facilities, standards, archives, and the administrative and professional labour necessary to maintain them. The objective is to distinguish the formation of resources through public expenditure from the particular rights, permissions, governance powers, and circulation arrangements associated with their subsequent use. Public finance is an important determinant of capital formation in many knowledge systems, while its presence alone leaves the organization of access and effective control to be specified.

Investment in basic research may support activities whose prospective value is difficult to appropriate within a single organization, whose applications remain uncertain, or whose benefits are distributed across multiple fields. Nelson's economic treatment of basic research helps identify the divergence that can arise between private incentives and broader social returns under particular assumptions [66]. David's historical analysis of open science places institutional choices within longer histories of patron-

age, reward, and the organization of scientific disclosure [23]. Together, these sources support an investigation of public science as an institutionally arranged productive activity rather than a self-executing consequence of knowledge's technical properties. Public funding can build laboratories and human capability, but the rules governing disclosure, evaluation, intellectual property, collaboration, and maintenance affect how that capability is reproduced and accessed.

Public investment may contribute at several levels of the generative structure. Schooling and higher education sustain linguistic, mathematical, methodological, and interpretive competencies. Research grants, shared facilities, and field stations create conditions for inquiry. Publicly funded archives and databases support the preservation and recombination of accumulated results. Statistical classifications, measurement procedures, and interoperability standards can enable many activities across institutional boundaries. Outputs may include particular publications or applications, but investment can also alter the feasible set of further investigations and the cost of entering them. The form of the benefit differs across levels: an improved public method may support many research pathways, while a specialised instrument may enable a restricted but scientifically important class of measurements.

Empirical work on links between public research and industrial research-and-development illustrates the heterogeneous routes through which those benefits may circulate. Using the Carnegie Mellon Survey of industrial research and development, Cohen, Nelson, and Walsh analysed reported influences of university and government-laboratory research among United States manufacturing firms [18]. Their findings identify differences across industries and multiple transmission channels, including publications, conferences, informal information exchange, and consulting. The reported influence also varied across firm types; survey reports of influence should be distinguished from experimentally identified causal effects. That study provides evidence for particular linkages, not a universal estimate of the public return on research funding. It also shows why transfer should not be reduced to formal technology licensing or a single commercialisation event. Publicly supported research may influence the identification of new projects and the resolution of existing research problems, while the organizational capacity to absorb and apply results differs across firms.

The acquisition of complementary resources becomes important at this point. Access to public publications does not confer comparable ability to exploit them when users differ in trained personnel, computing capacity, laboratory instruments, legal support, and established distribution channels. An enterprise with extensive complementary assets may transform public knowledge into proprietary services and revenue more rapidly than a small research collective can. Such unequal conversion can occur even where the original knowledge remains accessible under open conditions. The political-economic question concerns which complementary assets, contractual privileges, procurement relationships, or technical interfaces allow public investment to support multiple productive capabilities and which arrangements concentrate the effective benefits of that investment.

A public institution may simultaneously act as funder, direct producer, employer, steward, evaluator, and regulator. Each role carries distinct decision powers. A government-funded laboratory may own particular instruments and results; external researchers may receive access subject to safety, scheduling, and training rules; an institutional review body may authorize certain investigations; public law may require some forms of disclosure while allowing specific limitations. These differences caution against treating public ownership as synonymous with universal access or participatory governance. Conversely, a privately operated facility may serve a broadly accessible public research network under enforceable contractual, regulatory, or institutional conditions. The relevant object for analysis is the resulting configuration of effective capabilities and rights.

Institutional maintenance deserves independent accounting. An archive funded for initial construction may deteriorate without recurrent support; a shared platform may lose relevance when its interface standards become incompatible with widely used research systems; trained staff may depart without opportunities for succession. Public capital formation therefore includes the financing of continuity, adaptive governance, and the ability to revise infrastructure in light of changing knowledge practices. Frischmann's account of shared infrastructure emphasizes the social value that can arise from access to facilities that support diverse downstream activities [34]. Within the present paper, the further ques-

tion concerns how those activities contribute to maintaining and transforming the productive basis they employ.

Publicly supported formation can take place alongside private and commons-based accumulation. A university laboratory may develop a publicly funded method, a nonprofit collective may supply open software implementing it, and a firm may create a commercial application. Such a configuration can enlarge productive capability throughout the network while allocating financial returns, operational responsibilities, and decision powers in different ways. The initial public contribution should be analytically visible, as should the later innovations and material commitments of other participants. A satisfactory comparison therefore reconstructs the institutional conditions through which particular forms of value and productive capacity are generated, converted, appropriated, and reinvested.

5.4 Appropriation, Enclosure, and Separation from Productive Conditions

The distinction between productive formation and changes in control becomes particularly important when accumulated knowledge conditions become objects of appropriation or enclosure. The present subsection examines mechanisms through which an actor acquires an enforceable or practically effective power to exclude others from resources, infrastructures, or rules upon which their productive activities depend. Its analytical concern is the restructuring of relations among knowledge producers and the conditions of production. An enclosure may accompany investment in a new resource, arise through the acquisition of an existing resource, or operate through changes in interfaces, contracts, governance, and practical accessibility. These mechanisms have different implications for the formation of productive capital and the possibility of extraction.

Marxian primitive accumulation provides a historically specific analysis of the formation of capitalist relations through dispossession and the separation of producers from means of production [61]. The concept becomes analytically illuminating for knowledge production when a comparable relation of separation is actually established: contributors participate in producing a resource or capability yet lose effective access to, or decision-making power over, conditions required for the continuation of their own production, under arrangements that may create sustained dependency. An analogy to primitive accumulation does not establish a historical identity with the agrarian and industrial transformations analysed in *Capital*. Evidence is required to specify the actors, assets, rights, modes of livelihood, and institutional transformations involved. The paper therefore reserves the historically grounded concept of primitive accumulation for such clearly specified relations, while using *initial capital formation* for the wider family of productive-capacity formation processes.

The enclosure of information and the public domain has received sustained legal and political-economic examination. Boyle analysed a second enclosure movement involving expanding intellectual-property claims and the construction of the public domain as a politically relevant institutional category [13]. Peekhaus subsequently applied concepts of primitive accumulation and alienation to academic publishing [76]. These arguments identify possible institutional routes through which a resource originally created or circulated through broad participation becomes subject to more restrictive rights and economic arrangements. The present framework adds the generative-level question: which downstream activities rely upon that resource, how feasible are substitutes, and which elements of production become subject to changed control?

Possible enclosure mechanisms include the assignment of exclusive intellectual-property entitlements, transfer of database control, contractual restrictions on text or data processing, the withdrawal of open interfaces, proprietary extensions to a formerly interoperable format, exclusive control of certification, and the acquisition of a key archive or publishing channel. The mechanisms may also be less visible. Restrictive terms for access to high-quality datasets, a requirement to use a specific hosted environment, and the capacity to revise evaluation criteria can generate dependency without preventing circulation of the associated public articles. In each instance, legal title, technical control, and economic feasibility may be distributed across different actors. The relevant relation of exclusion must be described at the level at which it operates.

Separation is especially difficult to assess when productive knowledge remains cognitively available. A researcher can retain understanding of a method while being unable to access the required computing service, training environment, laboratory sample, or authoritative repository. A software contributor can retain a copy of source code while losing access to the authentication infrastructure, naming conventions, user community, or coordinated release process that makes the project practically useful. A scholarly author can retain knowledge of the research while lacking authority to distribute a formatted publication or reuse its associated data. These examples suggest a differentiated concept of separation: contributors may be separated from material facilities, legally protected outputs, operational infrastructure, governance rights, or the social conditions for recognized production. The degree and consequences of separation depend on available alternatives and the actors' ability to reorganize collective work.

Exclusionary entitlements also have potentially heterogeneous effects. Some rules can protect confidentiality, personal rights, research safety, or investment needed for long-term production. In other settings, fragmented exclusion rights can impose transaction costs or impede combinations of complementary research inputs. Heller and Eisenberg's analysis of the biomedical research anticommons articulates one pathway by which numerous rights to exclude may impede the use of knowledge resources for further research and product development [39]. Their argument is an identified possibility rather than evidence that every patent, exclusive licence, or restricted archive creates underuse. The present framework asks about the intensity of dependency, cumulative permission requirements, coordination costs, and accessible alternative routes in the specific system studied.

The economic capture of benefits should also be distinguished from extraction. An actor may receive revenue for creating, maintaining, or improving an infrastructure used by others. Assessment of an extractive relation requires examining how that revenue is generated, the rules governing access and contribution, the distribution of maintenance obligations, and effects on other participants' ability to continue production. A publishing intermediary's income does not establish extraction without further evidence; neither does voluntary provision of unpaid labour guarantee the absence of asymmetrical dependence. The investigative issue is whether control over productive conditions recurrently enables benefits to be captured from distributed contribution or dependence in ways that constrain other participants' effective agency or the reproduction of their productive capacities.

A wider historical issue concerns the creation of new productive facilities that simultaneously establish new dependencies. A proprietary platform may lower the cost of a complex analytical activity while embedding its users in data formats and workflows that are expensive to leave. Both effects can be genuine. The platform can expand feasible activities within its domain, while its governance arrangements may concentrate the power to alter access, price, validation, or distribution. A theoretical description attentive only to expanded productive volume would miss the change in control; a description attentive only to enclosure would miss the expanded set of capabilities. Political-economic analysis therefore requires parallel accounts of generative expansion and the configuration of rights and power through which expansion occurs.

5.5 Capital Formation Across Generative Levels

Initial formation may take place in resources located at different positions within a generative dependency structure. The purpose of distinguishing those positions is to clarify the reach and kind of productive conditions being formed, together with the pathways through which subsequent ownership or control may matter. A project's initial contribution can be a new application, a reusable method, a shared institution, or an alteration of epistemic conventions. These objects may have unequal downstream consequences while remaining incomparable in their social importance or their market value. The dependency relations specified in Section 4 offer a vocabulary for examining such differences without assuming a complete hierarchy of knowledge.

At a relatively near-output level, formation often concerns a situated artefact or task-specific solution: a local data product, translation procedure, specialized analytical script, or application of a scientific method. Its immediate productive role can be narrow, although subsequent reuse may expand that role.

Table 6: Illustrative formation of productive conditions across relative generative levels. The actual range of dependency and control requires case-specific evidence.

Relative position	Possible object of initial formation	Subsequent dependency and control questions
Applied activity and output	A situated analytical tool, data product, research result, or application	Reuse conditions, complementary resources, product rights, reproducibility
Methodological practice	A transferable protocol, model, interpretive method, or software library	Training, methodological legitimacy, licensing, feasible alternatives
Shared infrastructure	A repository, laboratory facility, standard, archive, or coordinated service	Access, maintenance, interfaces, migration costs, institutional governance
Meta-knowledge and epistemic conventions	Classification, criteria of evidence, inferential practice, or scholarly recognition procedure	Authority to revise, interpretive pluralism, recognition, contestability

Rights over the output and access to its supporting conditions may remain separable. A developer may own a script but lack authority to redistribute its training dataset; a researcher may possess a derived table but lack the instrument required for replication. Initial formation at this level can thus be studied through the actual assembly of resources needed to reproduce or modify the output rather than through the output's existence alone.

At a methodological level, capital formation may establish a technique that can be repeated across a class of tasks. A calibration protocol, comparative interpretive procedure, statistical estimator, experimental design, or interoperable software library may reduce the cost of later inquiry and make previously unmanageable problems approachable. Relevant accumulation includes documentation, skills for correct application, testing procedures, communities capable of critical revision, and standards that permit translation into other domains. Ownership or exclusion associated with the method may influence a larger collection of activities, depending on adoption, compatibility, and substitutability. A method with formal generality can nevertheless have limited actual use if institutions lack the capabilities necessary to operate it.

At an infrastructural level, formation can supply shared facilities or durable organizational arrangements: repositories, communication protocols, archives, laboratories, reference datasets, training institutions, and governance procedures. These resources may enable numerous downstream tasks while creating continuing obligations of maintenance. Infrastructural relations are frequently reciprocal: the use of an archive can produce new records, user communities can identify defects in a standard, and practical applications can finance or motivate its revision. As Star and Ruhleder's work suggests, infrastructure is intelligible through the relations and practices in which it is embedded [85]. Its productive contribution and its control potential consequently depend on access pathways, institutional interfaces, and the burdens of coordinating alternatives.

At a metaknowledge or epistemic level, the formation of evaluative criteria, classification systems, inferential conventions, or training practices may reshape the conditions under which claims become intelligible or credible to a community. This position is particularly sensitive to the distinction between generation and recognition. A new procedure for reviewing scientific evidence may influence which assertions enter an authoritative corpus, yet its effect depends on participation, interpretive pluralism, institutional jurisdiction, and opportunities for contestation. The histories of classification and scientific objectivity demonstrate that such rules are themselves formed and revised within particular practices [12, 21]. Their influence should therefore be traced rather than inferred from an abstract designation of foundational depth.

Table 6 brings these objects into a comparative frame. Each row identifies a possible newly formed productive condition and a separate route through which its governance could affect subsequent production. The examples do not imply that methods, infrastructure, and metaknowledge are mutually exclusive categories. In many historical settings, they are overlapping roles of the same assemblage, viewed in relation to different activities.

The possible consequences of enclosure differ accordingly. A restriction on a specific output may

directly affect a bounded set of users. A restriction on a widely adopted research protocol may influence many kinds of output. Control of a shared platform may create dependency through technical interoperability, accumulated datasets, and network coordination. Control of epistemic conventions can affect recognition and the admissibility of research claims. Yet an applied bottleneck can have a wider effective reach than a theoretically general epistemic rule, and competing standards can limit the practical leverage of an apparently central authority. Generative depth alone is therefore insufficient to establish either extractive power or its social consequences.

The same productive arrangement may also accumulate capital at several levels simultaneously. An open analytical library can yield a usable application, a reusable methodological component, a network of maintainers, and improved conventions of evidence checking. The historical process is multilevel even when its participants describe it as a single project. In assessing the resulting capital, it is useful to locate each acquired capability, the dependencies through which it supports other activities, and the institutions able to govern its continuation. Value produced at one level may finance work at another; likewise, a control restriction on one component may interrupt circulation among other levels. The detailed model of such heterogeneous value circulation is developed later in the manuscript.

A specific research question follows. Holding other conditions comparable, does the emergence of exclusive control at a generatively deep position yield more persistent dependency than exclusive control over a situated output? This is a provisional hypothesis requiring operational definitions of depth, breadth of downstream use, substitutability, and control. The proposition has plausible counterexamples: a specialised application can become a critical service for a large network, while a broad conceptual standard may remain easily contestable. An adequate test should examine actual changes in feasible activities and the costs of substitution as well as contractual and institutional powers. These observations give the notion of generative-level asymmetry an empirical direction without converting it into a deterministic ranking.

5.6 Path Dependence and the Reconfiguration of Initial Conditions

The formation of knowledge capital occurs within configurations whose accumulated conventions, technical investments, and governance relations condition further choices. Path dependence names a family of proposed mechanisms through which present feasible options and institutional costs are shaped by the ways earlier decisions, learning processes, and investments have been retained. The current analysis uses the term provisionally: a particular trajectory may exhibit switching costs, coordination effects, increasing returns, institutional inertia, or other forms of persistence, while alternative histories may remain possible. Establishing a path-dependent mechanism requires specifying the retained conditions and comparing plausible courses of development. The mere observation that a practice persists is insufficient to establish a specific causal account of persistence.

Knowledge-producing institutions can accumulate compatibility commitments that make later reorganization costly. A long-running archive may establish a classification scheme that supports retrieval while creating extensive conversion work for alternative categorizations. A laboratory network may depend on training systems and instrumentation calibrated to a shared method. A software community may build interfaces, documentation, datasets, and professional competence around a particular platform. These investments can generate real benefits of coordination and reproducibility. Their productive achievements also alter the relative costs of exiting or revising the arrangement. The same historically formed condition may therefore function both as shared capital and as a potential source of dependency when governance over future access or revision is concentrated.

Path dependence also operates through institutional recognition. Once publication venues, evaluation procedures, funding categories, and educational curricula are aligned around particular forms of research, participants can acquire strong incentives to develop corresponding competencies and outputs. The historical formation of those categories may expand productive capacity within certain fields while changing the opportunity costs of alternative inquiries. An actor with authority over evaluative conventions can affect recognition and allocation, yet that authority depends on its continuing acceptance,

1842 enforceability, and the availability of competing channels. Kuhn's historical analysis of research tra-
1843 ditions and changing paradigms provides one intellectual point of reference, although the institutional
1844 mechanisms of capital accumulation proposed here are not reducible to the concept of a paradigm [53].

1845 Initial conditions can be reconfigured through new tools, standards, collective organization, public
1846 investment, or institutional reform. A data format that had generated severe switching costs can become
1847 easier to replace through an interoperable translator. An academic field may revise publication criteria to
1848 recognize a wider variety of evidence and contribution. A formerly proprietary method may be supported
1849 by a publicly maintained alternative. These transformations change the range of accessible productive
1850 arrangements and may redistribute effective control without immediately altering legal ownership of
1851 previously produced artefacts. Conversely, a previously shared infrastructure can become a dependency
1852 bottleneck if a new distribution system, authentication regime, or complementary proprietary service
1853 governs practical use. Direction and magnitude are matters for historical and institutional inquiry.

1854 Because the framework treats generative levels as relational, structural reconfiguration can also
1855 change the apparent depth of a resource. A specialised tool may become foundational for an emerging re-
1856 search field as its outputs turn into reusable data, standards, or methods. A formerly central classification
1857 may lose practical significance as communities revise their objects of study and adopt alternative repre-
1858 sentations. These changes can affect productive capability, knowledge recognition, and capital control
1859 in different ways. The construction of a new representation by an observer should be separated from a
1860 change in participants' actual arrangements, and both from a change in what the participants themselves
1861 understand their practices to be. Historical interpretation can identify traces of these transformations
1862 while remaining open to conflicting periodizations and evidence.

1863 The formation of a new productive arrangement is consequently a possible site of reorganization of
1864 earlier rights and dependencies. New participants may assemble an accessible platform from resources
1865 that were previously scattered among institutions. An organization may invest in a facility while ac-
1866 quiring authority over a wider cooperative network. A commons-based group may reclaim productive
1867 independence by replicating an existing service with open components. These pathways illustrate why an
1868 initial formation event should be evaluated through multiple accounts: the change in feasible knowledge
1869 production, the reallocation of control over its enabling conditions, and the circulation of value among
1870 contributors and users. A process may expand total productive opportunity while creating asymmetries
1871 that merit separate ethical and political-economic assessment.

1872 The terminology of initial formation also raises a boundary problem. A change of institutional own-
1873 ership may appear as the founding of a new enterprise, while from the perspective of contributors it
1874 constitutes the reallocation of assets already formed through cooperative labour. A new public labora-
1875 tory may be established through state investment while incorporating knowledge accumulated in prior
1876 private and civic institutions. A community may announce an open research commons while continu-
1877 ing to rely on a proprietary cloud service or concentrated infrastructure support. These configurations
1878 illustrate different choices of analytical boundary. Their histories can be described without presupposing
1879 an absolute beginning of capital accumulation or an irreversible passage from earlier to later generative
1880 stages.

1881 The present account therefore identifies the formation of knowledge capital as a historically situ-
1882 ated process of assembling, sustaining, and transforming productive conditions. Whether that process is
1883 accompanied by primitive accumulation in the historically specific sense depends on relations of separa-
1884 tion, appropriation, and the constitution of capitalist production relations. Whether it yields wider shared
1885 capacity, concentrated power, or a mixture of both depends on the governance of inherited resources, co-
1886 operative labour, public investment, infrastructural control, and effective dependencies across generative
1887 levels. These distinctions establish the analytical basis for studying recursive accumulation and expan-
1888 sion in Section 6, while leaving empirical judgments about particular institutional arrangements open to
1889 investigation.

6 Recursive Accumulation and Expansion of Knowledge Capital

This section develops a relational account of how established knowledge-producing conditions can support their own renewal, modification, and extension. Its objective is to identify mechanisms of cumulative development, capability formation, recombination, cross-level expansion, feedback, and changes to the conditions of accumulation. The analysis is conceptual and comparative, drawing selectively on work in evolutionary economics, innovation studies, organizational knowledge, and commons-based production. It does not assume that accumulation follows a universally increasing trajectory, that its components can be reduced to a single stock, or that an expansion of knowledge production necessarily increases public access or collective autonomy. A claim of capital expansion requires an explicit account of *whose* productive options expand, *through which* reproducible conditions, and *under what* relations of effective control.

The relevant object is a historically situated arrangement containing knowledge resources, practical skills, cooperative relationships, infrastructures, evaluation procedures, and the institutions that authorize and sustain their use. Such an arrangement can generate research outputs and can also alter the means through which further outputs become possible. An experimental result may modify a method; a method may become a shared platform; a platform may support a field of applications; and experience with those applications may motivate revision of the platform's assumptions. These connections supply the central sense of *recursive* accumulation in this paper. A product of one organized activity may re-enter the productive conditions of another activity, sometimes including the revision of the rules and capacities that enabled its own generation.

Recursive relations do not establish a fixed chronological ordering or a single hierarchy of knowledge. The relevant ordering, where one is needed, is a specified relation of dependency, historical traceability, or institutional continuity. Some histories exhibit cycles of reinterpretation or redesign; some dependency relations admit multiple substitutes; and some changes concern only an observer's reconstruction of activities. Section 4 introduced generative levels as task-relative representations of these dependencies. The present section examines how capital accumulation may operate through them, while reserving a more explicit relational formalism for Section 13.

6.1 Knowledge Reproduction and Cumulative Development

Knowledge reproduction refers here to the organised preservation and renewed availability of conditions that enable identifiable knowledge-producing practices. The expression covers more than the copying of propositions or information. Reproduction may involve keeping experimental equipment operational, maintaining research software, teaching technical and interpretive skills, supporting critical communities, and securing rules under which research can continue. In the absence of such activities, accumulated artefacts can lose much of their productive relevance, even when their textual contents remain intact. The capacity to reproduce knowledge-generating practices is therefore an object of accumulation in its own right.

A mathematical result provides an elementary illustration. The published statement and proof can circulate at low marginal cost, but the capacity to evaluate, extend, and apply the result depends on training, shared notation, competent criticism, and connections to other problems. A reader's possession of a digital file does not by itself reproduce that capacity. Similarly, a laboratory procedure may survive in a written protocol while its reliable execution requires tacit calibration and continued access to reagents, instruments, and technical personnel. A documented programming interface may remain public while a changing runtime environment makes its implementation unusable. These examples identify different modes of reproduction: informational preservation, operational maintenance, social transmission, and institutional authorization. Their interaction matters for the apparent durability of knowledge capital.

Accumulation becomes cumulative when reproduced capacities participate in the creation or revision of further capacities. Research can produce new facts, methods, classifications, and skills, some of which become productive inputs within later identifiable activities. The accumulation of a shared corpus can improve the feasibility of comparative research. Improvements in experimental reliability can expand the

set of questions that can be meaningfully tested. New educational materials may allow a wider population to participate in a specialized field. This account remains conditional: additional information may also increase search burdens, produce incompatible conventions, amplify redundant work, or displace existing skills. Whether the accumulation of resources yields a greater feasible production repertoire depends on the organization of access, understanding, maintenance, and coordinated use.

Evolutionary approaches to economic change provide a useful disciplinary analogue because they examine firms and industries through evolving routines, search practices, and innovation rather than only through equilibrium allocations [67]. Their empirical and theoretical objects differ from the public knowledge-production arrangements considered here. The analogy is valuable insofar as the persistence of a productive routine may depend on enacted organisational competences, not solely on stored instructions. It remains limited where researchers contest the meaning of their work, revise epistemic norms, or participate in publicly governed practices that have different objectives from firm growth. The knowledge-capital framework accordingly treats reproduction as a composite process, open to methodological pluralism and revision of its own standards of success.

The public dimension of reproduction can be analysed through the conditions under which contributors and users retain effective opportunities to participate. Publicly accessible outputs may be sustained by work that is unevenly compensated or recognized. Conversely, an institution can deliberately allocate resources to maintenance, documentation, independent replication, and training, thereby strengthening the capacity of other participants to build upon existing work. The relevant question concerns the circulation of resources and opportunities back into the practices that produce and sustain knowledge. Generative-justice scholarship supplies one vocabulary for examining the return of value toward its contributors and generative conditions [26]. That vocabulary does not settle how to compare different forms of value or allocate competing claims. It directs attention to the continuing relations among contribution, benefit, and productive capacity.

A distinction is therefore required between the *reproduction of an arrangement* and the *reproduction of a given distribution of power within it*. A privately controlled scholarly platform may preserve documents while increasing the dependence of researchers on its services. A cooperative repository may preserve resources while expanding contributors' authority to inspect and modify preservation procedures. A public laboratory may reproduce sophisticated facilities while restricting access for reasons of safety, scarce capacity, or institutional priorities. These are analytically different distributions of reproductive authority. Reproduction of knowledge capital can coexist with change in ownership, with stability of governance, or with increased asymmetry of control.

Cumulative development likewise requires a bounded description of what has accumulated. A field may gain new methods while losing competence in older techniques; an archive may gain holdings while losing the staff required to interpret them; a software project may gain contributors while acquiring coordination demands that slow certain forms of change. Such histories can exhibit expansion along one dimension and contraction along another. The research task is to identify the productive capacities being compared and the historical evidence by which their continuity and transformation can be assessed. This task forms the starting point for the more specific analysis of generative capabilities.

6.2 Accumulation of Generative Capabilities

Generative capability denotes an actor's or organized collectivity's situated capacity to initiate, sustain, evaluate, or modify a specified family of knowledge-producing activities. This usage extends the account of productive capacity developed in Section 3 by emphasizing the creation of additional viable activities and the transformation of their enabling conditions. A capability may belong partly to persons, partly to a cooperative organization, and partly to shared infrastructures. These aspects are related through work practices, access rules, maintenance, and forms of practical understanding. Treating capability as a relational property avoids assigning an entire jointly maintained activity to the ownership of a single artefact holder.

The distinction between a resource and the capacity to use it is familiar from research on absorptive

capacity. Cohen and Levinthal theorized firms' capacity to recognize the value of external information, assimilate it, and apply it to commercial ends, stressing the significance of prior related knowledge [17]. Their model is firm-oriented; its extension to public or commons-based research requires separately defining productive outcomes and the institutions capable of learning. For public knowledge production, a comparable distinction helps explain why equal access to an article, dataset, or computational tool may yield unequal productive possibilities. Different educational histories, language resources, time budgets, complementary instruments, and institutional permissions affect whether an actor can integrate a resource into further activity. The firm-oriented construct should therefore be translated cautiously: the objective may be collective knowledge creation, cultural interpretation, public service, or critical understanding as well as commercial innovation.

A generative capability can accumulate through repeated practice, deliberate investment, shared learning, codification, and the formation of reliable cooperative relationships. Its renewal may depend on people who remain able to question procedures and teach alternatives. A large research consortium might improve its ability to coordinate complex experiments while an independent community develops accessible protocols that distribute a subset of comparable capabilities more widely. Both arrangements can experience capability accumulation, though their scales, resource needs, and forms of participation differ. Expansion should be described relative to an identifiable set of possible activities: for example, the ability to reproduce a class of results, test a new family of hypotheses, support independent peer criticism, or adapt a method across disciplines.

A distinction between *capacity* and *effective command* remains central. An institution may possess legal rights to a database while lacking the qualified staff or technical infrastructure to use it. A group of researchers may have methodological expertise but require permission or paid access to perform the relevant analyses. An individual may have high competence while being constrained by employment obligations, inaccessible equipment, or prohibitive computational costs. Accumulation of the materials that support production may thus occur independently of accumulation of the authority needed to mobilize them. Public capacity expands most clearly where additional participants gain practicable access to the requisite combination of resources, competences, and decision opportunities.

Capability is also partly reflexive. Researchers may accumulate the ability to examine the assumptions of their own instruments, revise classification systems, and challenge established validation procedures. Such capacities matter particularly near what the present paper calls meta-knowledge and methodological generative levels. An additional dataset may expand the scope of a measurement practice; an improved capacity for methodological criticism may change which measurements can be regarded as informative in the first place. These changes are not naturally comparable in a single quantity. An account of generative capital therefore benefits from a repertoire-based description of newly supportable activities, alongside a record of activities that become restricted or lose their earlier meaning.

Institutional change can redirect an apparently accumulated capability. A research group's specialization may deepen while its members lose opportunities to pursue questions outside a sponsor's priorities. An open software community may expand its contributor base while project governance becomes concentrated among maintainers who hold exclusive integration rights. Neither process can be assessed solely through counts of skills, downloads, or submissions. The analysis must ask how the actor set, feasible activity set, and procedures of evaluation are constituted. The ownership and governance distinctions developed in Section 3 remain relevant to these questions even where the physical assets and published outputs appear unchanged.

6.3 Capital Expansion Through Knowledge Recombination

Recombination is a mechanism through which accumulated knowledge resources and capabilities enter new productive configurations. An existing theorem may be connected to an experimental technique; an archival classification may be combined with computational search; a software library may be integrated with a previously separate workflow; or methods developed in one discipline may be adapted to unfamiliar sources of evidence. These activities can create products and can also create durable capabilities

for further recombination. The significance of recombination lies partly in the change of relationships among resources, not merely in the number of components brought together.

Kogut and Zander's theory of the firm emphasizes knowledge embodied in organizing principles and the development of capabilities through recombination [52]. The original account concerns firm boundaries, replication, and organizational learning; applications to public knowledge production are conceptual extensions that require institutional comparison. Their work offers a relevant explanation of why organizational knowledge cannot be reduced to a collection of individually owned items. The present inquiry extends the analytical problem to scientific communities, cultural and historical inquiry, public institutions, and commons-based production. In these settings, a newly created combination may depend on shared standards, freely available conceptual tools, public archives, or independently governed infrastructures. The organizations that coordinate a combination can acquire capital-like capacities even when no component becomes privately owned.

Recombination may occur through *complementarity*, where different capabilities are jointly necessary; *translation*, where a representation becomes usable in another practice; *modular integration*, where components connect through relatively stable interfaces; and *reconfiguration*, where the relationships among components or the standards of their use change. These are proposed analytical categories rather than exhaustive empirical types. Their consequences depend on the coherence of the component practices and on the work required to sustain an intelligible relationship among them. Formal compatibility of data schemas, for example, does not prove compatibility of the meanings or evidential standards attached to the data. A computational pipeline joining medical, social, and historical records may face substantive interpretive issues that a syntactically valid interface does not resolve.

Generative recombination can support extensive expansion when a reusable interface lowers the work required for many independent activities. A library exposing a stable numerical method may allow researchers to focus on problem-specific assumptions. A publicly maintained ontology may enable interoperability across archives. A common training resource may help practitioners cross disciplinary boundaries. In each case, the new productive possibility arises through a network of tools, expertise, and governance practices. The accumulation cannot be attributed solely to a single component without considering the contribution of complementary resources and labour. This observation is particularly important when a private intermediary earns revenue from a recombination that draws upon widely distributed public inputs.

Recombination can also introduce new dependencies. A common interface improves compatibility while creating a focal point for maintenance, revision, and authority. Participants who adopt a shared technical standard may face switching costs if alternative standards diverge. A widely used model architecture can facilitate reusable applications while concentrating resources among institutions able to train, evaluate, or host it. These possibilities do not imply that integration is intrinsically extractive. They show that a productive improvement can alter the opportunities for appropriation and the distribution of decision rights. The institutional arrangement determines which participants can revise the interface, inspect its implementation, propose alternatives, and retain independent routes of production.

The importance of recombination differs across the generative levels identified in Section 4. Near a specific application, combining two tools may create a new service or local research procedure. At a methodological level, integrating previously separate techniques can establish a reusable family of inquiry. At a more foundational epistemic level, reconsidering relationships among classificatory rules, standards of evidence, and generative descriptions may reorganize the fields of questions to which an inquiry can respond. The difference concerns the actual range of activities affected and the resources required to make changes effective. It cannot be read directly from a diagram in which one node has been placed nearer the root.

Some combinations fail, remain ephemeral, or produce tensions that later require institutional repair. A merged archive may compromise provenance; a cross-domain evaluation standard may obscure meaningful disciplinary differences; a complex software stack may be difficult to maintain without concentrated expertise. An adequate account of capital expansion therefore distinguishes the temporary production of a novel output from the durable formation of new productive conditions. It also distinguishes

Table 7: Illustrative pathways of knowledge-capital expansion across relative generative levels.

Primary site	Possible generative expansion	Relevant dependency and control question
Meta-knowledge and epistemic standards	Revision of categories, admissible evidence, or modes of representing inquiry across domains	Who participates in revising standards, and which alternative accounts remain intelligible?
Methodological systems	Reusable procedures enabling additional classes of testing, interpretation, or inference	Are validation resources, training, and procedural modifications accessible?
Shared infrastructures	Wider operational access through archives, computation, software, and coordination services	Who governs interfaces, continuity of service, interoperability, and switching?
Applications and generated outputs	New datasets, models, questions, artefacts, and feedback into methodological development	Can contributors reuse outputs and influence the conditions of subsequent production?

the enlargement of one actor's repertoire from a collective enlargement across affected contributors and users. In this way, recombination connects cumulative knowledge development to the political economy of shared production and differentiated control.

6.4 Cross-Level Capital Expansion and Generative Multiplication

Cross-level capital expansion concerns changes in productive possibilities that extend across the task-relative generative levels described in Section 4. One activity may produce a durable resource on which several other activities depend. A new method may support multiple applications; the resulting applications may then generate datasets, anomalies, and interpretive difficulties that motivate further methodological revision. An infrastructure can enable research while its users contribute documentation, maintenance, or new standards that alter the infrastructure itself. Such relations provide a basis for analysing recursively accumulated productive capacity without treating the levels as a fixed, unidirectional derivation tree.

The term *generative multiplication* is used provisionally for the phenomenon in which one change to the enabling conditions makes a plurality of additional, distinguishable activities feasible. This is an analytical claim about the widening of a situated activity repertoire. It is not an assertion that economic value, epistemic quality, or social benefit increases in a mathematically multiplicative manner. Two new applications may rely on the same scarce facility and therefore compete for capacity. A single widely shared tool may reduce the cost of participation while leaving the interpretation of outputs highly specialized. A change in formal representation may increase the number of expressible claims while decreasing some participants' ability to be recognized within the new standard. These countervailing effects are part of the proposed account.

Table 7 identifies illustrative pathways and the different conditions that would need to be examined in empirical work. Its levels are relational positions selected for a research question, and its cases are mechanisms rather than reported comparative findings.

Three separate quantities of interest can be identified without forcing them into a common metric. The first is the breadth of productive activities that a resource can potentially support. The second is the extent to which affected participants can *effectively* employ that resource in their own circumstances. The third is the distribution of authority over the continued maintenance, revision, and allocation of that resource. Broad downstream relevance is compatible with a narrow distribution of effective access. Wide access to a published output is compatible with concentrated control of the critical infrastructure through which the output becomes usable. An institutional comparison that measures only the number of supported applications may therefore overlook control and reproduction mechanisms.

Cross-level accumulation can create a feedback relation with the generative structures on which the

original investment relied. Suppose a collective produces an open research tool using shared mathematical libraries. Applications developed with the tool reveal computational limits and new interpretive requirements. Contributors then revise the library, document alternative procedures, and build new training resources. The resulting productive conditions may enable further applications in a changed range of tasks. This is a hypothetical case of reciprocal development among applications, methodological infrastructure, and practical epistemic knowledge. Its defining feature is the re-entry of generated work into the conditions of production, not a necessary progression from a privileged foundational node toward peripheral outputs.

The same structural description permits a different value-circulation arrangement. Suppose a proprietary service depends on public datasets and openly developed methods while controlling the only practicable high-volume implementation for a set of users. Its earnings and operational data can support improved service and further infrastructure investment. These developments may enlarge productive capacities in the system while concentrating the authority to activate them. The structural mechanism alone does not establish exploitation; a judgment would require evidence concerning contributions, entitlement, terms of access, dependence, surplus appropriation, and effects on contributors' continuing capacities. This distinction preserves the separation between capital expansion and the relations through which accumulated capital becomes a source of power.

Generative multiplication also interacts with bottlenecks. A relatively specialized application can become a shared point of dependence when its outputs are adopted as a mandatory benchmark, regulatory standard, or input to multiple production processes. Conversely, a broad foundational technique can lose effective leverage when open alternatives emerge or when users develop new capabilities that bypass an intermediary. Generative depth is therefore informative only together with effective reach, substitutes, and authority. The cross-level analysis ultimately concerns the topology of dependencies and the institutions through which participants can preserve, contest, and transform their connections.

6.5 Feedback, Increasing Returns, and Structural Transitions

Feedback describes a process in which outcomes alter conditions affecting the continuation or modification of a productive arrangement. In knowledge production, repeated use of an infrastructure can generate documentation, compatibility incentives, user communities, reputation, revenues, data, and maintenance needs. Some of these outcomes may strengthen the infrastructure; others can create congestion, competing obligations, or disaffection. An account of increasing returns identifies conditions under which cumulative adoption or investment raises the relative attractiveness or productive potential of continuing along a particular path. These concepts are relevant to recursive capital expansion but require a careful distinction between an economic model and its application to institutional histories of knowledge.

Arthur's model of adoption among competing technologies identifies conditions under which increasing returns can amplify contingent events and generate lock-in [4]. David's historical interpretation of QWERTY similarly directs attention to sequential adoption decisions and inherited technical complementarities [22]. These are distinct contributions: one offers a stylized formal mechanism, while the other provides a historically situated account subject to empirical debate. These contributions do not establish a general theorem that knowledge-production systems converge upon inefficient institutions or that each frequently used standard becomes a monopoly. They establish analytical reasons to investigate switching costs, complementarities, and the sequence of mutually reinforcing choices. A research infrastructure can acquire an advantage because its users share training materials and compatible data, even if the infrastructure's technical quality is only one part of its continuing attractiveness.

Positive feedback may support public accumulation. More contributors can improve error detection, translations, documentation, and maintenance in an open project, making it easier for others to contribute. Increased participation in a shared archive may attract investment in preservation and interoperability. An educational resource that is widely adapted may generate locally relevant translations and explanations that broaden collective capability. Each mechanism depends on governance, labour allocation, and quality assurance. Participation can also impose coordination costs; archives may face increased cura-

tion burdens; extensive reuse can expose errors in a reference that previously served a smaller group. A claim of increasing returns should specify both the reinforcing process and its constraints.

Positive feedback may also consolidate asymmetric control. A proprietary provider can use service revenue to develop complementary tools, acquire specialized personnel, establish interface standards, and attract further users. If those users become dependent on the provider's proprietary formats or computational resources, the provider can acquire new opportunities for charging fees, setting research terms, or determining permissible uses. Some benefits may simultaneously accrue to participants through technical quality and reduced coordination burdens. The question of extraction concerns the conditions under which the provider's appropriation and control are sustained by other actors' contributions and dependencies, and whether the arrangements constrain their capacity to reproduce or revise productive conditions. The economic magnitude of revenue alone cannot answer that question.

The circulation of heterogeneous value matters to both cases. Financial receipts may be reinvested in infrastructure, yet the resulting distribution of control depends on governance and rights. Reputation may attract contributors but also empower a small set of gatekeepers. Datasets may improve models but require labour for annotation, consent management, and correction. Professional recognition can support researchers' opportunities while reinforcing particular standards of evaluation. These value forms may be transformed into one another under identifiable institutional arrangements, though no generally valid exchange rate follows from their co-occurrence. The mechanisms of value creation, conversion, appropriation, and recirculation should therefore be traced separately when attributing a feedback effect to the accumulation of capital.

Negative feedback and structural discontinuity are equally important. Maintenance deficits can diminish the value of an expanding codebase. Concentrated decision rights can provoke contributor withdrawal or institutional challenge. Interoperable alternatives may lower switching costs and weaken an entrenched platform. New evidence can discredit a widely used classification, changing the practical significance of earlier investments. A funding shock, legal reform, or collective decision may rearrange the production conditions through which an accumulated resource is mobilized. These developments can alter the direction and distribution of further accumulation without requiring the disappearance of the underlying knowledge artefacts.

A structural transition occurs, in the sense used here, when the relationships constituting the production arrangement change sufficiently that the former description of productive options, dependencies, or governance ceases to be adequate. A transition may concern shared standards, the institutional allocation of control, the boundaries of relevant communities, or the practical meaning of a research procedure. Its identification depends on explicit analytical criteria and evidence, rather than on an assumed critical threshold of aggregate capital. A new open standard can redistribute opportunities among previously dependent users; a public archive can be transferred into a membership-governed institution; a research field can reconsider what constitutes valid observation. In such cases, the conditions of continued accumulation have changed along with the observed outputs.

The firm-oriented theory of dynamic capabilities supplies another limited point of comparison. Teece, Pisano, and Shuen analyse processes of combining and reconfiguring competences, asset positions, and organizational paths as potential determinants of private-enterprise advantage in rapidly changing technological environments [86]. This account provides a firm-specific comparison, while performance, public accessibility, and collective reproduction require different outcome measures. The present argument retains the relevance of reconfiguration while extending its questions to non-firm actors and to the reproduction of collectively accessible knowledge. Commercial advantage, shared epistemic capacity, and public value are distinguishable evaluation objects. An institution's success at accumulating capital may coexist with uneven social outcomes, while a publicly maintained system can broaden generative capability without maximizing proprietary returns. The analytical task is to identify which feedback loops are being sustained and what distributions of productive opportunity they create.

6.6 Changes in the Conditions of Further Accumulation

Recursive knowledge-capital expansion can transform the enabling conditions by which further accumulation is organized. This possibility extends beyond growth in the number of publications, instruments, models, or trained participants. New practices can revise standards of evidence, establish additional classes of research objects, create interoperable institutional networks, alter accepted forms of authorship and contribution, or change the infrastructure through which materials become available. Some modifications enlarge the activities open to a community; others may narrow recognition or require new complements that only a limited number of actors can provide. Changes to the conditions of accumulation therefore require simultaneous attention to productive feasibility, epistemic legitimacy, and institutional power.

The effect of a methodological innovation illustrates this point. An automated analysis procedure can make a formerly labour-intensive task more accessible and provide new opportunities for independent checking. If the same procedure becomes an exclusive requirement for funding, publication, or regulatory acceptance, its provider or governing institution may acquire a role in determining which work can enter a recognized knowledge system. The two processes may coexist. The institution can increase the speed or apparent precision of knowledge production while creating access requirements or interpretive dependencies. Evidence concerning actual practices is necessary before concluding that the arrangement is extractive or that its efficiency gains outweigh any losses of autonomy.

Changes at relatively deep generative levels may affect broad ranges of production when many dependent practices share standards, methods, or infrastructures and lack viable substitutes. A revision of an interoperable data standard can redirect the work of multiple communities; a new convention of citation and attribution can affect which forms of contribution receive recognition; an alteration in the criteria for admissible evidence may change what knowledge is institutionally legible. Such effects remain contingent on the network of actual dependencies. An apparently foundational rule with many alternatives may exercise less practical leverage than a highly specialized proprietary bottleneck. This contingency is central to the paper's account of generative-depth asymmetry.

The historical constitution of the actors and communities involved matters as much as the description of the resources. A knowledge commons may strengthen shared productive conditions through accessible documentation, mutual assistance, collectively revisable standards, and arrangements for distributing maintenance responsibilities [40, 8]. A public institution may provide long-term continuity for infrastructure that would be difficult to finance through individual contributions. A private enterprise may create broadly useful tools while setting exclusionary terms for particular uses. Hybrid arrangements may distribute ownership, financing, participation, and rule-making authority across several institutions. These institutional forms should be compared through their concrete governance and circulation mechanisms rather than treated as internally homogeneous categories.

A related distinction concerns *control over outputs*, *control over enabling resources*, and *control over the rules of continued generation*. Holding copyright in a research paper, managing a computing facility, maintaining a professional classification, and determining eligibility for public funding are different positions. An actor may occupy several of them, or the rights may be distributed. Their interaction influences the distribution of feasible activity and the conditions under which accumulated value returns to support further production. Analysis should trace the ways in which gains at one level can finance, legitimate, or technically support control at another level, while also identifying reciprocal opportunities for participants to reorganize those dependencies.

This argument also has an epistemic limit. An investigator's assertion that a new generative rule has emerged may reflect a revised description rather than a change in the participants' productive relations. To distinguish these possibilities, empirical investigation should examine procedural records, changes in authorized access, technical interoperability, maintained alternatives, resource flows, educational practices, and the situated explanations of relevant participants. Competing accounts may identify different boundaries and different transformations. A theory of recursive expansion should be able to preserve such disagreements without inferring that a single formal hierarchy discloses an ultimate structure of knowledge.

The mechanisms identified here concern renewal of productive conditions, the assembly and recombination of capabilities, the extension of feasible activities across generative levels, feedback, and changes to the conditions of further accumulation. They may coexist with growth in collective access or with intensified dependence, and the same configuration may exhibit both. This makes the institutional question in Section 7 more precise: which actors can maintain, govern, and alter the conditions on which recurrent expansion depends, and through what value-circulation arrangements are those capacities sustained?

7 Institutional Configurations of Knowledge Capital Accumulation

This section examines how arrangements of ownership, governance, access, and value circulation shape the formation and expansion of productive knowledge capital. Its objective is to compare institutional configurations while maintaining the analytical distinction between the development of productive capabilities and the distribution of authority over their conditions. The argument proceeds through capitalist organization, commons-based production, communist conceptions of collective production, public institutions and cooperatives, cross-institutional governance mechanisms, and a comparative assessment of conditions for accumulation and expansion. The approach is conceptual and historically informed. Named traditions and organizational forms serve as analytical reference points; the institutional illustrations indicate mechanisms requiring case-specific verification rather than empirical conclusions about an entire economic system.

Knowledge production commonly combines arrangements drawn from several legal and organizational domains. An enterprise can depend on public universities, shared standards, openly licensed code, and voluntary communities; a public laboratory can purchase proprietary instruments and rely on commercial publishers; and a cooperatively maintained repository may receive public grants and serve privately owned enterprises. Productive knowledge capital therefore need not correspond to one institutional category at every generative level. The empirical object is a situated configuration of practices and decision rights, including relations that cross organizational boundaries. A classification limited to the nominal owner of a database, laboratory, or platform can miss who performs productive work, whose contributions persist as shared inputs, who sets the terms for participation, and who can redirect accumulated benefits into subsequent production.

Two distinctions orient the comparison. First, initial knowledge-capital formation and recursive expansion can occur under varied forms of governance, whereas Marxian primitive accumulation refers to specific historical processes implicated in the formation of capitalist relations, including the separation of producers from their productive conditions [61]. Second, the social consequences of accumulation concern more than whether the accumulated assets are privately or collectively held. They depend on the actual organization of productive access, the possibilities for contesting decisions, the recognition of different kinds of contribution, and the circulation of heterogeneous values back to people and infrastructures that enable knowledge creation. These distinctions allow capitalist, commons-based, and collectively organized production to be examined through common analytical questions without treating their normative commitments or historical trajectories as interchangeable.

7.1 Capitalist Organization of Knowledge Production

The capitalist organization of knowledge production is examined here through the coordination of labour, productive assets, contractual relations, and claims on returns within profit-oriented accumulation. The relevant institutions include research-intensive enterprises, commercial platforms, publishing organizations, specialist service providers, and firms whose products incorporate knowledge acquired from a wider research environment. Such organizations can develop distinctive technical capabilities by combining paid work, investments in research, proprietary assets, and knowledge obtained through markets or collaboration. Economic returns may support further research, organizational learning, maintenance of infrastructure, and increased production capacity. Their effects on the broader knowledge system remain

contingent on the contractual and regulatory conditions under which participants exchange resources and make further use of the results.

The analytically significant property is the arrangement of decision rights and economic claims. Investors, owners, managers, workers, contractors, licensors, and external contributors may have different rights to direct research, determine access, protect outputs, and distribute income. An employment agreement can establish remuneration for specified work while allocating intellectual-property rights to an enterprise. A scientific collaboration can produce knowledge shared among partners while reserving particular commercial applications. Some proprietary rights can facilitate investment, coordination, and disclosure under certain arrangements; they may also restrict independent verification, adaptation, or participation when complementary resources are controlled by a narrow set of actors. The costs and benefits of these arrangements require analysis of the particular sector, alternatives available to users, the temporal and territorial scope of rights, and the consequences for productive capabilities.

At the level of knowledge capital, monetary revenues constitute one possible return among several. An enterprise may accumulate experimental routines, trained personnel, organizational memory, legitimacy, datasets, and privileged access to distribution channels. Its position in generative dependencies matters. Ownership of a specific application can generate revenue from a relatively circumscribed activity; the management of a widely used methodological interface or validation service can affect numerous downstream projects. A rule that conditions participation in scientific communication upon payment for a proprietary workflow may give its provider influence beyond the immediate transaction. The effective scope of that influence depends on alternative workflows, switching costs, professional conventions, and possible collective responses. Consequently, proprietary status by itself provides an incomplete account of generative leverage.

An additional problem concerns the origin of the knowledge incorporated into private accumulation. Commercial research may draw upon public educational systems, publicly financed basic science, professional norms, and shared research infrastructures. The economics of research has long examined spillovers and difficulties in fully appropriating the returns from knowledge creation [3, 66, 18]. Acknowledging those inherited and shared conditions does not predetermine how each commercial return should be distributed. It establishes the need to trace contributions and productive dependencies across institutional boundaries. Commercial success, scientific advancement, and collective access to productive capability may move in different directions, especially when returns from one institutional level enable control over rules or infrastructures at another.

The term *extraction* requires a further step beyond observing that an enterprise earns income or accumulates an advantage. Within the present inquiry, an extractive relation is a proposed institutional mechanism in which an actor systematically obtains value produced through distributed dependencies while exercising asymmetric control that materially constrains the capacities of contributors or dependent users to participate, contest terms, or reproduce their productive conditions. This formulation is a diagnostic proposal, and its application requires evidence of the claimed control, circulation pathways, and constraints. It also leaves space for legitimate compensation, negotiated exchange, risk bearing, and maintenance costs to be examined rather than assumed away. In scientific publishing, for example, arguments concerning enclosure and alienation identify possible relations among scholarly labour, commercial property claims, and access arrangements [76]; evaluating a particular publisher requires records of labour, rights, prices, access, and governance.

Capitalist coordination may thus support substantial knowledge-capital formation while distributing control and benefits asymmetrically. The section's comparative framework seeks to identify how those properties arise in definite institutional relations, without inferring one uniform development pattern from the legal category of the enterprise. Evidence should record who provides the productive inputs, who can alter the rules of access, which values become monetized, and how benefits finance or constrain further knowledge production at each relevant generative level.

7.2 Commons-Based Knowledge Production

Commons-based knowledge production is characterized here by a shared resource system whose access, contribution, maintenance, and governance are organized through a community and its rules. The resource may consist of publications, code, archives, data, educational materials, interpretive practices, or infrastructure. Commons governance is neither reducible to free-of-charge access nor necessarily identical to state ownership. Hess and Ostrom's treatment of knowledge as a commons foregrounds the interdependence of shared resources, communities, and institutional arrangements, including the difficulties posed by exclusion, preservation, and sustainable management [40]. Ostrom's wider institutional research likewise cautions against presuming that a single centralized or proprietary solution determines collective-action outcomes [70, 74].

Knowledge commons can form productive capital through the preservation and recombination of accessible resources, cooperative maintenance, reciprocal teaching, collective debugging, and shared methods of evaluation. A research community may create a data repository and accompany it with agreed metadata standards, reproducibility protocols, and publicly available guidance. Those resources acquire generative relevance as participants learn to use them, maintain their reliability, and contribute additional materials. Shared access can broaden the set of people able to enter a field and can provide complementary resources to organizations with quite different purposes. In that sense, a commons may accumulate productive capabilities that are distributed across persons, artefacts, and continuing institutions rather than placed under one residual private claimant.

Benkler's analysis of commons-based peer production is relevant to forms of coordination that depend on modular contributions, communication, and self-organization [8, 9]. The organizational possibilities emphasized by this literature do not amount to a universal claim that distributed production is superior. Complex equipment, long-term preservation, specialized expert judgment, participant safety, and reliable service provision may require substantial dedicated coordination and financing. Communities also encounter difficulties in allocating maintenance labour, deciding which contributions to accept, resolving disputes, and meeting the needs of participants who possess unequal resources. Openly licensed outputs may coexist with unequal authority over the project roadmap or with dependencies upon externally controlled hosting, hardware, or interfaces.

The circulation of value is therefore central to assessing the development of a commons. Users obtain epistemic and practical benefits from shared knowledge; some become contributors, reviewers, maintainers, translators, or educators. Benefits may circulate through access to improved resources, reputational recognition, training, cooperative relationships, and monetary funding for infrastructure. The routes and recipients of these benefits are heterogeneous. The accumulation of citations need not provide time or income to maintain an archive; volunteer recognition may coexist with exhaustion; and an increase in downstream commercial activity may supply little support for the shared infrastructure upon which it relies. The question of reproduction concerns whether contributors and maintainers have workable means to continue their activities and participate in decisions concerning future conditions.

Generative justice provides a related account of the significance of returning value toward the capacities and social relations through which it is created [26]. Its relevance here is structural: a commons may establish arrangements through which contributions improve the productive conditions available to later participants, while another arrangement may permit substantial downstream appropriation with limited recirculation. These differences can persist even when both systems use open licenses. Their assessment should consider funding pathways, community voice, authorized reuse, interoperability, and the distribution of work needed to keep resources usable. Potentially extractive relations may also occur *within* a commons if a small group acquires durable control over admission, recognition, infrastructure, or the terms of contribution.

Commons-based production accordingly supplies a distinct institutional possibility for collective capital formation, but it does not specify a complete economy, settle competing property claims, or eliminate power asymmetries by definition. Its comparative importance is the possibility of maintaining and extending productive knowledge capital through rules that permit shared use and meaningful collective revision. Whether that possibility is realized depends on governance, material support, and the relations

among shared resources and their external institutional environment.

7.3 Communist Conceptions of Collective Knowledge Production

Communist conceptions are considered here as a family of political-economic proposals concerning common control of productive conditions and the organization of production and distribution around collective needs. This is a theoretical category with a longer historical and intellectual scope than any one contemporary organization or state. It requires separation from the institutional category of a knowledge commons, which can operate within several broader economic systems. The point of comparison is the possible accumulation and expansion of productive knowledge capital within a social organization that aspires to collective control of its productive foundations. The discussion is interpretive rather than a claim that communist institutions have one universal historical form.

Marx's *Critique of the Gotha Programme* is especially pertinent because it explicitly discusses deductions from a cooperatively produced social product for the replacement of productive means, the expansion of production, reserves, administration, education, and support of collective needs [62]. Such deductions indicate, at the conceptual level, that collective production may devote some of its resources to maintaining and enlarging its conditions of further production. This observation has a direct bearing on the paper's thesis. Accumulation and expansion of productive capacities can form part of collective reproduction even when private appropriation of surplus is not the organizing objective. The allocation of resources to the future maintenance and development of productive means is analytically distinct from the private ownership and distribution of the resulting benefits.

Applied to knowledge production, a communist conception could involve jointly governed laboratories, libraries, educational institutions, infrastructures of communication, and shared methodological resources. Their development would still require labour, training, maintenance, technical decisions, and decisions regarding the allocation of scarce means. The relevant issues would include access to advanced instruments, determination of research priorities, the treatment of dissenting interpretations, the distribution of demanding or hazardous work, and the ability of participants to revise institutions. Certain capacities may remain scarce because knowledge artifacts can be reproduced more readily than specialized materials, expert attention, or large-scale facilities. Collective ownership thus leaves substantive questions about operational authority and the distribution of effective capabilities.

An important analytical boundary separates *collective title* from *effective collective governance*. State ownership or formally public designation may coexist with centralized administrative direction; conversely, a locally governed commons may exercise substantial practical autonomy without invoking a communist social theory. A proposed collective system must therefore be examined through actual rights of access, participation, revision, and withdrawal, alongside the durability of the institutions that reproduce its productive conditions. Centralized coordination may support expensive shared infrastructure, while concentration of authority can also narrow the range of accepted research agendas or generate dependencies that participants struggle to contest. These are possible institutional mechanisms rather than necessary characteristics of communism or of centralized provision.

The vocabulary of value circulation also requires explicit care in this setting. Marx's account of distributions and deductions within a cooperative social product should not be treated as an assertion that every contribution has one fully measurable value or that monetary exchange is a necessary medium for collective production. Knowledge production yields heterogeneous epistemic, material, social, and institutional consequences. The reproduction of a research community may involve accessible education, shared equipment, time for criticism, recognition of contributions, and means of subsistence. A collective arrangement can coordinate such conditions through several decision procedures. Its performance cannot be inferred solely from quantities of completed outputs or the rate at which an institution adds assets to its inventory.

At deeper generative levels, the communist conception raises further questions about the collective formation of standards of explanation and validation. A publicly accessible scientific doctrine may remain difficult to challenge if methodological recognition is tightly controlled, whereas a research culture

permitting plural criticism may provide wider opportunities to revise productive rules. Equal legal claims on resources can coexist with unequal expertise, educational opportunity, and influence. The present framework therefore asks how knowledge-making power is constituted and distributed, including the capacities to propose alternative rules and reorganize dependent activities. It treats the relation between collective economic organization and epistemic autonomy as a research question requiring independent historical and institutional examination.

The comparative contribution of communist conceptions is consequently conceptual: they clarify that capital formation, planned or emergent accumulation, and expansion of collective productive capacity can be theorized without identifying accumulation with private profit. This does not establish equivalence between communist production and commons governance. It specifies an additional institutional horizon against which the relation among ownership, authority, value circulation, and generative dependencies can be examined.

7.4 Public Institutions, Cooperatives, and Hybrid Arrangements

Public institutions, cooperatives, and hybrid arrangements illustrate the diversity of ways through which productive knowledge capital can be financed, held, governed, and shared. They warrant separate examination because legal public ownership, membership-based control, and the combination of multiple institutional arrangements specify different relations of responsibility and authority. The analytical object includes public universities, research libraries, publicly financed laboratories, cooperative publishing services, community-owned research infrastructure, and partnerships distributing particular rights across several organizations. Each may contain market transactions and non-market forms of contribution. Their institutional labels therefore provide an entry to comparison rather than a sufficient explanation of productive outcomes.

Public institutions can accumulate knowledge capital through long-term funding, training, collection development, experimental facilities, and legal mandates for public service. Their capacity to coordinate expensive shared infrastructure may enable research activities beyond the means of small groups. They can also provide continuity to archives and methods whose benefits are dispersed among participants or emerge through multiple types of use. Yet public financing does not by itself determine which publics gain effective access, how researchers influence strategic decisions, or how externally contracted components are governed. Facilities can be publicly funded while specialized interfaces, certification services, datasets, or dissemination channels remain privately controlled. Public accountability may support transparency and participatory revision; administrative procedures may alternatively produce rigid access hierarchies or overly narrow recognition of valuable knowledge work.

The UNESCO *Recommendation on Open Science*, adopted in 2021, gives an explicit international policy expression to collective benefit, equity, diversity, participation, and broad access throughout the scientific process [89]. It is a normative and standard-setting instrument, whose realization depends on implementation and local institutions. Its importance for the present analysis lies in the breadth of the productive conditions under consideration. Open publications alone are insufficient to describe equitable capacity to conduct inquiry when education, language, data, infrastructures, and opportunities for participation remain uneven. An institution can therefore be assessed through the practices that turn formal accessibility into effective generative opportunities.

Cooperative enterprises differ from public agencies in their membership relations and authority arrangements. The International Cooperative Alliance's adopted statement defines cooperatives through voluntary association, joint ownership, democratic member control, member economic participation, and collectively governed uses of surpluses [45]. These are constitutive principles and institutional commitments; the actual distribution of decision power and productive benefits in a particular cooperative requires observation. These principles offer a reference for examining cooperative knowledge production: members might pool funds for research infrastructure, allocate surpluses to education or maintenance, and maintain decision procedures concerning shared assets. A cooperative laboratory or publishing venture can nonetheless face uneven expertise, external capital requirements, membership boundaries, and

disagreements over whether organizational resources should prioritize current members or broader public beneficiaries. Its capacity to provide public knowledge depends on how the cooperative defines its obligations beyond its membership and negotiates their practical fulfilment.

Hybrid arrangements are especially common at generative interfaces. A publicly funded data collection may be preserved in a university archive, processed with cooperative software, analyzed by commercial researchers, and circulated through publishers using several licensing regimes. Another project may rely on public grants for development and charge institutional users for continuing support. Such combinations can help allocate specialized tasks and complementary resources. They can also obscure the location of authority if the actor charged with maintenance lacks rights to inspect or alter a critical technical component, or if public contributors cannot determine the use of outputs generated with their work. A hybrid organization should thus be studied as a network of relations and contracts, with attention to who bears maintenance obligations and who can change the terms upon which other participants depend.

Financing, ownership, control, and beneficiary designation are therefore distinct variables. A resource may be financed by public money, legally held by a nonprofit, administered by a professional board, and used principally by commercial clients. In another configuration, users may collectively own an entity but obtain essential technical services from a provider with considerable bargaining leverage. Analysis of these arrangements requires tracing decisions that alter the feasibility of knowledge production, rather than inferring such decisions from registration status or general mission. The institutional picture can also change as projects acquire equipment, invite more participants, or revise the meaning and boundaries of the resources they govern.

7.5 Governance and Capital Formation Across Institutional Configurations

The governing mechanisms of knowledge-capital formation involve the allocation and revision of practical authority over resources, productive activities, and the consequences of knowledge creation. The same organization may be open in relation to published outputs and restrictive in relation to financing, infrastructure modification, participation in evaluation, or the attribution of credit. Accordingly, the relevant analytical dimensions extend across the rights to access, use, contribute, modify, verify, maintain, exclude, transfer, and revise governing rules. These rights may be divided among persons and organizations, limited by legal constraints, and mediated by skills or material circumstances. The legal analysis of property-rights bundles and distinct incidents of entitlement supports careful separation of such positions [82, 43].

Capital formation can be affected by the relation among *initial contribution*, *control over resulting assets*, and *authority over subsequent production*. A contributor may supply research labour or interpretive expertise and receive authorship, a wage, membership rights, continuing access, some combination of these, or none of them. A funder may provide an instrument while reserving rights to decide priorities. A community may collectively establish a standard that later becomes embedded in privately controlled infrastructure. The resulting configuration can allocate credit, control, and practical benefit in different directions. Those differences need not imply injustice in every case, but they are indispensable for identifying whether capital expansion broadens collective productive capacity or deepens a particular dependency.

Power enters through both enforceable rights and control of effective alternatives. An institution can exercise influence through funding eligibility, technical compatibility, review criteria, employment conditions, hosting arrangements, or decisions over which contributions are made visible. Some authority is organized through public rules and subject to appeal; other authority operates through expertise, network position, or the practical expense of leaving an infrastructure. An openly licensed knowledge resource can be formally available while its most effective use depends on specialized hardware, undocumented routines, or a certification procedure held by another actor. These relations should be described as historically situated mechanisms, with attention to participant interpretations and contestation as well as contractual forms.

A multilevel account adds that a single governance decision can influence several kinds of productive activity. Control of a specialized publication output might affect a bounded set of uses, while control of a common classification or interoperability standard may condition many research practices. The relative depth of a controlled component offers an initial guide but does not establish its actual leverage. A high-level rule may have multiple alternatives, and an apparently peripheral interface may be indispensable for a widely adopted experimental system. Governance research should therefore reconstruct the actual dependencies, possibilities of substitution, and available pathways for institutional revision at the level of the specified historical configuration.

The operation of heterogeneous value circulation complicates both evaluation and governance. Commercial revenue, research recognition, access to trained personnel, public trust, available time for further inquiry, and preservation of shared infrastructure represent different benefits. Their distributions can be shaped by different institutions. A repository may be made financially sustainable through a licensing arrangement while contributors lose a practical ability to influence its design. A cooperative may improve member compensation but fail to address access barriers for nonmembers. A public authority may broaden access while allocating little support to the work of translation and curation. These outcomes call for a multidimensional record rather than a single net-value calculation. A normative conclusion requires explicit criteria and an account of whose judgments establish those criteria.

Governance of capital formation also concerns the degree of reversibility of an arrangement. Participants may gain procedural means to contest a standard, migrate data, fork software, authorize independent replication, or establish alternative sources of financing. Such capacities can modify the consequences of concentrated ownership. They may also be practically costly: the existence of a formal exit option does not assure that users can exercise it without abandoning a productive community or incurring major losses of accumulated expertise. Effective contestability depends on skills, complementary resources, institutional legitimacy, and the recognition of alternative outputs. Governance thus participates directly in the formation and transformation of the generative dependencies on which future production relies.

The comparison remains open to divergent normative traditions. Market coordination, cooperative democracy, public administration, and communal governance may emphasize different sources of legitimacy and different forms of accountability. A rigorous analysis can document their respective commitments and the results of their institutional practices while retaining the possibility that no single configuration is adequate across every productive scale and epistemic domain. The central research object is how governing relations allocate the capability to continue creating, maintaining, questioning, and transforming knowledge.

7.6 Comparative Conditions of Accumulation and Expansion

The comparative synthesis examines institutional arrangements as configurations of productive relations rather than as mutually exclusive types. Table 8 organizes typical decision loci, possible value-circulation routes, and questions that should remain open to evidence. The entries describe analytical possibilities rather than universal properties or estimates of prevalence. They are useful insofar as they direct attention to which actors accumulate capabilities, which actors command productive conditions, and how the benefits of the arrangement contribute to further knowledge production.

One comparison concerns *accumulation without exclusive ownership*. Distributed communities can collectively improve reusable knowledge and the capabilities needed to reproduce it, while several organizations draw upon the accumulated results. This arrangement may enlarge productive opportunities without establishing a singular owner of all downstream benefits. Its sustainability depends on ongoing resources, maintenance work, and mechanisms for revising shared commitments. A second comparison concerns *ownership without effective capacity*: legal title to a corpus or facility provides limited productive value where people lack the knowledge, authorization, or complementary resources required to use it. A third concerns *control without comprehensive ownership*: actors who govern certification, network access, or dominant standards may affect multiple producers without legally owning their outputs. These

Table 8: Institutional configurations and analytical questions for knowledge-capital accumulation. Entries indicate possible mechanisms, not necessary properties or empirical rankings.

Arrangement	Possible locus of control and value recirculation	Central dependency question
Capitalist enterprise	Owners, managers, and rights-holders; research investment from revenues and other funding	Dependency on proprietary inputs, access conditions, and interfaces
Commons-based production	Participants, stewards, and shared rules; reciprocal maintenance, training, and resource improvements	Governance of essential resources and unequal maintenance contributions
Communist conception	Collective decision structures; common provision and reproduction of productive means	Effective participation in priorities and methodological revision
Public institution	Public mandates, professional authorities, and public budgets; shared facilities and education	Uneven access and dependence on contracted components
Cooperative enterprise	Members and accountable delegates; reserves, member benefit, and cooperative learning	Boundaries of membership, expertise, and external finance
Hybrid arrangement	Interacting public, private, and collective centres; mixed contractual and noncontractual circulation	Divergence among financing, control, maintenance, and use

distinctions cross the institutional classifications in Table 8.

A further comparison concerns the conditions under which growth in productive capacity occurs alongside a narrowing of practical autonomy. A commercial enterprise may make an expensive technique widely available through a managed service while maintaining substantial control over access and future updates. A public institution may support the same technique as a shared facility with restricted capacity and administratively defined priorities. A cooperative may provide access through member commitments and pooled contributions; a commons may circulate open specifications while depending on external service providers. Each configuration can accumulate capital and expand feasible activities. Each can also generate bottlenecks that differ in their legal basis, costs of substitution, and possibilities for contestation. Their performance must be compared within a declared set of research tasks and relevant populations, without treating every benefit or constraint as convertible into a common metric.

Comparison across generative levels sharpens the inquiry. When capital accumulation concerns a domain-specific application, institutional effects may be localized, although a specialized bottleneck can still be decisive. When it concerns methods, data standards, educational systems, or epistemic validation infrastructures, its potential influence extends to other production processes that depend upon these conditions. The decisive questions are how extensive those dependencies actually are, which alternatives are available, and who can participate in changing the rules. Capital expansion at a relatively foundational level may become a resource for broad public generativity or for durable extraction, depending on its governance and the circulation of the value it enables. Neither result follows directly from the assigned depth of the resource or the proclaimed identity of the institution.

Historical and empirical research can operationalize these distinctions by recording resource origin, contribution pathways, access terms, governance procedures, changes in technical dependencies, maintenance funding, and the situated capacities of relevant actors. Institutional documents and contracts may establish formal control, while observation, interviews, technical audits, and records of participation may identify effective access and practical dependency. Competing descriptions should be compared explicitly, particularly where users, maintainers, managers, and funders disagree about the nature of a contribution or the meaning of public benefit. The descriptive analysis can then support a separately articulated normative inquiry into obligations, benefit sharing, collective autonomy, and justice.

The central finding of this theoretical comparison is a distinction among three questions: how productive knowledge capital is formed; how its reproduction and expansion are coordinated; and how rights, benefits, and authority over its continuing development are distributed. Capitalist, commons-based, com-

munist, public, cooperative, and hybrid configurations may each involve substantial accumulation and recursive expansion. Their differences become analytically consequential through mechanisms of governance, ownership, access, value circulation, and power operating across generative levels. The subsequent section therefore turns from institutional configurations to the specific rights and effective capacities through which knowledge outputs, productive infrastructures, and generative conditions are held, mobilized, and transformed.

8 Ownership, Access, and Control of Generative Conditions

This section examines the differentiated rights and practical capacities through which knowledge-producing actors hold, use, sustain, and modify the conditions of their work. Its objective is to specify the relations that intervene between the accumulation of knowledge resources and the capacity to mobilize those resources for further production. The analysis addresses rights over generated outputs, access to infrastructures, productive autonomy, control over generative rules, governance of reproduction, and cross-level configurations of ownership and effective power. It combines institutional analysis with a provisional relational vocabulary. Legal doctrines, sociological forms of authority, and generative dependencies are kept analytically distinct, since their interactions vary across jurisdictions, organizations, and disciplinary practices.

A knowledge-producing process can distribute several positions among different persons or organizations. A researcher may author a publication, an employer may hold specified economic rights, a public institution may operate the underlying laboratory, a consortium may govern data-access procedures, and a disciplinary community may determine what counts as sufficient validation. The participants can depend on educational systems, standards, archives, instruments, computational resources, and the accumulated skills of other workers. Consequently, an answer to the question of who owns a knowledge output provides only partial information about who can continue knowledge production under the prevailing arrangements. The analytical object is a configuration of entitlements, obligations, technical affordances, institutional authority, and actual capabilities.

Property-rights scholarship offers a starting point for disaggregating these relations. Hohfeld's analysis of legal relations distinguishes forms of right, duty, privilege, and power; Schlager and Ostrom distinguish bundles of access, withdrawal, management, exclusion, and alienation rights within resource governance [43, 82]. These concepts help identify which actions are authorized and who can revise the relevant rules. Their application to knowledge production requires care: an informational artefact, a laboratory instrument, a living skill, a professional norm, and a classificatory scheme are different kinds of object. Rights over one may affect the use of another without producing a single ownership relation embracing the whole generative system. The following subsections therefore trace the interface between formal authorization and effective productive capability.

8.1 Ownership of Knowledge Resources and Generated Outputs

The first analytical object is the allocation of rights over generated knowledge resources. Outputs include scholarly texts, designs, code, recorded observations, databases, protocols, models, teaching materials, and instruments that embody research knowledge. They also include less tangible results such as established claims, conceptual distinctions, and methodological competence. These objects possess heterogeneous legal and practical characteristics. Copyright generally concerns protected expression, while economic rights and authorial moral interests can be differentiated in many legal systems; patents, trade secrets, contracts, and data-protection rules address other interests under their respective conditions [92]. A scientific proposition may circulate as information through many publications without becoming an exclusively owned object simply because one publication expressing it is protected. The particular jurisdiction, legal category, contractual history, and applicable limitations are therefore indispensable to any claim about ownership.

For the present paper, a generated output is also a prospective input to other generative processes. A manuscript may become a teaching resource; code may become a library integrated into other systems; experimental observations may support validation outside the originating laboratory. The value of an output as knowledge capital is consequently dependent on the relations that make these reuses feasible. A legal entitlement to commercialize one artefact can coexist with broad scholarly access to its underlying ideas, while public availability of an article can coexist with limitations on acquiring the associated data or reproducing a computational workflow. A statement that knowledge has entered a public domain of discussion may describe an epistemic and communicative condition; it does not, by itself, specify the applicable legal public-domain status of the particular material.

A useful distinction separates authorship, title, licence, custody, and practical command. Authorship concerns attribution and creation under the relevant disciplinary and legal practices. Title or legally recognized rights may authorize particular exploitations. A licence can permit uses by others without transferring the underlying title. Custody identifies who stores or preserves a resource. Practical command concerns who can actually retrieve, understand, modify, and incorporate the resource in subsequent work. The same person or institution can occupy several of these positions, but they may be widely distributed. In long-running projects, stewardship and custody can shift through organizational dissolution, repository migration, or contract revision without an identical shift in authorship or in legally held rights.

The legal architecture of open licensing illustrates this differentiation. The Creative Commons Attribution 4.0 International licence grants broad permissions concerning reproduction, sharing, and adaptation of licensed material under specified conditions, while expressly reserving other domains such as patent and trademark rights from its licence grant [20]. This is one concrete example, with its own scope, of how extensive public permissions can be structured without an exhaustive transfer of every right. A licence's textual permissions also depend on adequate attribution practices, discoverability, accessible files, usable formats, and supporting expertise if they are to contribute to productive capability. Open licensing can improve the terms of circulation while leaving consequential infrastructure or verification bottlenecks elsewhere in the system.

The allocation of entitlements often reflects distributed creation. Scientific results may incorporate paid research labour, publicly supported education, institutional equipment, community-developed software, peer review, and earlier publicly available scholarship. Such contributions do not necessarily establish identical legal rights or equivalent obligations of remuneration. They do establish a reason to distinguish the ownership of a resulting object from the history of activities and infrastructures through which it was produced. An inquiry into appropriation should recover contractual rights alongside the contribution pathways, relevant expectations, and opportunities for future participation. Financial compensation, reputational recognition, access for further work, and authority over subsequent development may be allocated separately and may change through continuing institutional relations.

Generated outputs may also carry legitimate constraints arising from privacy, confidentiality, research ethics, cultural responsibilities, and the rights of affected populations. A general preference for the widest possible dissemination cannot resolve these questions without examining who bears risks and who is entitled to authorize particular uses. The CARE Principles for Indigenous Data Governance, for example, articulate collective benefit, authority to control, responsibility, and ethics as considerations in data governance, including the relation between secondary use and Indigenous peoples' interests [14]. This literature supplies a substantive reason to examine the authority of communities represented in datasets, alongside the claims of data collectors, curators, employers, and downstream users. The analysis therefore treats public knowledge production as a system of situated permissions and responsibilities, not as a presumption that all collected materials should be circulated without conditions.

8.2 Access to Productive Infrastructures and Research Resources

The second analytical object is effective access to the facilities, services, and resources through which knowledge outputs can be generated. Research infrastructures include physical laboratories, instruments, computing and storage services, communication networks, repositories, archives, software en-

vironments, and the organizational labour that maintains them. Their productive contribution may be distributed across multiple generative levels. A laboratory instrument can support the acquisition of domain-specific observations; a shared data format can enable research in many laboratories; a scholarly identification system can underpin discovery, attribution, and retrieval across fields. The infrastructural character of a resource is relational, emerging partly through patterns of routine use and dependence [85]frischmann2012infrastructure.

The term *access* encompasses several distinguishable conditions. Legal access concerns permissions to enter, retrieve, or use a resource. Financial access concerns prices, membership fees, payment arrangements, and the ability to bear them. Technical access concerns available interfaces, connectivity, formats, devices, and computational resources. Epistemic access concerns the background knowledge needed to understand and use the resource correctly. Institutional access concerns recognition, authorization, eligibility, and the ability to participate within established workflows. Temporal and operational access concerns scheduling, service reliability, preservation, and continuity of availability. These conditions may interact: access to a dataset of considerable size is of limited productive use when a researcher lacks compatible software, adequate storage, or lawful authority to process its contents.

A resource can therefore be described as publicly accessible for one purpose while remaining inaccessible for another. A publicly financed archive may permit reading but restrict high-volume computational reuse. A cloud-based research platform may be affordable for small-scale exploration while making export of accumulated annotations expensive or technically difficult. A laboratory may supply shared equipment but prioritize access according to professional qualifications or institutional affiliation. Such rules can be justified through resource scarcity, safety, privacy, or quality assurance, and they can also generate exclusion or dependency. The resulting effects depend on the justification, implementation, alternatives, and available mechanisms for review. A critical analysis should identify these conditions before evaluating the arrangement's distributive or productive consequences.

The FAIR Guiding Principles emphasize findability, accessibility, interoperability, and reusability as interrelated features of research-data stewardship, including machine-actionable conditions for reuse [91]. The principles provide a practical point of reference for investigating whether accumulated information can actually circulate into new productive work. Their accessibility principle expressly accommodates authentication and authorization where required; a FAIR-compliant resource therefore need not be publicly downloadable or licensed for unrestricted reuse. FAIR does not, by itself, determine legal openness, collective consent, institutional accountability, or equitable distribution of benefit. The corresponding emphasis of CARE on collective benefit and authority over Indigenous data illustrates that interoperability and the right to determine appropriate uses can be complementary yet potentially demanding governance objectives [14]. Their relationship should be specified for the data, community, and research activity under study.

Control of infrastructure becomes especially significant where activities require complementary inputs. Permission to reuse a statistical method may offer little independence if the only operational implementation depends on an inaccessible service. An open research dataset may support independent inquiry only if researchers can retain a stable copy, inspect metadata, reproduce transformations, and obtain adequate computation. Conversely, an institution may hold formal title to particular equipment while granting durable, portable, and accountable use rights to a broader community. The consequence of ownership is mediated by the design of the associated access regime and the presence of functional alternatives.

At the level of capital accumulation, infrastructural maintenance deserves separate attention from initial construction. Data curation, software updates, equipment calibration, security work, and user support can consume substantial effort without generating a new headline publication. The continuity of productive capacity depends on these activities, often performed by workers whose contributions are less visible within conventional systems of scholarly credit. An accumulation analysis that records acquisitions and outputs alone may consequently overstate the durability of the resulting capital. The appropriate observation includes maintenance labour, technical debt, recurrent financing, governance responsibility, and a pathway for replacing or reconfiguring failing components. Public availability becomes an enduring

productive condition through work and institutions that keep access usable.

8.3 Productive Capabilities, Autonomy, and Collective Agency

The third analytical object is the capability of persons and communities to undertake, evaluate, and redirect knowledge-producing activities. Productive capability includes learned judgment, tacit knowledge, disciplinary experience, the ability to coordinate work, technical fluency, and the practical confidence to challenge a method or revise an interpretation. Such capacities are formed through education, participation, mentoring, experimentation, and the accumulation of experience. They operate through relations among people and artefacts, and their exercise can require access to complementary infrastructures. Treating capability as knowledge capital in an analytical sense does not entail treating persons or their agency as transferable objects of property.

Four dimensions help specify productive autonomy. *Initiative* is the capability to formulate questions, projects, and directions of inquiry. *Execution* is the practical capacity to conduct work with available resources. *Evaluation* is the capability to inspect, contest, validate, and interpret results. *Transformation* is the capacity to revise the methods, infrastructures, and institutional conditions of subsequent work. These dimensions may be distributed differently. A highly trained researcher can possess substantial evaluative competence while having little influence over a platform's data-access policy. A small organization can initiate novel research but lack the sustained computational capacity required for execution. A community may maintain a repository without having representation in the institution that sets its long-term technical standards.

The ownership vocabulary is particularly prone to confusion in this domain. Individuals can hold employment or service contracts; organizations can own facilities, software, and specified intellectual-property rights. The institution's authority to direct a contractual task is analytically distinguishable from the researcher's embodied knowledge, practical judgment, or broader capacity for inquiry. Discussion of the *ownership of productive capacities* should therefore be translated into more specific questions about who may employ, remunerate, develop, mobilize, constrain, and govern their exercise, together with the rights and responsibilities of the people whose capacities are involved. These distinctions become more important where institutions claim broad rights in research outputs while relying on individuals' continual learning and discretionary cooperation.

Capability also has a collective dimension. Distributed teams may create productive routines that no single participant could reproduce independently, including processes for peer review, testing, fieldwork coordination, and the maintenance of research software. Collective capability can be durable even as individuals change roles, provided that experience is documented, newcomers can acquire necessary skills, and institutional relations support continued cooperation. It may also be fragile when essential expertise is concentrated in a small number of maintainers, when contributors lack resources to remain involved, or when organizational rules impede succession. The accumulation of collective knowledge capital thus raises questions of educational access, apprenticeship, care, documentation, and collective authority over the conditions of reproduction [8, 67].

Practical autonomy cannot be inferred directly from nominal alternatives. A software project may have a legal right to fork a shared codebase while lacking maintainers, funds, data-export capacity, or professional recognition needed to sustain an independent version. A research group may be permitted to change service providers while being bound to specialized formats, institutional review requirements, or deeply integrated workflows. Such dependencies can sometimes reduce coordination costs and improve reliability; they can also restrict the possibility of revising research priorities or contesting terms. The extent of constraint is a matter for empirical analysis. Relevant evidence includes the resources required to switch providers, the availability of interoperable interfaces, community skills, and the losses that transition would impose upon legitimate research goals.

The relation between capability and power consequently extends beyond the distribution of finished outputs. Access to education, computational tools, interdisciplinary collaboration, and institutional protection may determine which actors can recognize an opportunity and transform it into a viable research

programme. Those capacities can accumulate unevenly even within a formally open system. This observation matters for public knowledge production because the right to retrieve existing results can coexist with substantial differences in the ability to generate, validate, and disseminate new ones. A public-capability perspective asks whether institutional arrangements help participants build transferable competence and retain meaningful opportunities to take part in the evolving direction of inquiry.

8.4 Control of Generative Rules, Standards, and Methodologies

The fourth analytical object is authority over the generative rules through which knowledge-producing activities are organized. Such rules include technical protocols, data classifications, software interfaces, methodological conventions, measurement standards, publication formats, validation procedures, and criteria used to recognize research contributions. Some are encoded in software or formal documents; others are maintained through professional education, disciplinary judgment, and habitual practice. Their authority can arise from law, contract, organizational governance, expertise, consensus, infrastructural adoption, or combinations of these sources. The control of a rule need not rest on legal ownership of the knowledge outputs shaped by its use.

In the generative-level framework, the position of a rule depends on its relations to other activities. A narrowly specified protocol may govern a particular instrument. A shared statistical or metadata standard can support work across many fields. A widely adopted assessment procedure may affect funding, recruitment, publication, and the recognition of research. These are potentially far-reaching relations, but their scope and strength cannot be inferred solely from calling the rule *fundamental* or *meta-level*. Some research traditions sustain workable alternatives, while a seemingly specialized interface may become a bottleneck for numerous otherwise unrelated activities. Dependence is therefore assessed through actual patterns of use, substitutability, migration costs, and the capacity to develop alternative pathways.

One form of rule control concerns the power to define categories through which activities are recorded and evaluated. Classification systems can render some phenomena legible and others difficult to register, with consequences for what gets counted, stored, retrieved, and acted upon. Bowker and Star's analysis of classification and its consequences establishes a relevant science-and-technology-studies lineage for investigating these effects [12]. In knowledge production, categories may affect both research subjects and researchers: the construction of datasets, the coding of results, the eligibility of interdisciplinary work, or the identification of recognized contributions. Such effects should be examined as historically situated mechanisms of representation and authority, with attention to how participants themselves interpret and contest the classifications.

A second form concerns methodological authority. A disciplinary community may require certain procedures for reproducibility or evidential adequacy; standards can support coordination, safety, quality, and comparability. Their productive benefits may be substantial. At the same time, an authoritative procedure can privilege research activities already equipped with compatible instruments, funding, and skills. The relevant political-economic question is who may participate in revising the procedure, whose costs of compliance are recognized, and how exceptions and emerging alternatives are evaluated. This framework accommodates justified methodological standards while permitting scrutiny of unintended barriers, conflicts of interest, or self-reinforcing institutional advantages.

A third form concerns interface governance. Whoever controls a widely used application programming interface, repository schema, identifier system, or model access policy may influence diverse downstream projects without owning their underlying ideas or generated outputs. The right to use an interface today differs from the ability to maintain compatibility, receive notice of alterations, export dependent resources, or participate in setting the next version. In a cumulative knowledge system, such decisions may affect whether existing investments in code, training, annotations, and collaboration remain productive. Where alternatives are expensive or technically unavailable, even an apparently modest change in a standard can redistribute the costs and possibilities of subsequent work.

The consequences of rule control can also circulate recursively. Revenue, status, or institutional authority gained from controlling one productive interface may finance further research and shape the

criteria for acceptance of subsequent interfaces. A collectively maintained standard can likewise support a positive public feedback process when participants acquire shared skills, improve interoperability, and retain opportunities to propose changes. Both possibilities depend on the actual governance structure and on whether rule modification is subject to transparent procedures and meaningful contestation. The distinctive problem posed by deeper generative levels is thus a possible multiplication of consequences through dependency relations, rather than an automatic judgment that all control at such levels is illegitimate.

8.5 Governance of Knowledge Production and Reproduction

The fifth analytical object is governance: the processes through which actors establish, implement, contest, and revise the rules determining knowledge production and its reproduction. Governance concerns decisions about research priorities, resource allocation, access, authorship conventions, curation, quality assurance, safety, preservation, and the management of conflict. Formal governing bodies provide one part of this structure. Informal professional networks, funder requirements, technological defaults, editorial conventions, and maintenance practices may also shape outcomes. Institutional analysis therefore requires attention to multiple sites of decision rather than a presumption that one owner, manager, or public authority governs every relevant element.

The bundle-of-rights perspective offers a practical method for specifying participation. An actor may have permission to view or withdraw a resource while lacking authority to change its use rules. Another may govern admission but have limited control over the actual work of contributors. A third may possess authority to transfer a legally held asset but lack the expertise needed to maintain it. Schlager and Ostrom's distinctions among access, withdrawal, management, exclusion, and alienation provide an instructive vocabulary, although their categories arose in the analysis of natural-resource regimes and require adaptation for nonrival informational resources and multi-layer digital infrastructures [82]. The further distinction between formal rules and their practical exercise can be informed by Hohfeld's account of legal relations [43].

For comparison across generative levels, governance should include the right to participate in constituting future rights. A researcher who can currently access a platform may have limited security if the access policy can be changed unilaterally. A community that can review, propose, and approve revisions has a different relation to the conditions of its work, even where both arrangements provide identical access at a particular observation point. Public accountability, contractual notice, membership votes, independent review, and governance portability can furnish different avenues for influencing such decisions. Their effectiveness depends on actual participation, information, resources, and the treatment of dissent. The possibility to submit a comment is analytically distinct from meaningful authority over the eventual decision.

Table 9 sets out a provisional matrix for observing these distinctions. The columns separate formally recognized rights from effective productive use and from authority over subsequent transformation. The rows cover heterogeneous resources and practices, so the table should be read as a diagnostic map of questions rather than a legal taxonomy applying uniformly across jurisdictions. It identifies where empirical work must determine whether participants can exercise the capacities nominally assigned to them.

The reproduction of knowledge-producing capacity requires governance over maintenance and renewal as well as the allocation of current use. Funding may pay for the construction of a facility without securing its staffing, calibration, accessibility, or long-term preservation. Licences may permit copying code while the social relations supporting review and integration remain precarious. Scholarly norms may reward original findings while undervaluing curation, replication, translation, and teaching. These arrangements affect the direction of capital expansion because some productive conditions require recurrent care and institutional support to remain usable. Accounting for such work makes visible forms of contribution that are otherwise treated as background resources available without sustained investment.

Governance also mediates conflicts among legitimate interests. Disclosure can support replicability while compromising privacy or the rights of represented communities. A common technical standard can

Table 9: Analytical dimensions of rights, access, and transformative authority in knowledge production. Entries indicate questions for situated inquiry, not presumed entitlements.

Object or relation	Formal authorization	Effective productive capacity	Governance and transformation
Generated outputs	Authorship, licence, exploitation claims	Retrieval, interpretation, replication, adaptation	Revision, preservation, downstream permissions
Research infrastructure	Title, service access, admission	Usable tools, skills, reliability, resources	Maintenance priorities, interoperability, exit
Data and archives	Custody, reuse terms, privacy duties	Discoverability, formats, processing capability	Consent, stewardship, benefit sharing
Methods and standards	Specification rights, professional requirements	Implementation, validation, alternative methods	Standard-setting, exceptions, revision
Collective capabilities	Employment and participation arrangements	Learning, coordination, independent judgment	Training, representation, succession
Value and returns	Contractual claims, institutional mandates	Material support, recognition, continued participation	Allocation, reinvestment, accountability

improve coordination while raising participation costs for smaller laboratories. A participatory procedure can broaden voice while slowing decisions that require specialized technical judgment. The existence of these tensions suggests the need for explicit decision criteria, differentiated responsibilities, and routes for correction. Polycentric governance offers one conceptual approach to distributed decision-making where different centres retain authority over partially overlapping problems [74]; its suitability in a concrete knowledge system depends on coordination mechanisms and the ability to resolve conflicts across levels.

At this stage, the paper proposes an institutional distinction between the *capacity to use existing generative conditions* and the *capacity to participate in their continued constitution*. The first can be supported by licensing, public provision, educational access, or contractual arrangements. The second additionally concerns authority over maintenance, modification, priorities, institutional membership, and allocation of returns. The distinction applies within commercial, public, cooperative, and commons-based settings. Its normative evaluation remains context-sensitive: meaningful participation can take different forms depending on safety, expertise, rights of affected communities, and the scale of coordination. It nevertheless provides an observable dimension that is easily obscured by binary classifications of open and closed knowledge resources.

8.6 Cross-Level Configurations of Ownership and Control

The sixth analytical object is the configuration of entitlements and effective power across interdependent generative levels. A single research activity may rely on publicly available conceptual knowledge, proprietary instruments, collectively maintained code, institutionally controlled datasets, and disciplinary validation standards. The relevant positions of ownership, access, and governance are therefore distributed across a network of complementary conditions. A legal owner at one level may depend on institutions at another, and a party with limited property rights may nevertheless hold considerable influence through maintenance expertise, standard-setting, or the recognition of research results. Cross-level analysis traces these relations without treating higher assigned generative depth as a sufficient measure of authority.

Consider a hypothetical computational research infrastructure with an openly published method, a proprietary hosted implementation, a public training programme, and a community archive of reproducibility tests. Several organizations can use the published method while only one operates the hosted service. If the service offers unique computation or privileged access to an essential dataset, the provider may shape the practical choices of downstream research teams despite the open status of the formal method. If independent implementations become feasible and the archive supports verification and migration, the dependence may weaken without any change in ownership of the hosted software. The

configuration demonstrates that accumulated capital, legal rights, and effective generative leverage can evolve along different trajectories.

A contrasting hypothetical arrangement places an important methodological standard under a public or membership-based body, while the instruments required to implement it are commercially supplied. Collective governance of the standard may distribute rule-making authority, but constrained procurement, specialized expertise, or incompatible technical systems can create a separate bottleneck. A change in procurement rules, documentation, training, or interoperability might expand actual capability even without changing who governs the standard. This example prevents the analysis from identifying shared rule-making with complete independence. It also illustrates why public production requires scrutiny of the material and organizational conditions through which formal decisions become operative.

A third arrangement involves a relatively specialized application that becomes a pivotal interface for many other activities. Its position in an initial generative-level diagram may appear close to an output or leaf. Later research and institutional coordination can make numerous activities dependent on it as a shared service or de facto standard. This possibility cautions against ranking extractive significance solely by the apparent depth of a concept. The effective scope of control depends on historical uptake, alternative pathways, switching costs, and whether affected actors possess the capability and authority to replace or modify the interface. Generative levels may therefore be redrawn as the relations of dependency and institutional practice change.

Rights and capabilities are best documented as a relation among actors, resources, permitted actions, institutional procedures, and the activities those resources enable. Such a representation can record who holds a right, who must perform or refrain from an action, who has the technical capacity to act, whose work creates value, and which bodies can revise the arrangement. Its domain should be defined for a particular empirical inquiry rather than inferred from a universal theory of property. It may be useful to separate observed rights, claimed authority, and practical capability, especially where workers, users, institutions, and affected communities offer competing accounts of the system. Documentary evidence, interviews, observation, legal analysis, and technical audits may each disclose different aspects of the configuration.

Two pathways of accumulation follow from this relational perspective. In one, value generated through distributed knowledge production is recirculated into infrastructures, training, and collectively governed resources that expand the opportunities for further participation. In another, an actor may convert control of a critical condition into revenues, exclusive data access, or institutional influence that reinforces its subsequent control. These pathways can coexist, and their effects can be moderated by contracts, competition, professional norms, public regulation, and collective organization. The designation of a relation as *extractive* consequently requires evidence of persistent appropriation and constraints upon contributors' capacity to reproduce or transform the conditions of their participation, rather than a bare observation of concentrated ownership or higher returns.

The ownership of an output, the usability of an infrastructure, the authority to revise a generative rule, and the continued capability of participating producers thus constitute separable features of knowledge capital. Their interaction explains why openness at one level can coexist with concentrated command at another and why formal collective ownership can coexist with unequal productive opportunities. It also helps specify the reciprocal possibility: institutional structures can distribute genuine decision authority and sustain productive capacities despite uneven financial resources or specialized expertise. These distinctions establish the conditions for the subsequent analysis of heterogeneous value creation. The next section examines how different forms of value arise through labour, cooperation, knowledge conversion, and institutional recognition, before the discussion turns to their circulation and the role of power in shaping both processes.

9 Heterogeneous Value Creation in Knowledge Production

This section develops an analytical account of the kinds of value produced through public knowledge activities and the relations through which those values become recognizable. Its objective is to identify

what is created through knowledge work before examining how the results are circulated, controlled, or appropriated. The discussion distinguishes economic, epistemic, social, and institutional dimensions of value; examines labour and distributed contribution; compares value creation across generative levels; investigates recognition and evaluation; considers transformations between value forms; and identifies the generative capacities that become possible through prior creation. The method is conceptual and comparative. The proposed distinctions specify questions for situated empirical investigation and do not establish a complete ontology or a universally commensurable inventory of value.

Knowledge production can produce a validated result, a more reliable instrument, a useful dataset, an intelligible interpretation, a trained practitioner, an organizational capability, or a stronger relationship of cooperation. Several consequences may coexist within one activity. A publicly maintained archive, for example, can support a scholarly discovery, preserve otherwise vulnerable cultural materials, enable educational access, and improve the capacity of dispersed groups to inspect earlier claims. Some resulting benefits can be priced under particular institutional conditions; other consequences concern the credibility of inquiry, the freedom to participate, the preservation of interpretive alternatives, or the continued availability of productive conditions. Their coexistence calls for an explicitly plural vocabulary.

The distinction matters for the political economy of accumulation because the kinds of value that become publicly visible need not match the kinds of contribution that make production possible. An organization may generate revenue by selling a service built on publicly maintained methods; the revenue is observable under an accounting convention, while the epistemic and reproductive contributions of teaching, review, maintenance, and critical debate are harder to isolate. Equally, a large quantity of recognized scholarly output may coexist with weak infrastructures for verification, limited pathways for new participants, or unresolved harm to represented communities. The analysis therefore separates value creation, the institutional recognition of value, the attribution of value to contributors, and the assignment of claims over subsequent returns. These distinctions provide a basis for investigating power and circulation in later sections.

9.1 Economic, Epistemic, Social, and Institutional Values

The first analytical object is the heterogeneity of what participants value in a knowledge-producing arrangement. Economic value may appear in the capacity of knowledge to support production, reduce expenditure, enable exchange, generate income, or maintain productive assets. The relevant account depends on the economic theory and institutional setting. A market price, an estimate of social benefit, an accounting asset, and the Marxian category of value occupy different conceptual positions. They require separate operational definitions if used in an empirical comparison. The term *economic value* in the present discussion provisionally identifies an area of consequences and assessments, without resolving competing theories of value or treating observed prices as comprehensive expressions of social benefit.

Epistemic value concerns the contribution of an activity to the investigation, interpretation, assessment, and warranted use of claims. Illustrative dimensions include explanatory adequacy, reliability, conceptual discrimination, evidential accountability, reproducibility where appropriate, and the capacity to challenge accepted descriptions. These criteria are context-dependent. Historiography, formal proof, ethnographic interpretation, laboratory experiment, and public documentation rely on partly different standards of appraisal. The epistemic merit of a method must be assessed in relation to its objects and claims. Longino's account of science as socially constituted knowledge is pertinent because it locates values within evidential practices and the social conditions of criticism, rather than presuming that inquiry can be fully insulated from background commitments [57]. The present paper draws on that insight while keeping distinct the adequacy of a claim and the institutional authority assigned to its author.

Social value concerns changes in relations among participants and affected communities. Shared inquiry may extend opportunities to communicate, create trust under appropriate conditions, sustain interpretive communities, transmit skills, or improve collective ability to coordinate action. An educational project can contribute to individual competence while also creating a durable network for reciprocal assistance. At the same time, social relationships can impose expectations, exclusions, and obligations.

The emergence of more intense relations should therefore not be treated as an automatic social improvement. Assessments need to specify whose relationships are strengthened, what autonomy participants retain, whether dissent remains practicable, and how harms and benefits are distributed.

Institutional value concerns the contribution of an arrangement to the coordination, maintenance, and revision of collective activity. Governance procedures, archives, shared classifications, accreditation practices, reproducibility conventions, and mechanisms for resolving disputes can make otherwise dispersed productive actions possible. A standard may produce a common interface that lowers coordination costs, while an archival institution may provide continuity to evidence and interpretations across a change in personnel. Institutional value can also be contested. A shared rule that improves comparability for some participants may privilege their representational categories or increase the burden placed on others. The value of an institution consequently involves its demonstrated functions together with questions of accountability, participation, and its capacity for correction.

Plurality entails differences in kind, among evaluators, and across practical contexts. Anderson's account of plural modes of valuation provides a useful warning against applying a single market measure indiscriminately to goods constituted through different social practices [2]. For the present inquiry, plurality also means that values can coexist without admitting an agreed exchange ratio. Consider a research collaboration that improves a public method while demanding substantial unpaid maintenance and creating unequal opportunities for authorship. Its epistemic contribution, economic sustainability, social relations, and institutional distribution of responsibility cannot be inferred from one number. The analysis can compare specific dimensions, trace trade-offs, and identify the institutions that establish priorities without pretending to have discovered a universal value unit.

A useful analytical distinction separates *constituted value* from *valuations*. Constituted value refers here to an argued or demonstrated contribution under a specified evaluative perspective, such as an improved error bound or a demonstrably expanded opportunity to access an archive. Valuations are situated judgments, measurements, rankings, narratives, and institutional decisions concerning that contribution. The distinction does not imply that values exist in a completely observer-independent form waiting for administrative discovery. Many relevant goods arise through social practices, and the practices of assessment can alter what is produced. It nevertheless helps researchers investigate the correspondence between a valuation procedure, the claim made on its basis, and the underlying activities and consequences offered as evidence.

9.2 Labor, Contribution, and Relational Value Creation

The second analytical object is the distribution of contributions within a knowledge-producing relation. Knowledge activities commonly depend on combinations of intellectual labour, practical skill, maintenance, supervision, interpretation, caregiving, education, technical support, financing, and institutional administration. A publication may depend on conceptual work and recorded observations, as well as data cleaning, instrument calibration, software adaptation, review, translation, and the preservation of earlier resources. The historical accumulation of such contributions creates productive conditions for persons who did not participate directly in their original formation. A relational account consequently follows the dependency structure of a contribution rather than identifying its significance exclusively with a formally designated author, employer, or current resource owner.

Contributions are heterogeneous in their mode, timing, and scale. Some are embodied in identifiable artefacts; others become part of participants' capacities or the reliable functioning of a common process. A librarian's description of a collection, a maintainer's correction of a software vulnerability, and a scholar's conceptual distinction may each enable activities that are difficult to specify in advance. A research infrastructure may depend on continuing work whose effects are seen principally when that work is interrupted. The capacity to sustain an activity is a substantive contribution even where it produces few newly countable outputs. Such work may exhibit nonlinear complementarity: a particular research task becomes possible only when several independently accumulated capabilities and resources are jointly usable. In that case, observed outcomes provide an incomplete basis for allocating the whole

contribution to a single input.

The concept of *relational contribution* is used here to describe an actor's participation in creating, sustaining, or modifying a configuration that enables valued activities. It can include work on a resource, work on the relation connecting resources, and work on the institutional conditions under which their combination becomes feasible. The concept permits recognition of distributed labour while leaving particular legal entitlements and distributive obligations open to separate analysis. It also avoids turning every causal contribution into a proprietary claim over subsequent activity. For example, the historical contribution of education to an individual's skill does not establish ownership of that person's labour by the educational institution. A viable account must preserve rights of persons and the distinction between enabling contributions and command over productive agency.

Attribution becomes difficult when the same resource participates in numerous chains of use. A shared dataset may be curated by one group, methodologically reinterpreted by another, and combined with external knowledge to produce a novel result. The benefit of a general-purpose tool can depend on the capabilities of its users, and the value of those capabilities can depend on education and previous collective practices. The analytical question is consequently wider than identifying who made a particular output. It includes how contributors had access to productive conditions, how their labour interacted, what benefits and burdens arose, and which arrangements sustained the resulting capabilities. A decomposition into individual shares may be possible for a narrowly specified accounting purpose yet remain inadequate as a complete theory of historical contribution.

The relation between contribution and reward likewise requires explicit mediation. A contributor may receive wages, an authorship credit, public acknowledgment, enhanced skills, institutional influence, or access to subsequent results. These returns have different terms and depend on governance and recognition procedures. Merton's treatment of the Matthew effect is relevant to the possibility that scientific recognition accumulates unevenly in relation to contributions [64, 65]. Its usefulness here lies in identifying a mechanism for investigating cumulative advantage, without assuming that every observed difference in recognition is attributable to bias or that contribution can be independently measured with complete precision.

Within a commons-based activity, contributors may collectively produce and maintain conditions from which they and additional participants benefit. Within a commercially organized activity, paid labour and distributed public inputs may combine to produce outputs over which a firm holds enforceable claims. Public research institutes and hybrid collaborations can combine several such relations. Each setting may generate epistemic, economic, social, and institutional benefits. The comparative task is to specify who contributes what, which conditions are jointly produced, how particular benefits are attributed, and whether the arrangement enables contributors to continue or alter productive activities. Institutional labels provide context; evidence of actual labour, dependence, rights, and governance establishes the relation under study.

9.3 Value Creation Across Generative Levels

The third analytical object is the position of value-creating activities within the relative generative levels introduced in Section 4. A generative level is a feature of an explicitly reconstructed dependency structure, not a universal rank attached to an academic discipline or a category of labour. Accordingly, a method may appear foundational to one cluster of research activities and highly specialized within another. The level at which value is created should be characterized with reference to the activities enabled, the available alternative pathways, the costs of adaptation, and the rules through which the contribution is recognized. The analysis of cross-level value therefore concerns how a contribution changes productive possibilities and institutional relations in a situated network.

At the level of meta-knowledge, an activity can create value by clarifying the conditions under which representations, evidence, arguments, or interpretations become intelligible and assessable. For example, a new account of uncertainty may change how heterogeneous claims are compared within a defined research community. A shared conceptual vocabulary may enable scholars previously separated by in-

compatible classifications to communicate. Such contributions can affect many later activities, but their significance is conditioned by uptake, compatibility, resistance, and the legitimacy of the underlying assumptions. Their value cannot be read directly from the assigned label *meta-knowledge*. A broad concept that lacks demonstrable applications or critical scrutiny may have less effective generative significance than a relatively local method that directly enables valuable inquiry.

At theoretical and methodological levels, value can arise through explanatory structures, proof techniques, experimental strategies, critical methods, measurement protocols, or computational procedures. These structures may improve the capacity to formulate questions, distinguish alternatives, coordinate replication, or expose previous assumptions to criticism. Their productive contribution is partly counterfactual: which inquiries are newly feasible or more reliable with the method than under specified alternatives? The counterfactual depends on the skills and resources of intended users and on available implementation routes. A method that is freely described but impossible to execute under ordinary research conditions may make a substantial conceptual contribution while generating a narrower change in immediately usable productive capability.

At infrastructural levels, value can emerge through common services that connect knowledge-producing activities. Repositories, persistent identifiers, versioning systems, reference collections, instrument standards, and maintained computational environments can reduce coordination costs and support the reproduction of claims. Their benefit often depends on scale and interoperability. Infrastructural accumulation may also create a concentration of operational dependence where continued activity requires a particular service, standard, or authority. Frischmann's analysis of infrastructure as a shared productive resource informs the distinction between broad downstream benefit and the private incentives of particular operators [34]. The relevant inquiry concerns the specific network of uses, constraints, and public or private investments rather than an intrinsic declaration that infrastructure produces greater value than an application.

At application and output levels, knowledge creation may address concrete problems, generate usable artefacts, or reveal unexpected limitations of established theories. An improved diagnostic protocol, a reproducible local history collection, or an accessible educational tool can have direct importance for affected participants. The impact of an application can be extensive when it becomes an indispensable interface for subsequent practices. Moreover, observations from applications can challenge methodological assumptions, reveal neglected categories, or motivate a change in common standards. Generative dependency is thus often reciprocal in the relevant historical configuration. A representation resembling a tree can be a useful local heuristic, while a network with feedback and partial ordering may better describe the actual interdependence.

Value can be created *through* relations across levels as well as *at* particular levels. A shared measurement practice may become productive when a theoretical framework clarifies its interpretation and an application supplies observations that expose its limitations. The resulting change could involve a new method, greater practical reliability, revised interpretive standards, and an expanded capacity for further inquiry. Attribution to one level would miss the enabling relations among them. Conversely, a transformation at a deeply connected level may impose adjustment costs across many dependent activities. The same cross-level reach that enlarges generative potential can multiply the consequences of exclusion, instability, or inadequate governance.

Table 10 presents a diagnostic comparison. It distinguishes possible value-creating mechanisms from the routes through which their contributions become visible and the limits of direct measurement. The table does not rank levels by moral importance or presume that their values can be exchanged through a single coefficient. Its analytical purpose is to make explicit the mediating relations that would have to be observed before a claim about cross-level capital formation, extraction, or collective benefit can be supported.

A comparison of value creation across levels also requires attention to asymmetries in the location of costs. A widely adopted standard may benefit downstream producers while concentrating maintenance burdens on a small group. A proprietary service may internalize revenue from applications that depend on a publicly maintained theoretical framework. A research community may reward new findings while

Table 10: Indicative value-creating contributions across relative generative levels. The examples identify possible mechanisms and evidential questions, not a universal hierarchy of merit.

Relative level	Illustrative productive contribution	Possible means of recognition	Relevant uncertainty
Meta-knowledge	Revises concepts, evidential relations, or interpretive rules	Critical uptake, conceptual clarity, cross-domain interpretation	Plural standards and distant dependence
Methods and theories	Enlarges inquiry, validation, proof, or explanation	Replication, demonstrated use, disciplinary criticism	Context-specific applicability and alternative methods
Shared infrastructures	Sustains storage, interoperability, tools, and coordination	Reliability, accessibility, user capability, maintenance records	Unseen maintenance and concentrated bottlenecks
Applications and outputs	Addresses situated problems and generates artefacts or findings	Practical performance, interpretation, community appraisal	Uneven distribution and reciprocal effects on other levels
Cross-level relations	Enables conversion, combination, and revision among levels	Traceable dependencies and improved feasible activities	Joint causation, contingent uptake, delayed effects

drawing repeatedly on poorly remunerated educational and curatorial work. These possibilities motivate tracing both valued outcomes and the conditions required to sustain them. The existence of an interdependence does not by itself establish extraction; the relevant distribution of authority, contribution, returns, and continued capability must be investigated. The cross-level analysis identifies where such evidence is required.

9.4 Value Recognition, Evaluation, and Attribution

The fourth analytical object is the social and institutional mediation through which value is recognized, evaluated, and assigned to particular contributors or organizations. Scholarly judgments are made through peer assessment, publication practices, funding deliberations, professional norms, teaching, public reception, and the continuing practical use of knowledge. Evaluation provides information needed for coordination and accountability, yet it also shapes the distribution of research opportunities. Recognition can attract collaborators, employment, institutional support, or access to instruments; these resources can then influence later productive capability. Value recognition is therefore connected to the recursive processes of accumulation analysed in Section 6.

Criteria of epistemic quality may differ across forms of inquiry. Originality, explanatory adequacy, historical fidelity, reproducibility, conceptual coherence, interpretive insight, and relevance to affected communities can have different roles depending on the object of study. Lamont's empirical investigation of peer assessment in grant and fellowship settings documents disciplinary differences in the interpretation and negotiation of scholarly quality [55]. Her work supports treating evaluation as an institutional practice requiring situated study, rather than assuming that a general label such as *excellence* denotes a fully specified, identical standard across fields. The same observation cautions against equating the absence of easy numerical indicators with the absence of scholarly contribution.

An evaluation system can produce knowledge about contributions while also transforming the incentives under which contributions are made. Espeland and Sauder's study of rankings in legal education demonstrates mechanisms of reactivity through which public measures affect organizations' expectations and behaviour [27]. The present framework treats this as a mechanism that may also warrant investigation in knowledge-production institutions, without transferring specific empirical results to unrelated settings. A citation count, impact score, funding amount, or usage metric can serve a legitimate limited purpose; when its optimization becomes an objective, the kinds of activity rewarded may change. The appraisal procedure can privilege forms of value visible to its instruments and leave other contributions less legible.

Recognition also depends on the categories in which a contribution can be expressed. Some participants may produce knowledge through forms of practice that dominant evaluation systems represent incompletely. Fricker's distinction between testimonial and hermeneutical injustice is pertinent to the risks of unequal credibility and of shared interpretive resources that marginalize the experience of some knowers [33]. The present analysis uses that theoretical insight cautiously. A difference in publication frequency or professional recognition is not sufficient evidence of epistemic injustice. Claims about prejudicial credibility deficits, institutional silencing, or unequal access to interpretive resources require examination of the relevant practices, the affected participants' accounts, and credible alternative explanations.

The distinction between *recognition* and *attribution* is especially important. An infrastructure may be broadly recognized as useful while particular maintainers remain anonymous. A paper may receive credit for a discovery while the underlying datasets, translations, and community-generated observations remain poorly acknowledged. Conversely, acknowledgment does not necessarily secure access to the resulting knowledge or participation in later decisions. Attribution practices therefore connect an epistemic judgment about contribution with governance and legal questions concerning rights, rewards, and continued productive capacities. Authorship rules, software contributor records, provenance documentation, and participatory forms of reporting provide different forms of traceability, each with domain-specific limitations.

Recognition can be cumulative, but it can also be corrected. Critical reappraisal, replication, historical scholarship, retraction, methodological revision, and community review may alter accepted judgments. A value-recognition system should therefore be analysed as a historically situated process capable of learning and error. Its degree of openness to criticism matters for public knowledge production because an early assessment can shape the subsequent availability of funding, platforms, careers, or institutional authority. The political-economic consequence lies in the relation between appraisal and the capacity to continue producing knowledge, a relation that can be studied without presuming that every favourable judgment is an act of capitalization.

9.5 Value Transformation and Capitalization

The fifth analytical object is the transformation of value across practices, institutions, and forms of accumulation. A useful scientific method may be transformed into a commercial service, an educational curriculum, a shared technical standard, or a source of institutional credibility. A public archive may support a revenue-generating publication while also creating opportunities for collective historical interpretation. These examples concern different productive relations and valuation procedures. A transformation between value forms is therefore better understood as a situated process of translation, institutional mediation, and recombination than as the movement of a conserved quantity between containers. The value created at one site may be augmented, contested, redistributed, or partly lost in the process of making it usable elsewhere.

Capitalization denotes a narrower set of operations within this larger field. An institution may translate an expected stream of future payments into an asset valuation, assign exclusive rights over a knowledge-based product, or organize accumulated skills and infrastructures for recurrent economic returns. Such processes can reinforce productive investment, and they may also establish dependence on the actor controlling the resource or service. The conditions for conversion include legal enforceability, organizational capacity, market or administrative demand, complementary assets, and the availability of alternatives. These conditions vary substantially across jurisdictions and sectors. A public resource may produce economic benefits without becoming privately owned, and a proprietary knowledge asset may fail to generate sustainable returns. The presence of knowledge, commercial relevance, and a realized capital position should accordingly be distinguished.

Value transformation can occur in several directions. Economic resources can sustain epistemic capabilities by financing instruments, teaching, collaborative review, or preservation. Epistemic accomplishments can support institutional value by establishing shared methods and trustworthy procedures.

Social relations can enable new knowledge through cooperation, while institutional arrangements can shape which forms of social participation become feasible. In an open research consortium, financial support may be converted into documentation and shared infrastructure, which expand participants' productive capacity and permit further work. In a corporate setting, revenues from licensed applications may support fundamental research, shared training, or additional proprietary assets. These arrangements should be compared in terms of observed flows, rights, obligations, and consequences for continued production, rather than assigned an outcome from their ownership labels alone.

The conversion process may entail *loss of epistemic context*. A concept developed for a narrowly defined evidential situation may be reused as a general performance metric; a qualitative judgment can become a numerical proxy that is easier to trade or administer. Such conversions may be useful, but they can change what the measure tracks and which forms of knowledge remain intelligible. Longino's account of contextual values and Espeland and Sauder's analysis of commensuration and reactivity offer different starting points for investigating these transformations [57, 27]. An empirical study would need to document the original context, the translation procedure, the uses of the new representation, and any change in the participants' available alternatives. Conceptual caution is important because a disagreement over valuation may reflect divergent objects of concern rather than measurement error alone.

Some transformations affect the relation between contributors and their productive conditions. Consider a hypothetical open computational method developed through collective labour and subsequently implemented as a closed, hosted service. The service may contribute useful maintenance, computational scale, and reliability. It may also create dependence where users lack access to compatible infrastructure or cannot export their data and routines. The resulting arrangement can create additional value and produce an asymmetry in its appropriation at the same time. Whether it constitutes a structurally extractive relation requires evidence about bargaining power, access conditions, contributors' alternatives, the distribution of benefits and burdens, and their effective ability to continue or transform their work. A similar inquiry can be conducted in a collectively governed organization if decision authority or the burdens of maintenance become concentrated within a small group.

These distinctions caution against identifying commercial conversion with extraction as a matter of definition. They equally caution against inferring equitable circulation from nominal public status. The proposed analytic sequence is to identify the activity that produces a value, examine the conventions through which it is recognized, trace the institutional mechanism that converts it into another form, establish the rights and capacities governing access to the results, and assess the implications for continued creation. Section 8 supplies the vocabulary for the rights and capacities involved, while subsequent sections develop value circulation and power in greater detail. The present section remains focused on the constitution of value and the mechanisms through which its form and recognizability change.

9.6 Generative Capabilities and the Production of Further Value

The sixth analytical object is the contribution of knowledge creation to the conditions of further creation. A completed research activity may leave behind an artefact, but it can also change the skills of participants, the coordination capacity of a community, the available research questions, or the interpretive standards used in subsequent projects. These changes are relevant to capital expansion because they affect which productive activities are feasible under a new relational configuration. Their importance depends on the persistence, accessibility, and reproducibility of the relevant conditions. A dataset with uncertain provenance may be difficult to reuse; a validated method with extensive documentation and training may support many independent lines of inquiry. The effective generativity of a result is therefore a contextual property of its relation to users, infrastructures, institutions, and competing methods.

Within the present framework, *generative capability* refers to the situated capacity of a person, group, or institutional arrangement to participate in specified knowledge-producing transformations. Its assessment requires the specification of agents, accessible resources, applicable rules, skills, and a domain of feasible activities. A change in a collection of feasible activities should be described relative to a historically specified comparison, without interpreting the represented ordering as an ontologically universal

progression. Nor does the possibility of an activity imply that it will be realized. A capability may exist without being exercised, and an observed output may conceal the depletion of capabilities that supported it. This separation between capability and realization preserves room for uncertainty, agency, conflicting priorities, and institutional change.

The distinction also clarifies why the production of further value cannot be reduced to a monotonic increase in outputs. A research environment may produce more publications while losing the capacity for independent critical replication. A shared technical platform may become more capable in one direction while preventing users from modifying its interfaces. Conversely, a maintenance project may generate few immediately visible outputs while preserving a heterogeneous repertoire of future research activities. An adequate study can compare several dimensions of generative capability, including diversity of methods, technical reliability, access and usability, interpretive openness, and the capacity of affected participants to influence governing procedures. Such dimensions may conflict, and the relevant weights are themselves subjects of institutional and normative judgment.

The capacity to generate value also depends on the *distribution* of productive capability. Concentrated expertise or infrastructure can provide coordination advantages in tasks requiring significant specialization, yet create vulnerability when participation depends on a single provider or institutional authority. Distributed capabilities can provide multiple routes of entry and correction, while imposing costs of coordination and sustaining common standards. The present inquiry makes neither concentration nor decentralization a universal criterion of productive merit. The relevant questions concern task requirements, redundancy, substitutability, accessibility, governance, and the stability of arrangements supporting continued work. The significance of a particular generative level derives from those relations, including changes produced by applications that reshape foundational methods.

An illustration may help identify the competing consequences. Suppose a collective develops a research protocol and educational resources that several independent laboratories can use. One institutional arrangement invests the resulting benefits in shared training, documentation, and procedures for revising the protocol. Another arrangement channels a substantial portion of the returns to a provider of a complementary service while users remain dependent on its platform. Both may improve immediate performance, and the second provider may contribute genuine operational value. Their consequences for generative capability depend on whether participants can acquire skills, maintain alternatives, revise the protocol, and participate in decisions governing essential resources. Their difference cannot be established solely by the sum of financial returns or by the legal label of the organizations.

Kitcher's account of science and democratic purposes is relevant to the additional question of which inquiries deserve support when productive capacities and priorities are publicly consequential [51]. Knowledge creation may satisfy a field-specific standard of intellectual merit while serving a limited constituency; another activity may address a pressing collective need while requiring forms of evidence unfamiliar to prevailing evaluation systems. The question of public value therefore calls for procedures capable of relating epistemic standards to affected interests, without subordinating all scholarly judgment to immediate demand. Public participation, accountable expert assessment, protection of dissent, and recognition of different forms of knowledge may contribute to such procedures under appropriately designed conditions. Their operation and limitations require empirical inquiry rather than institutional idealization.

The analysis of heterogeneous value creation yields a provisional account of knowledge-capital expansion. Value can arise in outputs, relations, methods, collective capabilities, and the institutional conditions that sustain them. Recognition and capitalization can translate selected consequences into enforceable claims, economic returns, reputational positions, or opportunities for continued production. These transformations interact across relative generative levels, but their effects depend on the distribution of productive conditions and the ability of participants to retain or reshape them. A process may thus expand a system's generative repertoire while concentrating command over some of its enabling conditions. It may also distribute effective capabilities and sustain a broader range of productive contributors. Explaining these possibilities requires the analysis of circulation across persons, institutions, and levels of knowledge production.

The relevant empirical record must identify the value produced, its contributors and beneficiaries, the conventions through which it is recognized, and the rights under which its consequences can be converted into further productive opportunities. Section 10 examines the distinct circulation processes through which these consequences move across institutions and generative levels, return to support maintenance, or become unavailable to some contributors. Separating the two questions prevents an observed gain in knowledge production from being interpreted, without further evidence, as a corresponding gain in the producing community's capacity to continue its work.

10 Value Circulation and the Reproduction of Knowledge Capital

This section examines how values created through knowledge production enter circulation and how particular circulation arrangements affect the reproduction of productive conditions. Its objective is to trace the relations among heterogeneous benefits, institutional channels, control of resources, and the continued capacity to generate knowledge. The discussion first establishes a relational vocabulary of circulation; compares market, public, and commons-based arrangements; develops the problem of cross-level value conversion; considers appropriation and reinvestment; examines collective reproduction; identifies interruption, loss, and structural asymmetry; and analyses recursive circulation across changing generative structures. The argument is conceptual and comparative, with references to established scholarship and explicitly hypothetical configurations. Claims about actual distributions or causal effects require case-specific inquiry.

The production of a valuable result and the circulation of its benefits occupy analytically different positions. A published method may enable independent inquiries, support education, confer recognition on its authors, yield fees to an intermediary, or provide training material for a later commercial service. Each consequence involves additional relations through which knowledge becomes accessible, intelligible, usable, credited, or appropriable. A benefit may return to those who helped establish its conditions, travel toward a different organization, remain in an institutional reserve, or disappear through neglect and changing relevance. These trajectories influence what forms of knowledge can continue to be produced. For that reason, circulation is a constituent dimension of knowledge-capital reproduction rather than an accounting appendix to a completed act of production.

A comparative analysis must also distinguish circulation from a presupposed conservation of value. Money can be traced through transfers with identifiable accounting units, subject to their own institutional definitions. Learning through shared use may increase the capabilities of several participants without subtracting an equivalent quantity from the source. Trust can strengthen or weaken through interpretation, and epistemic validity is assessed through inquiry rather than transferred as a divisible commodity. A repository can distribute a copy at low marginal cost while incurring consequential maintenance, verification, security, governance, and preservation costs. The study therefore treats heterogeneous circulation as a set of situated transitions among people, resources, institutions, representations, and productive capacities. It does not impose one scalar ledger on the resulting economic, epistemic, social, and institutional changes.

10.1 Heterogeneous Value Circulation in Relational Production Systems

The first analytical object is a circulation relation: a structured connection through which one activity's consequences become conditions, claims, resources, or constraints for another activity. A circulation relation can involve payment, access, teaching, citation, peer review, shared maintenance, data reuse, interpretive translation, reputational recognition, or rule-setting authority. The character of the relation depends on the resources and persons involved, the governing permissions, and the practical capacity of participants to realize what is formally available. In a public knowledge system, an unrestricted download, a comprehensible explanation, a reusable instrument, and participation in the governance of an instrument are distinct forms of circulation, even when they concern the same artefact.

A useful description distinguishes at least four positions: the activity in which a contribution originates; the institutional or technical intermediary through which it passes; the participant who realizes a benefit or bears a burden; and the productive condition altered by that encounter. These positions are analytical roles, not predetermined categories of actor. A researcher can be an originator in one relation, a beneficiary in another, and an intermediary when teaching an inherited method. A public university may provide an instrument while drawing on community-generated materials and external software maintenance. Accordingly, circulation paths are often branching, overlapping, and recursively connected; their local order must be reconstructed rather than inferred from a universal sequence of production, exchange, and consumption.

The meaning of circulation also depends on the type of value under examination. Monetary income can finance research time, but that purchase does not by itself establish epistemic quality. Access to a dataset can support inquiry where its documentation and provenance are adequate, yet the same data can be unusable or harmful when the governing purposes or interpretive limits are disregarded. Recognition can attract collaborators while concentrating evaluation authority in a narrow institution. The consequences are heterogeneous even within a single channel. Anderson's analysis of plural modes of valuation is relevant to the conceptual caution against treating all valued consequences as units of market exchange [2]. The proposed relational account builds on this caution by investigating what each channel makes possible and whose capabilities it alters.

The circulation of knowledge may be expansive in one dimension and restrictive in another. Copying an open educational resource can extend access across institutions. The content may remain hard to understand without prior training, and future revisions may depend on maintainers who lack stable support. A commercial provider can improve usability while making the continued use of the service dependent on fees or proprietary interfaces. A public archive can distribute records broadly while legitimately limiting access to materials whose release would conflict with established duties toward individuals or communities. These configurations show why openness, welfare, sustainability, and autonomy require separate assessments, even when they are pursued together.

For empirical investigation, the circulation relation should therefore be recorded with its object, participants, enabling resources, applicable rights, cost-bearing positions, criteria of recognition, and observed consequences for continued production. The same relation may be described differently by participants whose experiences and stakes diverge. Such differences are part of the evidence rather than noise to be eliminated through an assumed comprehensive measure. The central analytical task is to identify how the circuit enables or constrains generative activity under identifiable institutional conditions.

10.2 Circulation Through Markets, Public Institutions, and Commons

The second analytical object is the institutional configuration through which a circulation relation is organized. Market transactions, public allocation, and commons governance provide distinguishable coordination mechanisms, although they regularly coexist within one production system. A market may direct resources through prices and contracts; a public institution may distribute research support through budgets, mandates, or access obligations; a commons may govern shared resources through participant rules, established responsibilities, and practices of commoning. The comparison concerns the concrete allocation of authority, contributions, returns, and reproductive obligations. An institutional designation alone does not determine the quality of these arrangements.

In market-mediated knowledge production, revenues can reward the development of useful services, maintain specialized facilities, and support work that would otherwise lack a funding channel. Revenue may also accrue to intermediaries that govern an indispensable publication, authentication, or computational interface. The relation between revenue and the reproduction of collectively generated knowledge depends on contracts, competitive conditions, maintenance practices, intellectual property rules, and the ability of affected producers to secure alternatives. Where a privately operated service builds on shared methods or volunteer-maintained software, market payment to the service operator and sustained support

for the shared inputs need to be traced as distinct transactions. Frischmann's account of shared infrastructures provides a framework for analysing how broad social benefits and the incentives of particular providers may diverge [34].

Publicly supported systems can maintain research facilities, archives, libraries, education, and other conditions whose benefits extend beyond their immediate users. Their circulation mechanisms may include taxation, grants, employment, public procurement, legal access guarantees, and provision without a user-facing price. Yet public funding also entails decisions about eligibility, institutional priorities, accountability, and the distribution of authority over results. Research institutions may combine publicly funded production with privately controlled dissemination or service provision. Allocation through a public budget does not by itself settle whether contributors receive recognition, whether underserved groups obtain effective access, or whether the institution can revise its priorities in response to criticism. The study of circulation therefore examines budgetary inputs together with epistemic and practical outcomes.

Commons-based circulation can provide shared productive resources through peer contribution, reciprocal maintenance, open licensing, or locally negotiated rules. Hess and Ostrom's treatment of knowledge commons helps locate resource use within the arrangements that organize contribution, access, and governance [40]. Ostrom's institutional-analysis framework further directs attention to participants, rules-in-use, attributes of a resource, and the action situations within which participants make decisions [71]. In such settings, a participant may derive learning benefits from helping another user, without a corresponding payment. Lakhani and von Hippel examined user-to-user support in the Apache web-server community and reported substantial direct learning benefits for the people providing help. Their case makes the returns to contributors and the organization of support important to understanding unpaid participation; it does not establish the motivations or benefits of all open-source maintainers [54]. This case supports a bounded mechanism, not an assumption that every unpaid contribution yields an adequate private benefit.

A communist conception of collective knowledge production concerns broader relations of production and distribution, and may articulate principles of common control over productive conditions. It should be analysed separately from the descriptive category of a knowledge commons. Cooperative associations likewise may combine member governance with commercial transactions, while public agencies may sponsor open infrastructures maintained by transnational communities. The resulting systems are better represented as combinations of circulation arrangements than as isolated institutional types. Marx's discussion of common production and collective reserves in the *Critique of the Gotha Programme* illustrates the importance of deductions for reproduction and expansion when considering the distribution of social output [62]; its historical and normative context should be retained when extending the inquiry to contemporary knowledge systems.

The significance of institutional comparison lies in identifying who can intervene when an established circuit fails to reproduce its productive conditions. A contract may be renegotiated, a budget revised, or common rules amended through participant governance. Different arrangements make these interventions available to different constituencies. A circulation system becomes institutionally legible when its authority to allocate benefits is analysed alongside its responsibility and capacity to maintain the sources of those benefits.

10.3 Value Conversion Across Generative Levels

The third analytical object is the conversion of benefits or resources across relative generative levels. Meta-knowledge, methods, infrastructures, and applications refer to positions within historically reconstructed dependency relations, as developed in Section 4. Their interactions can support knowledge creation across heterogeneous settings. A new application may generate observations that motivate changes to an experimental protocol. A shared methodological improvement may reduce the resources needed for a class of inquiries. A conceptual revision may alter which observations are meaningful, while continuing application practice reveals limitations in the revised account. Each interaction can enable a circulation

path, but the existence of a dependency does not specify how resulting benefits will be distributed.

Cross-level value conversion frequently depends on mediating labour. Translating a proof into reliable software requires design, testing, documentation, and decisions about relevant approximations. Converting field observations into a reusable dataset requires interpretation, consent or other legitimate authority where applicable, curatorial judgment, and records of limitations. Making a theoretical principle actionable in a public service requires training, institutional decisions, and feedback from affected users. The conversion therefore creates additional work and can introduce new forms of value or loss. A successful technical translation is insufficient evidence that the social purposes or epistemic claims associated with the source have been preserved.

A hypothetical knowledge-production network illustrates the distinction. A publicly funded group develops a general-purpose analytical method. Community contributors maintain an openly licensed implementation, and a firm integrates the implementation into a paid application. Customers receive useful services, the firm receives revenue, and software maintainers may receive recognition, bug reports, occasional sponsorship, or little return. A public authority may in turn use revenues collected through general taxation to finance related research, with no automatic correspondence between that public investment and the original contributors. Each relation requires its own evidence about obligations, returns, and the reproduction of capacities. The commercial revenue should neither be assumed to represent the entire value of the method nor treated as intrinsically illegitimate because some inputs were public.

Cross-level conversion can make one resource a structural bottleneck. A shared interface, certification procedure, database, or reference standard may become difficult to bypass because several methods and applications depend on it. The operator may provide an indispensable maintenance service; it may also acquire leverage to establish fees, select participants, determine permissible reuse, or shape evaluation criteria. The influence of the operator arises from the effective network of alternatives, switching costs, legal permissions, expertise, and governance arrangements. These dependencies may be revised by newly developed methods or by cooperation among users. Generative depth is therefore one aspect of the inquiry, while actual reach and substitutability are the more immediate determinants of cross-level circulation effects.

Value conversion can also move in the direction of public reproduction. Income from a specialized application may finance the upkeep of a common research instrument. Experience with a practical problem may lead to a publicly released dataset or correction of a shared measurement standard. Training materials produced for an institution may later be adapted by a wider educational community under legitimate permissions. Such examples show that public return is a relation to be investigated, rather than a property determined by the source of revenue. An arrangement may combine private benefit with substantial public investment, or public dissemination with insufficient support for those who maintain the common inputs.

The proposed comparative unit is thus a *conversion pathway*: a traceable series of transformations linking a contribution at one generative level to an effective change in resources, authority, or productive capability at another. Evidence should include the work required for conversion, the actors who determine its terms, the rights attached to transformed outputs, the opportunity to contest assessments, and the resources available for later maintenance. Since generative levels can be reconfigured by their own interactions, a pathway remains conditional on the representational and historical scope of the study.

10.4 Distribution, Appropriation, and Reinvestment

The fourth analytical object is the distribution of benefits and burdens, including the decision to reinvest resources in productive conditions. Distribution concerns who receives an identified benefit or bears a cost. Appropriation concerns the institutional means by which a participant secures claims over benefits, outputs, or enabling resources. Reinvestment concerns the assignment of some available resources to the continued or altered production of knowledge. The three processes can coincide, yet their separation is analytically useful. A publicly accessible product may be governed through an exclusive contract; a privately owned facility may provide subsidized access; and a surplus allocated to research may be used

for maintenance, expansion, or a change in organizational priorities.

Appropriation can support productive coordination when an identifiable claim enables the responsible actor to undertake investment and assume continuing obligations. It can also be structured around a dependency that prevents other contributors from obtaining access to productive conditions or meaningful participation in rule-setting. The normative and economic significance depends on the history of contribution, governing agreements, alternatives available to affected participants, institutional responsibilities, and the consequences for continued generative capability. The earlier distinction among ownership, access, and effective control in Section 8 remains relevant: a license to use an output need not confer authority to maintain the infrastructure that delivers it, and public funding of an instrument does not automatically ensure public governance of its future modifications.

The allocation of a monetary surplus offers one observable example. A publisher may divide revenues among editorial activities, platform costs, salaries, dividends, archiving, and investment in new services. A cooperative may assign a portion of its income to a collective reserve, staff development, or member services. A publicly funded institution may direct available budget to infrastructure maintenance, expanding access, training, or research grants. These allocations affect reproduction in different ways. However, an expenditure labelled as investment does not establish an increase in effective capability, and a payment labelled as compensation does not settle whether contributors have influence over productive conditions. Long-run outcomes require investigation of realized activities as well as stated intentions.

Reinvestment can also be nonmonetary. A participant who writes documentation may reduce the effort required for another person to understand a tool. A research group that maintains reproducible workflows may create a more reliable basis for criticism and subsequent inquiry. A community that establishes accountable procedures for revising a shared taxonomy may improve its capacity to respond to mistakes and exclusionary classifications. Such activities are forms of reproductive contribution even when they generate little directly observable revenue. Jackson's account of repair treats maintenance and continuing care as substantive sites of knowledge, invention, and institutional relations [46]. The present paper draws from this insight to examine reproduction as ongoing generative work, while preserving distinctions between technological repair, care obligations, and economic investment.

A comparative analysis must attend to the people and relationships affected by allocation decisions. Research assistants, teachers, librarians, data stewards, translators, community participants, reviewers, and technical maintainers contribute through different forms of labour and knowledge. They may receive wages, credit, access, learning, public benefits, and opportunities for further work in different combinations. Their preferences and legitimate claims can diverge, and the consequences of an allocation may vary among them. An assessment of extractive appropriation should accordingly consider the terms of participation, reasonable alternatives, governance voice, the distribution of risk, and the capability to continue contributing, rather than infer exploitation solely from unequal financial returns.

In this framework, reinvestment is a situated response to the reproductive requirements of knowledge production. Its adequacy depends on what kinds of capability the system is seeking to maintain, the burdens involved in maintaining them, and whose purposes govern the decision. The process has no automatic direction toward either collective prosperity or concentration. It can maintain established arrangements, widen productive participation, or consolidate access to consequential infrastructural and epistemic decisions. These alternative trajectories are central to the political economy of multilevel accumulation.

10.5 Value Recirculation and Collective Productive Capacity

The fifth analytical object is recirculation that contributes to the renewal or enlargement of shared productive conditions. A benefit generated through one knowledge activity may become a resource for another through financial support, learning, correction, institutional trust, reciprocal service, or renewed access to instruments. Reproduction in this sense includes continuing capacities to inspect, contest, modify, and create knowledge. It encompasses preservation of inherited resources, support for participants, and

the adaptation of methods and governance to emerging needs. A recirculating benefit matters because of the change it supports in these conditions, regardless of whether the benefit returns to its immediate originator.

A public repository illustrates the distinction. Use of the repository may produce citations and technical feedback. Citations can strengthen the visibility of stored works, while feedback can lead to corrections and better metadata. Financial contributions may support storage and curation, and shared documentation may make participation possible for additional contributors. Each pathway can reinforce the repository's productive role. Yet reproduction may be fragile if curation remains concentrated in a small group whose efforts are insufficiently supported. Eghbal's report on public digital infrastructure documents problems associated with dependence on lightly resourced maintenance and the misalignment between widespread use and support for the people providing shared code [25]. It is evidence concerning a particular digital-infrastructure context, and its mechanism should be tested independently in academic archives, civic knowledge systems, and other settings.

The capacity to maintain a resource includes governance as well as technical resources. Collective rules can allocate responsibilities, establish processes for resolving disagreement, and authorize changes in shared standards. Participants may contribute more sustainably when decision procedures make relevant work visible and allow affected people to challenge allocations. Ostrom's work on institutional diversity demonstrates the importance of studying rules-in-use and governance arrangements in their settings [71]. The implication for the present theoretical framework is methodological: the public character of a resource should be evaluated through the practicable rights and capabilities of participants and the continuity of the supporting institutional relations. Shared access and collective authority are distinct, potentially complementary dimensions.

Recirculation may strengthen both individual and collective capacity. A maintainer can learn from resolving another user's problem, as the Apache support study suggests under the specific conditions it examined [54]. Training one group may create the capabilities needed for later collaboration; a reproducibility exercise may improve the quality of a common measurement practice; and public funding of archival preservation may provide benefits to people who have no direct relationship with original producers. These gains can be distributed unevenly and may be accompanied by additional burdens. An adequate analysis examines whether productive autonomy broadens, whether contributors can sustain their participation, and whether the system can recognize and correct failures.

The relation between value recirculation and generative justice requires a further distinction. Recirculation describes a pattern of benefits and productive effects; justice concerns the legitimacy of the relationships under which such circulation is organized. Generative justice, as developed in the work of Eglash and collaborators, emphasizes the recirculation of value to its creators and the conditions of its creation [26]. The present inquiry uses that contribution as a normative interlocutor while leaving room for legitimate collective expenditures whose beneficiaries extend beyond the original contributors. A system may justifiably fund education, preservation, or accessibility for wider publics, provided the applicable responsibilities and rights are adequately considered. Questions of fairness, recognition, authority, and historical disadvantage require situated deliberation and evidence.

The relevant reproductive test is therefore multidimensional. Does the circulation arrangement preserve the resources on which continued inquiry depends? Does it improve or diminish the ability of diverse participants to access and meaningfully use them? Are responsibilities for maintenance distributed through legitimate and feasible arrangements? Can participants revise rules when circumstances or evaluative judgments change? Does the arrangement sustain the interpretive and social conditions of critical inquiry? These questions connect capital expansion to public generativity without equating expansion with a single quantity of outputs or funds.

10.6 Circulation Constraints, Losses, and Structural Asymmetries

The sixth analytical object is the set of conditions under which a circulation pathway fails, loses significance, or becomes structurally asymmetric. Monetary insufficiency can prevent maintenance; inacces-

sible documentation can limit meaningful reuse; a change in governing permissions can alter who may participate; and a reference standard may become difficult to revise even as evidence of its limitations accumulates. Some interruptions are accidental, while others arise from institutional decisions or contested purposes. Knowledge can also lose practical applicability because of scientific criticism, social transformation, obsolescence, or legitimate restrictions. Treating each interruption as extraction would obscure these differences. The inquiry instead asks how a disruption arises and how it changes the distribution of capabilities and burdens.

Technical and social infrastructures are especially vulnerable to hidden reproductive requirements. Systems may appear stable to users while depending on extensive maintenance, translation, repair, and coordination. Star and Ruhleder's study of collaborative scientific infrastructure demonstrates how access and effective use depend on organizational and communicative relations, even where a technical platform has been developed for a research community [85]. The example supports a general diagnostic question: which apparently available resources are productive only because less visible participants maintain interfaces, interpretations, and routines? Failure to support these relations may impair the capacity of the broader system, independent of whether the immediate resource remains formally accessible.

Structural asymmetry arises where actors occupy different positions in the capacity to create, channel, redirect, or appropriate benefits. A dominant intermediary may set the conditions of access to a widely used platform. A grant-making institution may determine which epistemic claims are recognized and thus which groups receive opportunities for sustained work. A consortium may maintain an indispensable standard while excluding affected practitioners from revision. The degree of dependence is conditioned by technical substitutability, transition costs, legal rules, tacit knowledge, and the existence of alternative organizations. An actor's apparent location at a foundational generative level is therefore insufficient to determine its leverage. Effective dependency must be documented in the situated network.

A particular extractive pattern is possible when one set of participants persistently benefits from value produced through distributed contributions while controlling the conditions under which contributors may continue producing. For instance, a hypothetical proprietary research interface could derive significant commercial benefit from open methods and shared datasets, while imposing high exit costs and offering limited opportunities to influence its maintenance or standards. This arrangement might create useful services and provide legitimate returns to its operator; whether it is structurally extractive depends on the full contribution history, rights, alternatives, risks, costs, and consequences for the affected community. The analysis treats extraction as an evidence-dependent diagnosis of relations, not a property implied automatically by profit, institutional scale, or concentrated expertise.

The reproduction problem becomes acute when the benefits supporting one organizational centre are accompanied by declining capacities elsewhere in its generative dependency network. In an analogous but broader social-theoretical context, Fraser analyses tensions between capital accumulation and the social-reproductive conditions upon which economic production depends [32]. Fraser's object is social reproduction, including human care, provisioning, and the maintenance of social relations; this object is broader than technical knowledge-infrastructure maintenance. Her analysis motivates a distinct hypothesis that capitalized returns may coexist with the underprovision of shared knowledge-producing capacities. Testing this extension requires evidence about both the human work sustaining knowledge institutions and the maintenance of their specific epistemic and technical conditions.

Analytically, a circulation study should trace which pathways remain available after a constraint is imposed, which participants can adapt, and whether the observed change is temporary, persistent, or offset by other forms of support. It should compare interpretations offered by different affected actors and record foreseeable tradeoffs, including privacy, consent, security, epistemic reliability, and public accessibility. An apparent restriction may protect an important legitimate interest, while a formal opening may leave the most consequential bottleneck intact. Attention to actual capabilities, rather than one visible dimension of access or revenue, is necessary for discriminating among these cases.

Table 11: Indicative circulation pathways and their possible effects on the reproduction of knowledge capital. These are diagnostic distinctions rather than a typology of institutionally predetermined outcomes.

Circulation pathway	Possible change in productive conditions	Possible asymmetry or loss	Principal investigative question
Financial support and reinvestment	Sustained staffing, instruments, archives, and training	Allocation concentrated apart from contributors	Who chooses reproductive priorities?
Knowledge reuse and mutual learning	Expanded methods, understanding, and participation	Unequal capacity to absorb and apply resources	Who can put the resource to productive use?
Recognition and institutional endorsement	Access to collaborators, legitimacy, and resources	Selective visibility and cumulative advantage	Whose contributions become consequential?
Maintenance and reciprocal support	Reliability, correction, and continuity of common tools	Unfunded labour and uneven duties	Who bears the cost of sustained availability?
Cross-level service conversion	Practical applications and support for broader inquiry	Bottlenecks, lock-in, and restricted revision	Who governs the interface and its alternatives?
Governance feedback and rule revision	Capacity to correct and transform productive conditions	Restricted voice and interpretive exclusion	Who can contest and change the rules?

10.7 Recursive Value Circulation and Generative Expansion

The final analytical object is the manner in which circulation arrangements alter the conditions of later circulation and knowledge production. An organization can use income from a specialized service to improve an infrastructure on which further services depend. A commons can use corrections, documentation, and training generated through use to enlarge the range of feasible contributions. A public institution can direct experience from community projects into revised standards, funding procedures, or educational programmes. These relations exemplify feedback in the formation of productive capabilities. The relevant history may contain branching pathways, reciprocal revision, and changes in institutional categories; its ordering is reconstructed for specific analytical purposes rather than treated as a universal temporal sequence.

One potential pathway is cumulative public capability. Participants use a shared method, create new knowledge, improve the method's documentation, train additional participants, and establish practices for maintaining the resulting resources. A second pathway is increasing institutional concentration. An intermediary obtains returns from broad dependence on a common resource, invests in proprietary complements, raises switching costs, and gains more authority to shape the conditions of further use. A third pathway combines these effects: a widely used proprietary service may help disseminate valuable knowledge while concentrating decisions about infrastructure, standards, and the disposition of economic returns. These scenarios are analytically distinct configurations that may overlap in concrete settings. Their frequency and consequences remain empirical questions.

Table 11 maps several illustrative circulation relations to their reproductive effects and central governance questions. Its purpose is to identify what would need to be observed when moving from a description of value creation to a claim about accumulation across generative levels. The entries are deliberately open to alternative realizations; a given institutional channel can sustain several different pathways in the same period or under different arrangements.

Recursive circulation should also be examined for its effects on the form of capital itself. Productive knowledge capital may be strengthened through preserved technical competence while institutional control becomes more concentrated. Conversely, collective authority may expand while technical maintenance capacity becomes fragile. A new standard can reorganize dependencies among formerly separate activities, and a public archive can make previously inaccessible histories available for reinterpretation. These changes affect the map of feasible knowledge production as well as the distribution of benefits

within it. They are particularly important when capitalization at a deeply connected level alters who can establish the terms of further research and whose interpretive or practical capacities remain supported.

Value circulation affects knowledge-capital expansion through the productive, epistemic, and institutional conditions that recipients can consequently maintain or transform. The appropriate evidence concerns specific transfers, conversions, reproduction obligations, access rules, and feasible alternatives, rather than an assumed requirement that each benefit return directly to its source. Section 11 examines how actors exercise power over these circulation pathways and how unequal authority can alter their consequences across generative levels.

11 Power in Knowledge Capital Formation and Circulation

This section examines power as a set of historically situated relations through which actors can shape the conditions, trajectories, and benefits of knowledge production. Its objective is to specify the ways in which power operates upon productive resources, generative capacities, epistemic recognition, and the circulation of heterogeneous value. The discussion develops a relational account of power; differentiates control over productive conditions from the exercise of productive capability; examines epistemic and interpretive authority; considers the institutional regulation of value circulation; analyses asymmetries across generative levels; investigates the accumulation of power through changes in generative structures; and addresses collective agency, contestation, and institutional revision. The method is conceptual and comparative. Hypothetical configurations clarify the proposed mechanisms, while empirical conclusions remain dependent upon evidence concerning particular institutions and histories.

Knowledge-capital accumulation presupposes arrangements through which people coordinate labour, make resources available, adjudicate claims, and maintain productive conditions. These arrangements involve decisions about access, evaluation, responsibility, allocation, and revision. Power enters knowledge production through the capacity to influence such decisions and through the more diffuse formation of options, expectations, categories, and dependencies within which decisions take place. An actor who can finance an archive, set a technical standard, validate a claim, operate a service, or deny access to an instrument may affect the possibilities available to other participants. The effects depend upon the actual alternatives, reciprocal obligations, collective practices, and institutional safeguards that shape the relevant relation. They may expand public generativity, constrain it, or bring about both kinds of consequences across different parts of a system.

The presence of power, accordingly, raises an analytical question rather than settling a normative verdict. Specialized authority may make large-scale coordination and reliable quality control possible. The same concentration can create conditions under which participants have little influence over infrastructures or epistemic rules that structure their activities. The task is to examine which decisions can be taken by whom, which forms of influence are available, how these powers are reproduced, and whose continued productive capabilities are affected. Such an inquiry also distinguishes power from realized exploitation. A structure with potentially unequal bargaining positions supplies grounds for closer investigation; an allegation of extraction requires evidence about value appropriation, dependencies, available remedies, and the reproduction of productive conditions.

11.1 Relational Constitution of Power in Knowledge Production

The first analytical object is the relational constitution of power. For the purposes of this paper, power refers provisionally to an actor's or organized collectivity's situated capacity to affect the feasible actions, recognized claims, allocation processes, or rule-changing opportunities of other participants in a knowledge-producing configuration. The definition is deliberately broad enough to encompass legal authority, technical mediation, resource control, professional expertise, collective mobilization, and institutional influence. Its application requires specification of the domain of action, the relevant participants, the mechanisms of influence, and the historical configuration in which the capacity becomes effective.

Formal authority, perceived legitimacy, exercised discretion, and the resulting consequences remain distinguishable objects of inquiry.

Several intellectual traditions illuminate different aspects of this problem. Lukes' multidimensional analysis of power draws attention to agenda-setting and the circumstances in which observable choices may be shaped by the organization of available alternatives [58]. Foucault's account of power relations as action upon possible actions directs inquiry toward practices that structure conduct, resistance, and the formation of subjects [29]. Applied here, this is an interpretive lens for investigating epistemic opportunities, rather than evidence that a particular knowledge institution exercises domination. The co-production perspective synthesized in the collection edited by Jasanoff treats scientific knowledge and social order as mutually implicated in historical practice [47]. These approaches share interests in relations that exceed an isolated transaction, yet they differ in their explanatory commitments and in the objects of analysis to which they give priority. The present discussion borrows limited questions from each and does not claim that their accounts are theoretically equivalent.

For empirical purposes, a useful distinction concerns an actor's capacity to conduct productive activity, its capacity to govern the conditions of another actor's activity, and its capacity to alter the rules through which capacities and claims are recognized. The first may be called *productive agency*; the second *relational command over conditions*; and the third *transformative institutional authority*. They frequently interact. An expert committee can contribute genuine technical competence, exercise discretion over access to public equipment, and participate in revising standards of merit. An individual may possess advanced practical knowledge while lacking institutional authority to change the rules used to evaluate that knowledge. A collectively governed infrastructure may distribute some rule-changing authority across its participants while concentrating operational responsibility in a smaller technical team.

Power also has a temporal and historical dimension, although the ordering of historical configurations requires an explicit analytical account. An existing rule can shape the range of future admissible transformations; a realized response may reinforce, reinterpret, or invalidate the rule; and the observer's account of the same events may change as additional evidence appears. These are distinct forms of change. A study of power should therefore identify the records, institutional procedures, and inferential assumptions through which it reconstructs succession, continuity, and transformation. The mere placement of two configurations in an ordered narrative cannot establish a causal relation between them.

A relational analysis also keeps the legitimacy and effects of power open to inquiry. Authority over a safety-critical laboratory or a confidential dataset may rest upon justified responsibilities. A maintenance team may require discretion to preserve interoperability and service continuity. Affected contributors may nevertheless encounter decisions for which they lack an effective appeal or meaningful participation. Each conclusion requires attention to institutional purpose, expertise, distribution of responsibility, rights of affected persons, and the available paths of contestation. The importance of power for political economy lies in its influence upon productive opportunities and the pathways through which value and authority are maintained or reallocated.

11.2 Power over Productive Conditions and Generative Capabilities

This subsection examines power exercised through control of the conditions required for knowledge production. Relevant conditions include instruments, computing facilities, datasets, archives, laboratories, publishing channels, skilled labour, institutional credentials, protocols, financing, and stable arrangements for collective maintenance. Their significance emerges from the activities they support and from their relation to other complementary resources. Ownership of one facility may convey limited influence when substitutes are accessible. Control of a modestly priced service may convey substantial influence when dispersed projects depend upon its standards and cannot readily migrate their data, skills, or organizational workflows. Effective power over conditions is therefore a feature of dependency relations and available alternatives as well as of formal property rights.

Consider a hypothetical research community that contributes to an openly licensed dataset while relying on a privately operated platform for curation, identity management, authentication, and compu-

tational access. The data licence may permit reuse, while the practical conditions for processing require specialized hardware, compatible metadata, and continuous service provision. A platform operator might be able to change pricing, access priority, export functionality, or interface conventions, thereby affecting the effective options of data contributors and downstream users. The example does not imply misuse by the operator. It identifies the questions necessary for evaluating the relation: the technical substitutability of services, the portability of contributions, the distribution of maintenance costs, the terms of participation, and the decision procedures governing future changes.

The exercise of productive capability also depends upon training, time, security, and interpretive competence. Formal permission to inspect a resource may have little practical value to a participant who cannot obtain necessary documentation or computational capacity. Conversely, experienced contributors may create viable alternatives through collective maintenance even where their financial resources are limited. Analyses that equate power with asset ownership alone would miss these relations. The differentiation among access, withdrawal, management, exclusion, and alienation in property-rights scholarship offers an initial language for describing distinct claims over resources [82]. The further question here concerns the effective capacities through which participants can use, maintain, and transform the relevant productive arrangement.

Power over conditions may arise from control of complementary resources. A research institution may possess the equipment necessary to perform an experiment while depending on an external company for proprietary calibration software. A community archive may preserve manuscripts but rely upon a registry or identification infrastructure for stable discovery. A funder may have no proprietary claim over the results of a project yet possess consequential discretion over the continuation of staff and facilities. In each case, the investigator should distinguish the formal source of authority, the operational capacity to exercise it, the extent of dependence, and the actors who bear the costs of interruption or adaptation.

The formation of institutional bottlenecks is an important but conditional possibility. Bottlenecks can coordinate compatible contributions, reduce duplication, support common standards, and create collective economies of scale. They can also provide points of control when meaningful alternatives, participation rights, or accountability mechanisms are weak. Evaluating these consequences requires evidence concerning the actual quality and cost of alternatives, not only a count of service providers. A nominal alternative may require substantial retraining or migration, while an ostensibly concentrated service may remain subject to strong public duties, transparent procedures, and credible collective oversight.

Finally, productive conditions include the human capacities that maintain knowledge systems. Labour time, accumulated experience, and the ability to act autonomously have moral and institutional properties that differ from the ownership of an instrument or database. Employment contracts and professional hierarchies may allocate decision-making powers, but they do not convert a person's practical knowledge, agency, or dignity into ordinary alienable objects. A political economy of knowledge production must therefore examine labour conditions, participation, and the practical possibility of refusing, renegotiating, or changing arrangements alongside more conventional questions of capital ownership.

11.3 Epistemic Authority, Recognition, and Interpretive Power

The third analytical object is power over the recognition and interpretation of knowledge. A knowledge-producing institution operates through judgments concerning evidence, disciplinary relevance, methodological credibility, originality, and appropriate standards of validation. These judgments are necessary to organized inquiry, yet the procedures that produce them may create asymmetries among participants and among competing ways of understanding a phenomenon. Epistemic authority includes recognized expertise and warranted responsibility for evaluation; interpretive power concerns the effective influence of categories, frames, and representational conventions upon what can be expressed, compared, or rendered visible. Their relations with material capital vary across institutional settings.

Research assessment offers a clear instance. Committees and reviewers allocate attention and opportunities through evaluations of proposals, publications, and scientific claims. Disciplinary expertise may

support the identification of errors and improve standards of argument, while uncertainty, differences among fields, institutional incentives, and established conventions influence the resulting judgments. Lamont's qualitative study of peer review illuminates variation in evaluative practices and the deliberative character of academic judgment [55]. The present framework extends the question from the quality of individual evaluations to their consequences for the distribution of future productive opportunities. A judgment may affect access to research time, recruitment, infrastructure, and a community's capacity to develop alternative methods.

The authority to establish categories and standards can have effects beyond the review of individual outputs. Classification systems may stabilize communications among institutions and make complex resources collectively manageable. They may also privilege certain distinctions, erase relevant differences, or impose high costs on practices that fit poorly into the available categories. Bowker and Star's analysis of classification infrastructures establishes the institutional and practical significance of such ordering systems [12]. The influence of a standard depends upon its adoption, interoperability, revision procedures, and the existence of other meaningful forms of representation. In the language of generative levels, control over a widely used classification or evidential interface may shape numerous downstream research activities without establishing a universal hierarchy among knowledge domains.

Epistemic injustice provides a further set of analytical concerns. Fricker's account identifies ways in which prejudicial credibility deficits and gaps in shared interpretive resources can impair participants as knowers [33]. Dotson develops an analysis of testimonial silencing and epistemic violence that emphasizes hearers' failures to meet the vulnerabilities of speakers within communicative exchange [24]. These works address distinct phenomena and normative commitments. They nevertheless motivate questions about whose contributions enter the recognized record, whose accounts are treated as credible, and which groups can influence the categories through which public knowledge is produced. Evidence of such harms should be drawn from situated practice rather than inferred merely from unequal citation counts or asymmetrical institutional status.

Epistemic recognition can be converted into other forms of advantage. Visibility and reputation may attract funding, collaborators, platform access, students, and opportunities to participate in the revision of research priorities. Some of these conversions may track genuine expertise and valuable contributions. Others may reflect institutional path dependence or the unequal visibility of maintenance, teaching, translation, and criticism. The relationship between recognition and capital expansion consequently requires a processual inquiry. It is useful to trace who makes evaluative decisions, which materials are considered, which alternative interpretations remain admissible, and how particular decisions affect the capacity to conduct further inquiry.

An additional difficulty concerns the difference between knowledge being represented within a system and a participant's practical ability to contest the terms of representation. A repository may permit a community to submit records while requiring categories that do not adequately express that community's understandings. A scientific database may include formal provisions for correction while making consequential changes dependent on resource-intensive technical processes. Interpretive power thus interacts with access to expertise, infrastructure, language, and governance. A public knowledge system can improve openness at the level of outputs while leaving interpretive authority comparatively concentrated. The resulting asymmetry is a subject for empirical and normative investigation, especially where it influences further production conditions.

11.4 Institutional Power and the Regulation of Value Circulation

The preceding section distinguished value creation from the routes through which heterogeneous benefits are distributed, appropriated, converted, and returned to knowledge-producing conditions. The present subsection examines how institutional power structures those routes. Rules concerning employment, funding, licensing, access fees, authorship, attribution, data custodianship, and the maintenance of common infrastructure affect both recognized benefits and the capacities that support further creation. Circulation is consequently mediated by legal claims, negotiated agreements, professional conventions,

technical interfaces, and decisions about the allocation of collective resources.

A simplified analytic vocabulary distinguishes *allocation power*, which concerns the assignment of resources and opportunities; *conversion power*, which concerns the institutional pathways through which one kind of value becomes another; *gatekeeping power*, which concerns access to those pathways; and *revision power*, which concerns authority to change their governing conditions. These names denote potentially overlapping practices rather than independent quantities. A foundation's grant programme can allocate funds while shaping which outputs are legible as successful research. A software service can convert voluntary maintenance into commercial reliability, and its operator may decide whether some part of the ensuing income supports maintainers. A public repository can create social and epistemic value while a governing body determines preservation priorities and the conditions of reuse.

The distribution of monetary returns supplies only one perspective on these processes. Non-monetary benefits can include stable access to instruments, opportunities to learn, improved credibility, authority over standards, community recognition, and the preservation of cultural materials. Circulation may also involve burdens: unpaid maintenance, risks of exposure, training requirements, or responsibilities for correction. In some settings, a participant receives a recognizable financial return while another bears a diffuse cost of sustaining the shared system. A comprehensive account should follow these heterogeneous effects as distinct and potentially incommensurable features of the historical configuration. The plurality of valuation practices explored by Anderson and the institutional dimensions of research evaluation discussed by Lamont are relevant to interpreting such disparities [2, 55].

The institutional conversion of values can amplify existing power. An actor recognized as an authoritative evaluator may influence which projects receive investment and thereby contribute to the reproduction of the standards on which that authority rests. An organization controlling a widely adopted distribution channel may convert public contributions into customer relationships, usage data, financial revenue, or a greater influence over technical interfaces. These effects require investigation of the relevant contractual and technological arrangements. They also admit countervailing possibilities: revenue from specialized services can fund open maintenance, and concentrated administration can be paired with democratically contestable rules for resource allocation.

The inquiry must distinguish the conditions for value capture from evidence of extraction. A research institution may allocate disproportionate resources to an expensive facility because that facility enables an important programme of collective research. A community may grant a maintenance team discretionary authority because rapid technical decisions are required. Such asymmetries are compatible with arrangements that remain publicly accountable and contribute to the reproduction of shared capacities. A stronger claim of structural extraction would call for evidence that appropriation is sustained through dependencies or exclusionary powers while reducing contributors' practical ability to benefit from, contest, or reproduce the conditions of their contribution. The relevant comparison should include feasible institutional alternatives and the costs borne by different participants.

The circulation of value may also reshape the categories under which value is counted. A research institution that rewards only easily recorded outputs may gradually direct labour toward activities recognized in those records. Changes in assessment criteria can reallocate attention among experimental work, theoretical contributions, replication, infrastructure maintenance, and community engagement. The analysis of rankings and reactivity by Espeland and Sauder provides an empirically grounded example of evaluation systems influencing organizational practice, though its findings must be scoped to the studied institutional context [27]. A political economy of circulation therefore investigates evaluative rules as possible causes of productive change as well as representations of outputs already produced.

11.5 Power Asymmetries Across Generative Levels

Generative levels provide a way to locate power within systems of knowledge dependency. A level is a relative analytical position defined by the conditions an activity draws upon and the further activities it can support. Meta-knowledge, theoretical methods, interoperable infrastructures, specialized applications, and particular outputs may occupy different positions for a given domain of analysis. Practi-

Table 12: Illustrative sites of power across relative generative levels. Each row identifies questions for case-specific analysis rather than an invariant ranking of importance or risk.

Site	Possible mechanisms of influence	Evidence relevant to effective dependency
Meta-knowledge and evaluative rules	Control of credibility criteria, admissible categories, and procedures for revising standards	Appeals, alternative standards, participation in rule revision, excluded interpretive practices
Methodological systems	Control of protocols, validation procedures, training, and compatibility	Method portability, comparative validation, switching costs, availability of other competent teams
Shared infrastructures	Control of compute, archives, identity services, interfaces, and maintenance	Service interdependence, technical export, operating contracts, continuity plans, governance records
Applications and platforms	Control of distribution, interfaces, user relationships, and complementary assets	User migration, interoperability, downstream integration, alternative implementations
Generated outputs and claims	Control of licensing, access permissions, recognition, and derivative use	Actual reuse, rights bundles, attribution practices, opportunities to correct and contest

cal knowledge production generally involves overlapping dependencies and reciprocal transformations rather than a single universal derivation tree. The significance of power at a given position depends upon the breadth and character of effective dependencies, substitutability, governance, and the mechanisms through which those dependencies can be exercised.

Control over a widely used methodological standard can influence which observations become mutually comparable and which training investments remain useful. Control over a research infrastructure can regulate access to computational capacity or archives that support diverse projects. Control over an application may affect a narrower field of activity, although a widely adopted application can become an infrastructural dependency in its own right. Conversely, control of an abstract theoretical framework may have weak institutional effects when investigators can readily employ multiple rival frameworks. Generative depth and effective leverage must consequently remain distinct. The latter requires a situated investigation of actual bottlenecks and feasible substitutions.

Table 12 compares possible locations of power and the kinds of evidence necessary to assess their effects. The rows represent analytical viewpoints that may overlap in practice. A platform can supply research data, encode classificatory rules, and function as the principal channel for publishing results. An institution's authority over a single platform may therefore operate simultaneously through infrastructural, epistemic, and distributive mechanisms. Treating these mechanisms separately makes their interaction more visible without presuming that they can be fully isolated in the historical system.

A useful hypothetical comparison concerns two forms of knowledge capital. In the first, an organization possesses exclusive rights to a specialized application whose functions are readily reproduced by several alternatives. In the second, an organization controls an authentication and validation infrastructure on which multiple otherwise independent research communities rely. The second position may allow the organization to influence a larger set of productive activities, even when the monetary value of its own services is smaller. Yet the inference depends on real dependencies, portability, credible substitutes, and the rights of participants to revise governance. A broadly used open standard may create extensive coordination benefits while remaining accountable to its users. A highly specialized application may become indispensable in a safety-critical context. Apparent depth alone settles neither its economic significance nor its ethical appraisal.

Cross-level power also includes the ability to move resources and influence between positions. Revenue generated through applications can finance fundamental inquiry, support open infrastructure, or fund private control of shared interfaces. Scientific recognition acquired through methodological work can influence policy boards and allocation committees. Such transformations can increase productive options for a community, reinforce a privileged position, or combine these effects. The decisive questions concern the terms of conversion, the populations whose activities depend on the resulting arrangement, and the mechanisms for revision when distributed contributions or affected interests remain weakly represented.

11.6 Power Accumulation and the Transformation of Generative Structures

The accumulation of power becomes particularly significant when the exercise of control changes the conditions through which further control and knowledge production become possible. A set of rules governing the allocation of computing resources can influence which projects are undertaken; those projects may generate technical expertise, usage records, revenues, or institutional legitimacy; and the resulting resources may affect who can modify the rules governing the computing system. This is a possible recursive mechanism. Its existence and direction cannot be inferred from a single observed allocation, because the relevant transformations depend on participant responses, external options, political institutions, technological changes, and the continuing legitimacy of the arrangement.

A conceptual distinction helps locate this problem. *Accumulated productive power* concerns enhanced capability to conduct or support knowledge-producing activity. *Accumulated regulatory power* concerns increased ability to determine the terms on which other participants pursue such activity. *Accumulated interpretive power* concerns stronger influence over the criteria through which research, contributions, or outcomes are rendered meaningful. The three can reinforce one another but may also diverge. A publicly funded laboratory can gain productive capacity under oversight that constrains discretionary exclusion. A privately financed open tool can become epistemically influential through widespread use while its licence grants broad independent rights. A formally collective organization can accumulate decision-making power in a narrow executive group despite retaining common ownership of the infrastructure.

Positive feedback may arise when dependence creates opportunities for additional control. For instance, a platform may acquire more users because it offers reliable shared interfaces, derive more resources from their use, and invest in services that strengthen the platform's coordinating role. Such development could increase public benefits, raise exit costs, or both. Analysing these possibilities requires a comparison of technological complements, governance obligations, contractual revisions, and opportunities for third-party innovation. Path-dependence research provides reasons to examine how increasing returns and earlier commitments shape later available alternatives [4, 22]; it does not establish that a dominant arrangement is inefficient, illegitimate, or historically inevitable.

The recursion may also change the location of effective generative dependencies. A locally useful research application can acquire common metadata formats and collaborative infrastructure; over the course of a historically reconstructed trajectory, it may become a shared methodological reference point. A theoretical convention can become less consequential when new instruments enable researchers to coordinate across previously incompatible formalisms. Collective organization can create alternative infrastructure and thereby change the leverage associated with an incumbent service. These cases illustrate a central feature of the multilevel framework: relative generative positions can be reconstituted through the very practices that they help make possible.

For empirical research, tracing such transformations calls for more than comparing asset shares or bibliometric indicators at two dates. Relevant materials may include earlier contracts, decisions about data portability, technical documentation, participation records, contested evaluative judgments, budget allocations, and accounts by contributors whose practices changed. Investigators should identify the mechanism linking a reconstructed configuration to another and separate observed changes in practices from changes in how the researcher describes them. When historical evidence is incomplete, alternative pathways should remain visible. The analysis is concerned with the contingency and transformability of power relations, including the roles of opposition, learning, institutional redesign, and unexpected technical developments.

Accumulated power can further affect the recognition of the power relation itself. Where institutional categories treat certain maintenance tasks as peripheral, the resources supporting those tasks may become increasingly difficult to justify through formal performance metrics. Where a platform controls both the relevant activity records and the terms of their interpretation, external assessment can require independent access to evidence. These scenarios motivate reflexive analysis of the researcher's evidential position. Documentary records supplied by a governing body, testimony from users, audits of technical systems, and independent observation can reveal different aspects of the same configuration. Contradic-

tions between them may be substantive evidence of contested authority rather than errors to be eliminated by methodological fiat.

11.7 Collective Agency, Contestation, and Institutional Revision

The final analytical object is the possibility of changing power relations through collective action and institutional revision. Knowledge-producing arrangements are sustained by practices of maintenance, consent, professional coordination, legal obligation, conflict, and adaptation. Participants may organize to negotiate employment conditions, require transparent evaluation, develop open alternatives, revise standards, contest data use, or redirect the circulation of returns toward shared productive infrastructures. Such responses are forms of agency whose effectiveness depends upon resources, rights, organizational capacity, and the feasibility of alternative arrangements.

Hirschman's distinction between *exit* and *voice* offers a useful starting vocabulary for the responses available to participants experiencing organizational deterioration [42]. In knowledge production, exit can mean moving a project to another infrastructure, changing research affiliation, or maintaining an independent implementation of a shared method. Voice can involve appeals, participation in governance, collective negotiation, public criticism, or revision of a technical standard. The two options may be complementary in some conditions and difficult to combine in others. Leaving an institution may preserve an individual's autonomy while weakening the capacity to reform collective infrastructure; remaining to contest an arrangement may impose costs that participants cannot sustain. Loyalty and other attachments can alter these judgments. These patterns must be reconstructed for actual groups and cannot be taken as uniform behavioural predictions.

Collective agency also depends on control over the prerequisites of participation. A nominal right to vote on technical standards may be difficult to exercise without access to the implementation, adequate notice, interpretive assistance, and time for deliberation. A documented appeal procedure may remain ineffective when the affected group lacks resources to assemble evidence or when meaningful remedy falls outside the decision body's competence. A claim of democratic governance should therefore be assessed through the distribution of agenda-setting, information, technical capacity, revision rights, and enforceable procedures, alongside the formal allocation of votes. Ostrom's comparative work on rules-in-use and institutional diversity supports attention to how operative arrangements differ from their abstract legal descriptions [71, 74].

Several kinds of institutional revision may be considered without presuming a preferred ownership regime. Technical changes can improve portability, interoperability, auditability, and independent reimplementation. Legal arrangements can clarify rights to use, preserve, and adapt shared resources. Governance reforms can broaden representation, provide reason-giving duties, establish independent appeals, or create enforceable responsibilities for maintenance. Funding arrangements can support otherwise invisible work such as documentation, replication, translation, training, and repair. Epistemic revisions can create procedures for reviewing the categories by which contributions are evaluated and represented. Their adequacy depends on the particular public purposes, institutional capacities, safety responsibilities, and interests at stake.

Countervailing power should also be studied for its potential unintended consequences. Fragmentation of a shared infrastructure may reduce dependence on one operator while increasing incompatibility and maintenance burdens. Decentralized governance can create participation opportunities while leaving technical knowledge concentrated among a small group. Restrictions on private appropriation may sustain common resources under some conditions and weaken financing for essential services under others. Public ownership can create obligations of accountability yet coexist with bureaucratic exclusion or rigid evaluation. A comparative political economy therefore asks how actual arrangements distribute productive capacities, secure legitimate authority, and enable contestation, rather than assigning normative outcomes by institutional label.

The relation between contestation and value circulation is especially important. A change in governance may return financial revenue to contributors, redistribute access to instruments, make professional

recognition more inclusive, or preserve the infrastructure needed for future collaboration. Other reforms may improve procedural legitimacy without materially changing the allocation of economic benefits. A situated assessment should trace the forms of value affected, the actors who have the practical opportunity to participate, and the continuation of the capacities upon which collective production depends. Justice, in this setting, concerns both the treatment of existing contributions and the conditions under which participants may continue to create and transform common productive arrangements.

Power thus enters knowledge-capital accumulation through material conditions, epistemic categories, allocation rules, and recursive dependencies between generative levels. Its consequences remain open to historical and institutional analysis. Concentrated authority can sustain coordination or contribute to exclusion; distributed arrangements can broaden collective capacity while retaining unequal practical influence. The conceptual task established here is to identify mechanisms, actual options, and processes of revision with enough specificity to distinguish these outcomes. The following section will examine the further conditions under which such power relations organize persistent extraction across generative levels.

12 Extractive Structures Across Generative Levels

This section develops criteria for identifying extractive structures within public knowledge production and examines how their operation may differ across relative generative levels. Its objective is to distinguish extraction from concentration, contractual remuneration, and the productive use of accumulated capital, while explaining how control over dependent knowledge-producing activities may permit recurring value capture. The discussion proceeds from structural conditions to application-level arrangements, shared methodologies and infrastructures, meta-knowledge and epistemic standards, dependency and substitutability, cross-level propagation, recursive accumulation, and institutional alternatives. Its arguments are conceptual and comparative. The examples describe hypothetical arrangements unless an existing study is expressly cited; determining whether a particular institution extracts value requires independent historical, organizational, and distributive evidence.

Knowledge production brings together inherited understanding, living labour, infrastructures, research methods, institutional authorization, and historically formed conventions of credibility. Participants can gain from the same productive arrangement in different ways: one may receive a wage, another a publication or accreditation, an institution a reusable data asset, and a wider public access to knowledge or services. Unequal benefits may reflect different contributions, negotiated terms, scarce expertise, public obligations, or advantages in bargaining power. An analysis of extraction must therefore reconstruct the relation by which some actors obtain benefits from the contributions and dependencies of others, including the effects upon continued productive capacity. A descriptive observation that one actor receives more than another does not, on its own, establish the relevant mechanism.

The analysis also distinguishes several senses of extraction. In political economy, the appropriation of surplus labour and the ability to obtain rents have different theoretical histories and empirical tests. In knowledge production, dependence can additionally take epistemic and institutional forms, such as control over classifications, standards of assessment, and the recognized channels through which knowledge becomes usable. These possibilities call for comparative precision. The present inquiry uses *extractive structure* as a provisional relational category for configurations in which an actor's durable command over a productive condition enables recurrent appropriation of benefits generated through distributed contributions, under terms that materially constrain contributors' access to, participation in, or reproduction of relevant productive capacities. The category identifies a mechanism for investigation; it does not replace labor-law, competition-law, moral-philosophical, or specifically Marxian criteria of exploitation.

12.1 Structural Conditions of Extraction in Knowledge Production

The first task is to differentiate ordinary interdependence from arrangements in which dependency becomes a channel for asymmetrical appropriation. An archive may impose fees to finance curation and

preservation; a journal may require payment for genuine editorial services; a software provider may sell access to computing resources it develops and maintains. Such arrangements can sustain activities whose real costs must be met. The distributive and normative questions emerge from the particular conditions governing pricing, contribution, participation, accountability, and alternatives. A recurring fee can be consistent with collective reproduction, while an apparently costless service can impose nonmonetary conditions that redirect knowledge, data, or decision authority toward its operator.

Within the present framework, an extractive configuration is provisionally indicated by a conjunction of several properties. First, participants make contributions that generate economic, epistemic, social, or institutional value, including contributions that are not formally recorded as labour. Second, one actor has a durable advantage in the effective control of a resource, right, procedure, or infrastructural interface on which those contributions depend. Third, that position supports recurrent appropriation or conversion of value on terms shaped by the dependence itself. Fourth, the arrangement restricts the capacity of contributing actors or communities to recover, contest, redirect, or reproduce a consequential part of the productive conditions. These properties specify research questions. Their evidential thresholds vary with the institution and the form of value under examination.

A useful distinction concerns *appropriation*, *rent*, *extraction*, and *exploitation*. Appropriation denotes a transfer or establishment of claim over a resource or benefit and can occur through consensual, public, cooperative, or coercive procedures. A rent may arise from control of a scarce asset or protected position, with its economic content dependent upon the counterfactual institutional and market arrangement. Christophers' political economy of rentier capitalism examines income and power associated with control of scarce assets, drawing particularly on the United Kingdom. Its geographical and sectoral findings require separate assessment before application to global knowledge infrastructures [16]. Extraction, as proposed here, concerns the reproduction of an appropriative advantage through asymmetric generative dependence and its effects upon the contributing system. Exploitation is a further theoretical or normative characterization requiring criteria such as surplus appropriation, unfair terms, domination, or impaired agency, depending on the analytical tradition. These terms may coincide in particular cases but should remain distinguishable in evidence and argument.

The Marxian concept of primitive accumulation retains its specific association with the historical formation of capitalist relations, including processes separating producers from the means of production [61]. Later forms of enclosure and institutional dependency may resemble particular mechanisms of separation without reproducing that history in every respect. Peekhaus uses primitive accumulation and alienation to interpret changes in academic publishing and its knowledge commons [76]. The present paper treats that interpretation as a substantial theoretical precedent and examines the additional problem of where the controlled condition lies within an evolving structure of knowledge-generative dependency.

Evidence of extraction should include the real distribution of benefits and obligations, the legal rights attached to assets, participants' practical alternatives, the costs of sustaining the productive resource, and the processes by which its governance can be changed. Evidence might show that a service provider earns substantial revenue while also subsidizing public access, or that a formally collective entity imposes effective exclusion through technical requirements and concentrated agenda-setting. The institutional label supplies context, not a verdict. A defensible account states which contributions have been made, by whom, how the terms of appropriation operate, which capacities are affected, and whether plausible alternative arrangements would alter those relations.

12.2 Extraction at Application and Output Levels

At relatively application-proximate levels, productive advantage may arise from control of a particular research output, a domain-specific dataset, a specialized instrument, a software service, or an interface through which users obtain results. These positions can support investment and maintenance through licensing, subscriptions, contracts, and the sale of complementary services. They can also become loci of appropriation when a provider systematically converts others' contributions into assets or revenues while controlling the terms on which contributors can continue using the resulting resource. An evaluation must

trace the activity and the rights involved rather than infer extraction solely from a proprietary licence.

Consider a hypothetical community that jointly develops a corpus for a particular research purpose. An intermediary supplies annotation software, servers, and project management under terms accepted by the contributors. If the agreement provides portable copies, documented rights, fair remuneration for services, and meaningful choices about future use, the intermediary's revenues may be compatible with collective knowledge reproduction. The same corpus could support a more extractive relation if the intermediary obtains exclusive control over contributed data and downstream derivatives, restricts meaningful export, and requires increasingly expensive access for the researchers whose work produced the corpus. The difference concerns contractual and practical powers, alternative arrangements, and effects on continued research capacity. The corpus itself need not become less publicly visible for its generative use to become more asymmetrically controlled.

The conversion of unpaid or undervalued participation into marketable assets also requires specific attention. Contributors may produce annotations, evaluate systems, supply error reports, improve documentation, or perform quality-control tasks essential to the apparent autonomy of a digital service. Gray and Suri's study of *ghost work* documents forms of often obscured human labour supporting commercial digital systems [37]. Their findings do not show that every instance of user feedback constitutes exploitation. They motivate inquiry into contractual status, compensation, recognition, conditions of work, and the ability of contributors to benefit from or contest subsequent commercialization. A corresponding knowledge-production case may involve research assistants whose interpretive or maintenance labour becomes invisible in the representation of the final output.

Control of distribution can compound the problem. A publisher, repository interface, or application marketplace may enable the discovery and reuse of results while also determining ranking, promotion, access conditions, and the visibility of contributors. Noble's analysis of search engines documents how discoverability can be structured by commercial and discriminatory logics [68]. An extension to knowledge-producing environments asks whether particular systems of ranking or presentation affect the recognition of researchers, the availability of competing accounts, or the demand for specific research products. Such an inference requires investigation of the actual interface and its social setting. Control over a channel of discovery and control over the content of knowledge are distinct, even though they may interact.

Application-level positions may appear close to the leaves of a generative grammar, but their systemic significance cannot be read from that analogy alone. A specialised application with widely available substitutes may exert limited dependency leverage. An application operating as an obligatory gateway for a regulated, safety-critical, or technically integrated workflow may support a much broader set of activities. Furthermore, an initially local application may acquire shared metadata conventions, authentication mechanisms, or an accepted evaluation benchmark. The application can then participate in the constitution of method-level and infrastructural conditions. These changes warrant historical reconstruction rather than assignment to a permanently fixed level.

A comparison of application-level arrangements should therefore examine the separation between the right to obtain outputs, the right to inspect inputs and methods, the ability to migrate elsewhere, and the authority to revise the conditions of further production. A contract may grant ownership of particular results while leaving shared methods open to independent implementation. Conversely, a publicly readable output can depend on a privately controlled pipeline that only a small group can operate. The distribution of capacity across these dimensions shapes the possibilities for appropriation and continuing participation. Monetary revenues and publication counts describe some outcomes; they do not disclose the entire structure of dependence.

12.3 Extraction Through Research Infrastructures and Methodologies

Shared infrastructures create a second class of dependency. They include computational systems, research repositories, communications services, physical instruments, preservation arrangements, identity infrastructures, and the administrative or professional activities that sustain them. Their generative sig-

nificance derives partly from the range of otherwise distinct projects that can make use of their services. Frischmann's analysis of infrastructure and shared-resource value supports inquiry into the social benefits that may exceed the operator's directly monetized returns [34]. The economics and institutional governance of infrastructure depend on the resource, its capacity constraints, and obligations concerning safety, confidentiality, durability, and equitable access.

Potential extraction can occur when a provider controls a shared interface and derives recurring benefits from the dependence of many contributors. Imagine a hypothetical public research repository whose maintainers are unable to export metadata, preserve persistent identifiers independently, or negotiate the uses of the records contributed by their institutions. A provider might offer reliable services while exercising a unilateral power to increase charges, condition access on new data rights, or prioritize downstream analytics products. The researchers' published outputs remain distributed, but the condition through which those outputs can be found, compared, and preserved becomes a point of concentrated authority. The normative interpretation depends on contract terms, cost evidence, regulatory constraints, governance options, and the quality of feasible alternatives.

Methodological dependencies are related yet distinguishable. A proprietary validation procedure may become essential because a profession, regulator, funder, or research community adopts it as a condition for acceptance. Under some arrangements, licensing revenues remunerate the creation of a reliable procedure and its continuing quality assurance. Under others, exclusive control over a required test can permit revenue capture while restricting independent replication and critical modification. The relevant locus of power lies partly in the method, partly in the institution that requires its use, and partly in the technical and professional capacities necessary to implement it. The economic character of a single licence does not reveal the whole arrangement.

An additional problem concerns complementarity. Access to a nominally open dataset can be of limited practical use without specialised computation, documentation, standards-compliant software, or trained personnel. A publicly funded laboratory may release its results under an open licence while commercial or institutional actors gain disproportionate benefits because they alone possess these complements. Such asymmetry could reflect prior investment, accumulated expertise, or unequal starting resources; it would become an extractive relation only if a demonstrated mechanism links those positions to appropriative constraints upon contributing groups. Intellectual monopoly research, including Rikap's analysis of control over knowledge and data and of connections to university and open-source production, offers a relevant political-economic interpretation [80]. The present account generalizes neither her empirical claims nor a uniform inference from private investment to extraction.

Infrastructure can also distribute benefits productively across institutions. Centralized preservation, shared compute scheduling, and jointly maintained methods may reduce duplication and expand access to specialized capacities. A relatively concentrated operator may be subject to enforceable access conditions, transparent pricing, shared governance, independent auditing, and portability duties. A decentralised set of owners may create licensing fragmentation or incompatible standards. Heller and Eisenberg's biomedical anticommons analysis proposes a mechanism through which multiple exclusion rights may obstruct combinations of research inputs [39]. It identifies a plausible institutional risk; the existence and magnitude of actual obstruction require evidence from the relevant field and period. Thus the number of owners, taken alone, supplies an inadequate measure of the generative opportunities available to a research community.

A situated comparison should identify the real operating costs of infrastructure, responsibility for failures, interoperability at both technical and institutional levels, and the capacity to sustain service independently. Where an apparent monopoly reflects unusually difficult maintenance, an alternative arrangement may require new funding and governance rather than a simple change in title. Where switching costs are deliberately enlarged through contracts or technical restrictions, analysis should locate the practices that produce those costs. The inquiry concerns the combined configuration of resources, legal powers, practical capabilities, and institutional responsibilities through which recurrent extraction may become possible.

12.4 Extraction Through Meta-Knowledge and Epistemic Standards

Meta-knowledge refers here to historically situated capacities, rules, and practices through which knowledge is represented, evaluated, interpreted, classified, and rendered reproducible across contexts. It can include taxonomies, methodological grammars, epistemic criteria, disciplinary conventions, and institutional processes for conferring authority. These elements occupy relatively deep generative positions where many activities depend on them, but their locations are contingent upon the research domain and the history selected for reconstruction. Their governing authority may be formal, professional, technical, or distributed across complementary institutions.

Control over such structures may create a qualitatively distinctive capacity for appropriation. An actor able to specify the categories under which contributions become visible may influence whose work is counted; a body that controls widely accepted validation criteria may influence which research agendas can obtain recognition; an infrastructure operator that defines reusable evidence formats may condition the options available to downstream projects. These powers can alter the very terms on which participants establish the value and legitimacy of their work. They may thereby affect economic revenues, professional opportunities, intellectual autonomy, and the continued reproduction of alternative knowledge traditions.

The sociology of standardization provides useful caution. Timmermans and Epstein examine how standards are formed and maintained, the practical difficulties of making them work, resistance, and their heterogeneous consequences [88]. Standardization can create comparability, coordination, and public accountability. Its effects depend upon who participates in developing standards, whose practices are represented by the categories, how exceptions are recognized, and what mechanisms exist to revise the standard. Standard-setting authority becomes a possible channel of extraction when a durable dependency on the standard supports an appropriative advantage while limiting contributors' power to maintain or transform their own productive conditions.

Consider a hypothetical cross-disciplinary evaluation infrastructure that defines one classificatory ontology as the necessary language for evidence submission. A participating research community may benefit from comparability and collective search. Other communities may need to spend substantial effort translating their concepts, often with loss of distinctions that matter to their inquiry. If the governing institution then appropriates the resulting encoded records and uses participation in the system to impose exclusive derivative rights, the situation combines epistemic conversion with resource appropriation. Investigation would need to identify the concrete costs of translation, decisions concerning ownership, actual routes of appeal, and the possible benefits of common coordination. Differences between epistemic traditions should not be collapsed into an assumption of simple one-to-one translation.

Meta-knowledge extraction also may occur without visible price increases. A narrow set of accepted evidence types might redirect labour toward codifiable outcomes at the expense of inquiry that contributes to public understanding through other methods. A knowledge-sharing platform can recognize particular forms of contribution while leaving oral histories, translation, contextual interpretation, or maintenance weakly represented. Studies of epistemic injustice and the co-production of social and knowledge order furnish relevant conceptual resources [33, 47]. Applying them to particular institutions requires care: exclusion from a specific classification can be appropriate for its limited purpose, while systematic denial of credible participation can carry wider epistemic and political significance.

The proposed concern with deep-level extraction should be stated as a conditional hypothesis rather than a general law. A foundational rule with many apparent descendants may permit relatively little control if the rule is openly specified, multiple implementations are effective, rival epistemic traditions can cooperate, and affected participants possess credible governance rights. Conversely, an application-proximate discovery service may acquire enormous leverage when it becomes the principal means through which diverse forms of knowledge are found. The determining issues include effective dependency, available alternatives, the control of interfaces, and the possibility of revising the structure of production itself. In this respect, depth identifies a location for inquiry, whereas extractive leverage is a relational consequence to be investigated.

Table 13: Diagnostic dimensions of potentially extractive dependencies across generative levels. The examples indicate mechanisms to investigate; they do not assign extraction to an ownership regime or level.

Analytical position	Possible appropriation and control mechanisms	Required evidence and countervailing conditions
Generated outputs and applications	Licensing, data capture, derivative rights, terms of distribution	Contributor contracts, compensation, portability, rival applications, use restrictions
Methodologies and technical protocols	Certified testing, method access, validation gateways, training dependencies	Independent replication, licensing terms, accepted substitutes, revision rights
Shared infrastructures	Charges and data rights tied to indispensable interfaces, storage, or preservation	Actual service costs, export capacity, public obligations, continuity and governance
Meta-knowledge and standards	Classification, credibility criteria, agendas, and recognized forms of evidence	Participation, alternate frameworks, translation losses, appeal and standard revision
Cross-level arrangements	Conversion of returns from one site into control of conditions elsewhere	Ownership histories, contractual connections, reinvestment flows, dependency changes

12.5 Generative Depth, Dependency, and Substitutability

A comparative analysis of extraction requires attention to the structure of dependencies. Generative *depth* is a relative position in an analytical reconstruction of the conditions supporting a set of activities. Dependency concerns the extent to which those activities actually rely upon a particular condition; substitutability concerns the practical availability of other conditions capable of supporting an appropriate range of productive ends. Control concerns the rights and effective powers through which a participant may regulate that condition. These dimensions can vary independently. A deeply located representation convention may be easily replaceable; a particular application may be difficult to replace because it is embedded in legal procedures, archived work, or trained expertise.

The relevant counterfactual is therefore richer than imagining the disappearance of an abstract component. Researchers should ask what feasible alternatives a community could actually implement, with which investments, delays, risks, and distributive consequences. A theoretically available replacement may require equipment, skills, collective coordination, or permissions that affected researchers do not possess. An institution may authorize exit in law while retaining technical formats, identity records, and historical metadata that make exit practically disruptive. On the other hand, an expensive replacement may still be achievable through shared investment or reciprocal access agreements. A defensible account of substitutability includes the actors' capacities and the governance of transitions, not merely a catalogue of products said to perform similar functions.

Dependency has several analytically separate dimensions. *Operational dependency* concerns the immediate performance of a task, such as running a computation or obtaining materials. *Epistemic dependency* concerns comparability, validation, interpretability, and recognized credibility. *Institutional dependency* concerns permissions, contracts, funding conditions, and accreditation. *Historical dependency* concerns inherited investments, training, archives, and practices that shape the feasibility of transformation. A single infrastructure can participate in each dimension. Their relative importance varies across scientific, humanistic, educational, and civic domains of inquiry.

Table 13 organizes the evidence required for an inquiry into extraction. It is designed to be used in comparisons of concrete institutions rather than as a scoring instrument. An investigator might begin with an observed restriction of access and reconstruct which rights, infrastructures, rules, and productive capacities make that restriction consequential. The same observed result can arise through different causal paths. A price increase may reflect costly preservation or the exercise of a protected position. Low uptake of a method may reflect incompatible research objects, insufficient training, or access barriers created by institutional control. Explanations should be compared against independent records and accounts from differently situated participants.

A related difficulty concerns the population whose dependencies are counted. A standard that serves one scientific community well may marginalize relevant evidence in another. A globally deployed re-

search platform can offer valuable services to well-resourced institutions while creating disproportionate switching costs for smaller contributors. The assessment of generative importance therefore depends on the domain of production, the groups represented, and the purposes selected for analysis. The paper does not propose a universal ranking of disciplines, epistemic methods, or types of contribution. It proposes reconstructing the relevant dependencies and the possibilities for their revision.

The proposition motivating the multilevel framework can now be stated with appropriate scope. Where comparable levels of appropriative control operate upon resources of differing generative positions, the resource with broader effective dependency, weaker substitutability, and fewer rights of independent revision may permit more extensive propagation of extractive effects. Greater assigned depth is neither sufficient nor necessary for this outcome. Formal representation of this conditional proposition will require carefully specified counterfactual tasks and capability measures; The present section supplies the conceptual criteria, while the following formal section will address their representational limits. The claim remains a hypothesis about mechanisms, open to counterexamples and historical testing.

12.6 Cross-Level Propagation of Extractive Relations

A comparison of apparent bottlenecks should also distinguish a jointly executable restriction plan from a set of separately controllable access gates. Equation 35 formalizes the former. Where only a subset of substitution routes has been observed, Proposition 13.3 shows that the resulting dependency score can be an upper bound rather than a point estimate of actual vulnerability. These qualifications constrain any inference from structural depth to extractive power.

Extractive relations become particularly consequential when their effects move between generative positions. A source of revenue at the application level may finance control over a shared infrastructure. Authority over an infrastructure may shape the methods and data formats available to researchers. Control of a widely used classification may influence which applications attract funds, recognition, and further contribution. These connections should be represented as possible transformations mediated by decisions, material resources, professional practices, and institutional rules. A structural diagram can clarify pathways, but it does not establish that a given pathway occurred.

One hypothetical trajectory begins with collective production of openly available research records. A service provider develops a widely useful search interface and receives financial support from users. These revenues permit investment in proprietary analytical tools. If the service subsequently acquires contractual control over persistent identifiers and metadata exports, its position may extend from an application service to a shared infrastructural condition. Should evaluative institutions then adopt the provider's analytics as a dominant criterion of research recognition, the same actor's influence may also reach an epistemic-standard-setting position. The resulting arrangement could provide substantial coordination benefits; it could also support extractive leverage if participation requires surrendering rights or labour under terms the contributing community cannot meaningfully revise.

A different trajectory runs from meta-knowledge toward particular outputs. A classification regime might make only certain kinds of evidence eligible for publication, grants, or educational certification. Researchers may redirect training, data collection, and project design to meet these terms. Resulting products then strengthen the institution's claim that its categories capture the relevant knowledge field. The mechanism is recursive only if the outcomes of the dependent production feed into the maintenance or intensification of the initial rule. Historical investigation must document these connections rather than infer them from the coexistence of a classification and a subsequent pattern of publication.

The circulation of heterogeneous value complicates propagation. Income may be extracted through licensing fees; symbolic value through the concentration of citation credit; data value through exclusive access to behavioural or research records; institutional value through control over accreditation; epistemic value through privileged authority to classify or validate. These forms can be converted under particular arrangements, but their conversions do not imply commensurability. A university might obtain higher prestige through adoption of a proprietary infrastructure while its researchers incur continuing costs. Contributors may gain visibility at the price of diminished control over subsequent uses of their

material. Other arrangements may return financial revenues to public preservation, enhance collective recognition, or enable new epistemic alternatives. Identifying which conversions actually occur requires the reconstruction of budgets, labour arrangements, licences, governance decisions, and social practices.

Couldry and Mejias theorize data colonialism as a process by which infrastructures for capturing social data enable commercial appropriation of ordinary human activity [19]. This is an interpretive political-economic account; identifying an instance of the proposed mechanism requires case-specific evidence of data collection, authorization, use, and benefit capture. Their framework offers one interpretation of value conversion between participation, informational resources, and capital accumulation. An extension to research infrastructures may be instructive when scholarly or civic contributions are converted into exclusive data assets; the analytical connection must remain conditional and case-specific. Such arrangements may also involve confidentiality, consent, and legitimate constraints on data access that cannot be reduced to a preference for unrestricted circulation.

Propagation may be attenuated or interrupted. Institutional obligations can prevent an operator from conditioning scholarly access on derivative rights. Technical interoperability can make alternative providers viable. Independent archives, transparent evaluation practices, collective bargaining, public investment, and contestable standards can disperse dependencies. A new method may make an established input obsolete, while a successful application can generate competing infrastructures. These possibilities are integral to the model. Relational dependencies develop within historically changing environments whose trajectories may be reconfigured by collective agency and unforeseen discoveries. A claim of inevitable expansion from deeper control to universal domination would exceed what the framework supports.

12.7 Recursive Extraction and the Concentration of Capital

Recursive extraction concerns situations in which benefits obtained from controlling a generative condition are used to strengthen or extend the conditions that make further appropriation possible. The recurrence may involve money, intellectual property, technical expertise, data accumulation, professional authority, reputational standing, or influence over institutional standards. Its characteristic feature is the feedback between appropriative advantage and the future configuration of productive dependence. The presence of repetition alone does not establish the mechanism. Historical evidence must identify links connecting an earlier allocation of benefits to a later increase in effective control, and account for alternative explanations.

A simple hypothetical account illustrates the distinction. A research platform receives fees from institutions for curation, interoperability, and preservation. A share of the revenue finances an accessible public archive, staff training, independent export interfaces, and durable community governance. The platform becomes larger and more capable while its contributors retain substantial rights and alternative means of productive participation. Here recursive accumulation may expand knowledge capital without satisfying the proposed diagnostic conditions of extraction. In a second hypothetical configuration, the same revenue is used to purchase exclusive rights to complementary datasets, restrict technical portability, influence evaluation standards, and bind contributors to the platform. Where those moves support recurring value appropriation while narrowing the contributors' capacity for independent production, the account describes a possible recursive extractive mechanism.

The mechanisms may coexist. Investment in a better shared interface can increase efficiency and widen participation while simultaneously strengthening an operator's bargaining position. A reputable validation standard can improve reliability yet become costly to contest. A public university can build widely useful infrastructure while allowing decision rights to concentrate in a small administrative group. The analysis should therefore avoid a binary classification in which an entire institution is either generative or extractive. Particular rights, processes, and distributions can be evaluated separately, including their interactions and the historical contingencies that bind them together.

The growth of the controlled asset's market value can be a consequence of such feedback, yet accounting value is only one indicator. Recursion may instead appear in the decreasing feasibility of independent

verification, the migration of epistemic authority toward one framework, the accumulation of training commitments that tie researchers to a provider, or dependence on a single route for legitimizing results. Rikap's treatment of intellectual monopoly and Christophers' account of rentier relations provide distinct theoretical accounts of links between asset control, income, and institutional power [80, 16]. The present analysis adds an explicit question about the changing location and significance of those assets within knowledge-generative dependencies; neither author is claimed to have established the proposed multilevel representation.

Concentration also admits several forms. *Asset concentration* concerns ownership or custody of resources. *Decision concentration* concerns authority over their use or revision. *Epistemic concentration* concerns control of the criteria by which knowledge and contribution are recognized. *Dependency concentration* concerns the extent to which diverse productive activities come to rely upon a comparatively restricted set of interfaces or institutions. These forms are related but empirically separable. A large public archive might hold extensive data while offering open governance, transparent policies, and strong rights of independent replication. A modest privately owned technical standard might influence a large fraction of a field's practice. A method that appears dominant within one archive could coexist with several effective alternatives elsewhere.

A longitudinal empirical design would trace rights and decisions through a succession of documented institutional configurations without assuming a privileged global time coordinate. Evidence could include revisions of licences, procurement contracts, governance minutes, staff and user testimony, data-export records, changes in access conditions, documentation of alternative implementations, and accounts of the costs borne by contributors. Such records permit tests of whether appropriation financed new productive public goods, increased exclusivity, or combined these trajectories. The theoretical problem concerns the conditions of continuation: whether a particular configuration tends to broaden the capabilities available to multiple actors or to make further knowledge production increasingly contingent upon concentrated permission.

12.8 Structural Alternatives and the Reconfiguration of Dependencies

The final subsection examines institutional and technical transformations that may alter extractive dependencies without presupposing a single preferred ownership arrangement. Possible interventions include enforceable interoperability requirements, independent preservation, alternative funding mechanisms, collective governance, procedural review of standards, recognition of maintenance labour, equitable contracts, and shared decision rights concerning downstream uses of contributed resources. Their consequences depend upon context. An intervention that broadens access may create additional maintenance costs; an open licence may be ineffective without training and compute; dispersing decision rights may reduce concentrated control while increasing coordination demands.

One class of alternatives concerns the portability of productive conditions. Exportable records, documented formats, independent implementations, and transferable credentials can make exit practically meaningful. Portability has institutional dimensions: participants may need rights to the relevant records, sufficient resources to operate replacements, and collective capacity to coordinate migration. Interoperability therefore concerns real options for continued production rather than the mere existence of a technical specification. It can preserve the ability to change providers while retaining a compatible infrastructure, or support plural infrastructures whose users exchange knowledge under agreed conventions.

A second class concerns the governance of deep-level generative rules. Participatory standard-setting, documented appeals, procedures for accommodating heterogeneous knowledge traditions, and periodic review can create possibilities for contesting the categories through which contribution is recognized. Such procedures require material support and credible accountability. Consultation alone may leave authority unchanged when the consulted groups cannot obtain reasons, propose revisions, examine consequences, or seek remedy. The sociology of standards indicates the importance of their formation, implementation, and contestation in particular social contexts [88]; the design of any concrete governance arrangement should be assessed in relation to those contexts.

A third class concerns the circulation of value. Royalties, service fees, public grants, community funds, labour compensation, authorship recognition, shared data rights, and financing for repair can distribute benefits and reproductive obligations in different ways. Generative justice provides a relevant account of value recirculation toward its creators [26]. In knowledge production, that question extends to the long-term maintenance of collective capabilities and the right to revise their supporting structures. Returning revenue to an institution can be socially useful, yet a specific study should establish whose contributions support that revenue, who governs its allocation, and whether those contributors can sustain independent or collective participation.

The institutional contrast remains open. Market enterprises may face competition, fiduciary duties, or enforceable public obligations; commons arrangements may distribute authority through collective rules and shared assets; public organizations may use statutory duties and legislative oversight; cooperative structures may combine shared economic participation with specialized delegated administration. Each can support accumulation and expansion of knowledge capital. Each can also encounter concentrated practical authority, poorly recognized labour, exclusionary classifications, or weaknesses in reproduction and accountability. A comparative analysis should identify the operative rights and power relations within the institution rather than treat its formal designation as determinative.

The availability of alternatives may itself become an object of collective creation. A group affected by dependence on a proprietary platform can build a shared implementation, negotiate an interoperable interface, or establish a public service with transparent governance. Such initiatives require accumulated knowledge, organized labour, infrastructure, coordination, and continuing resources; they therefore constitute further episodes of knowledge-capital formation. Their effects on extractive leverage may unfold through changes in the dependency structure rather than through redistribution of existing revenues alone. At the same time, an alternative may inherit dependencies upon standards, computational facilities, or funding arrangements that require separate analysis. Structural change can relocate a bottleneck as well as relieve it.

The proposed extractive mechanism is conditional: a specified actor must command relevant productive gates, value must be appropriated through identifiable arrangements, and the consequences for contributors' feasible production and reproduction must be established against credible alternatives. Relative generative depth can enlarge the scope of a mechanism when dependencies extend across levels, but depth alone establishes neither control nor extraction. Section 13 translates these distinctions into typed relations and counterfactual comparisons, with explicit limits on inference from incomplete route enumeration or disputed valuation.

13 A Relational Formalism for Multilevel Knowledge Capital Accumulation

The present section develops a preliminary formal language for analysing knowledge-capital formation, expansion, ownership, and value circulation across relative generative levels. Its purpose is to make the preceding political-economic distinctions operationally explicit, to exhibit the assumptions under which relations of dependency can amplify control, and to identify which further observations would be required for empirical interpretation. The construction proceeds through representational assumptions, typed generative dependencies, historical configurations, productive capabilities, heterogeneous circulation, differentiated rights and power, dependency-sensitive extractive leverage, recursive change, and formal limitations. Definitions and derived results are internal to the proposed representation. They neither establish an exhaustive ontology of knowledge nor license a general inference from a mathematical dependency to a historical relation of exploitation.

A knowledge-producing system may be represented through a finite or locally finite collection of artifacts, procedures, infrastructures, activities, institutional positions, and recorded interactions. Such a collection is a researcher's specification of an analytical boundary. Its useful resolution depends on the problem at hand: a laboratory study may require separate treatment of devices, protocols, personnel

and validation tasks, whereas an inquiry into a scholarly publishing system may distinguish repositories, editorial decisions, standards, contractual rights and maintenance work. The same historical activity admits multiple admissible representations, and changing the granularity can alter calculated levels or dependency scores. It is therefore necessary to record representational choices and their evidential limits alongside formal outputs.

13.1 Representational Scope and Formal Assumptions

The basic object of analysis is a *historical knowledge-production configuration*, denoted by $\mathcal{H}$. A configuration comprises a typed family of relationally connected objects, the activities for which those objects serve as conditions, and the institutional arrangements governing their use. For a finite case-study representation, Equation 1 specifies the proposed data structure.

$$\mathcal{H} = (V, E, A, Q, P, R, X, I), \quad (1)$$

Here V is a set of represented generative components; E is a set of typed dependency relations; A is a set of actors or organized collectivities; Q is a set of production activities or tasks; P specifies practices and production protocols; R records rights, access arrangements and effective powers; X records value-generating and value-circulating events; and I denotes interpretive, evidential and institutional context. The letters distinguish types of information rather than independent substances. For example, a publicly operated database may appear in V as an infrastructure component, in R as the object of several authority relations, and in X as a site through which usage benefits and maintenance burdens circulate.

The representation makes four provisional assumptions. First, the boundary and unit of analysis is declared; components within V are selected for an explanatory purpose. Second, a dependency between components is interpreted relative to a specified productive activity and institutional context. Third, productive access and capacity can be assessed through at least a partial description of feasible activities. Fourth, rights, valuation conventions and observational practices may vary with the configuration. In this way, model revision and structural change can be distinguished conceptually. The formalism permits either phenomenon; evidence is required to identify which has occurred in a concrete study.

Definition 13.1 (Representational adequacy). A representation $\mathcal{H}$ is *adequate relative to a research question* when its selected components, dependencies, rights, valuation conventions and observations are sufficiently explicit to evaluate the comparisons claimed in that inquiry, including their relevant alternatives and uncertainties.

Definition 13.1 is deliberately local. A representation may be adequate for tracing the circulation of maintenance funding and inadequate for interpreting a community's understanding of epistemic authority. Likewise, a valid description of a license may leave unresolved whether participants possess sufficient expertise and practical access to exercise the permitted rights. This distinction guards against conflating formal permissions with realizable freedoms or institutional legitimacy.

The choice of compositional and relation-based representations is compatible with formal approaches to resource theories and applied category theory, which provide mathematical languages for combining processes and constraints [28]. The present paper draws upon their representational possibilities without assuming that knowledge-producing institutions satisfy an established categorical semantics. Empirically specified social relationships, especially relations of obligation and interpretation, would require independent evidence and justification.

13.2 Generative Dependency Structures and Partial Orders

A dependency relation may require several components jointly. For example, an analysis can depend on a public dataset, a statistical method, available computing resources, and a validation procedure. An ordinary directed graph with single-source edges can obscure such conjunctions and the existence of alternative productive routes. The provisional model therefore employs a directed, typed hypergraph.

Each hyperedge e contains a finite prerequisite set $S_e \subseteq V$, a target component or activity $y_e \in V \sqcup Q$, and a dependency type κ_e , where $\sqcup$ denotes a disjoint union. Equation 2 gives the admissible form.

$$E \subseteq \mathcal{P}_f(V) \times (V \sqcup Q) \times \mathcal{K}, \quad (2)$$

The type set $\mathcal{K}$ can distinguish technical, informational, methodological, legal, organizational and evaluative dependencies. A represented relation means that its prerequisite family has a specified role in supporting an output or activity under some context. It does not establish an unqualified necessity relation. In particular, multiple hyperedges with the same target may encode alternative ways of conducting an activity.

An activity-specific feasibility predicate $\phi_{\mathcal{H}}(a, q; w)$ records whether actor a can execute task q under an admissible productive arrangement $w \in W_a(\mathcal{H})$. An arrangement includes a component-input set $B(w) \subseteq V$ together with the relevant permissions, expertise, resources, maintenance commitments, and coordination conditions. A component-only support test is consequently a projection of this richer feasibility assessment, not a distinct use of the same predicate with an incompatible input type. Where evidence permits, feasibility is coded as 1 or 0 under a declared task-quality threshold. Where the evidence is insufficient, its status is recorded as unknown outside the binary evaluation; an undocumented route is not thereby treated as demonstrably infeasible. Numerical computation presupposes an adequate local specification.

The representation admits a relative *generative precedence* relation when prerequisite connections are established for a given class of activities. Yet cycles arise naturally: research instruments are refined through empirical results; methodological concepts are reconstructed through applications; and standards change in response to the practices they enable. A general precedence relation need therefore be neither acyclic nor total. For analyses requiring a partial order, one may first condense strongly connected dependency components and then take reachability on the resulting acyclic graph. This condensation expresses a chosen abstraction of reciprocal support, not a proof that the original relations are temporally simultaneous or ontologically identical.

Let $[v]_{\mathcal{H}}$ denote the equivalence class of component v in such a condensation, when that operation is warranted. Equation 3 defines a relative order through reachability.

$$[v]_{\mathcal{H}} \preceq_{\mathcal{H}} [w]_{\mathcal{H}} \iff \text{a dependency path connects } [v]_{\mathcal{H}} \text{ to } [w]_{\mathcal{H}}, \quad (3)$$

where the empty path establishes reflexivity and path orientation follows prerequisite-to-target support. The relation in Equation 3 has the properties of a partial order on the condensation classes. However, a hypergraph requires specification of how conjunctive source sets are interpreted when constructing the auxiliary directed graph. The resulting order is relative to that projection and the chosen task scope. Its validity as an account of effective dependency is assessed independently.

The expressions *deeper generative level* and *nearer application level* may be useful when a component supports several layers of tasks in such a projection. They remain qualitative summaries of a relational position. A component at a short graph distance from applications may be a difficult-to-substitute operational bottleneck; a formally upstream principle may have little effective influence where alternative methods are readily usable. Generative distance, downstream reach, irreducible dependency and institutional control are consequently retained as separate observables.

13.3 Relational Histories and the Formation of Productive Conditions

Knowledge-capital accumulation is historically constituted. An archive draws upon prior practices of collection, classification, funding and preservation; an experimental method may depend on inherited instruments and communities of validation; and an organizational capability often develops through continued coordination. For present purposes, a history is represented by a structured family of configurations connected by admissible transformations. The transformations may be only partially ordered, and the model need not posit one global clock, a privileged present, or a universal sequence of development.

A represented transition τ connects a configuration $\mathcal{H}$ to a configuration $\mathcal{H}'$ by recording specified changes in components, feasibility conditions, institutional authority, and circulation arrangements. Equation 4 describes its formal signature.

$$\tau : \mathcal{H} \longrightarrow \mathcal{H}', \quad \tau \in \text{Adm}(\mathcal{H}, \mathcal{H}'), \quad (4)$$

Here Adm is a declared family of admissible transformations. The arrow in Equation 4 represents a morphism of the selected analytical model. It should not be read as an ontological assertion about a unique direction of time. A sequence of transformations may correspond to an observed historical record, a hypothetical continuation, or a counterfactual reconstruction, and these statuses must be labeled distinctly. The emergence of new actors, activities, dependency types or valuation conventions can change the objects available for comparison.

To differentiate a productive transformation from a transformation of its representation, one may specify an observation mapping $O_{\mathcal{H}}$ and a documentation process ρ . An empirical claim that productive conditions changed requires evidence for changes in practices, outcomes, access or institutional relations, rather than the sole substitution of $O_{\mathcal{H}}$ by a new observation scheme. A change in the perceived status of a research contribution can be causally consequential, but the mechanism lies in the institutional response to the new interpretation, not merely in the analyst's redescription.

Initial capital formation can be represented as a change in the availability, coordination or endurance of productive conditions. Primitive accumulation in the historically specific Marxian sense requires further identification of processes such as separation, enclosure and changed relations of command [61]. The same formal transition signature can describe a newly funded public archive or the privatization of its access conditions. These transformations differ in their historical content; the equations do not erase that difference. A comparative inquiry must identify who provided inherited resources, who contributed labour, and how the resulting capacities became available or restricted within the transformed configuration.

13.4 Capital Accumulation and Generative Capability Operators

The central operational question concerns the range of productive activities actors can perform under specified conditions. Let $\mathcal{Q}$ be a common task universe for a locally comparable family of configurations, and let $W_a(\mathcal{H})$ denote the admissible combinations of labour, expertise, resources and coordination through which actor a can act. Equation 5 defines the actor's represented capability set.

$$\text{Cap}_a(\mathcal{H}) = \{q \in \mathcal{Q} : \exists w \in W_a(\mathcal{H}) \text{ with } \phi_{\mathcal{H}}(a, q; w) = 1\}. \quad (5)$$

Here w denotes the admissible productive arrangement defined above, including component access and collective arrangements rather than personally owned resources. The predicate in Equation 5 is evaluated only for specified actor–task–arrangement triples; unobserved feasibility requires an explicit missing-evidence designation. The equation is an analytical account of feasible performance, not a claim that people or their skills can be owned as capital. Some capabilities may be distributed among teams and realized through cooperation; the relevant actor a can accordingly be a collective, with internal inequalities investigated separately. Under incomplete observation, the set of independently confirmed feasible tasks, $\widehat{\text{Cap}}_a(\mathcal{H})$, supplies at most a documented lower bound on the capability set in Equation 5, assuming the positive feasibility assessments are sound. Failure to observe a feasible arrangement does not establish a negative capability finding. A claim of equality requires a sufficiently complete and validated evaluation of the candidate productive arrangements.

A transition from $\mathcal{H}$ to $\mathcal{H}'$ can enlarge, preserve, redirect or reduce capability sets. Under a fixed task universe and compatible criteria, Equation 6 compares expansion and contraction without imposing a scalar measure.

$$\begin{aligned} \text{Gain}_a(\tau) &= \text{Cap}_a(\mathcal{H}') \setminus \text{Cap}_a(\mathcal{H}), \\ \text{Loss}_a(\tau) &= \text{Cap}_a(\mathcal{H}) \setminus \text{Cap}_a(\mathcal{H}'). \end{aligned} \quad (6)$$

The simultaneous presence of gains and losses matters. A new standard may make research across institutions easier while reducing the practical usability of older formats; a new platform may enable unfamiliar types of analysis while increasing dependence on its operator. A statement about aggregate expansion requires a separate ordering, weighting convention or empirical outcome measure. Different communities may evaluate the relevance of tasks differently, and the distribution of gains and losses can matter independently of their number.

Knowledge capital is treated here as an historically accumulated configuration of reproducible productive conditions that supports such capability sets. An accumulation process is a set of admissible transformations through which material, organizational, methodological or epistemic resources become more durable, combinable or effectively usable. Capitalization further involves specified institutional relations that convert resources or outcomes into appropriable claims, income streams or strategically controlled positions. The two processes can coexist while remaining analytically distinguishable. A publicly shared method may expand several actors' capability sets without granting an exclusive claimant control over its deployment. An exclusive service can accumulate infrastructure while simultaneously enlarging some tasks and constraining others.

A provisional generativity operator $\Gamma_{\mathcal{H}}$ assigns to the configuration and to eligible actors the set of admissible transformations of productive activities and, where relevant, transformations of their conditions. Equation 7 states the operator's domain and codomain at this abstraction level.

$$\Gamma_{\mathcal{H}} : A \longrightarrow \mathcal{P}(\text{Adm}_{\mathcal{H}}). \quad (7)$$

The operator in Equation 7 extends the feasible-task representation: an activity may generate a result, sustain the capability to reproduce that result, or modify the rules that make further activities possible. Its values are conditional possibilities within the selected model. They should not be confused with realized histories or a metaphysically privileged realm of futures. The interpretation of a transformation depends on the specified institutional practices and the evidence supporting its admissibility.

The basic accumulation comparison now has two aspects. One concerns changes in Cap_a ; the other concerns changes in $\Gamma_{\mathcal{H}}(a)$ and the dependency structures that support it. A knowledge-producing system may gain new outputs without substantially improving its capacity to sustain inquiry. Conversely, investment in shared verification procedures may support little immediate output while changing the conditions for a wide range of later research activities. This difference offers an analytically concrete reason to locate accumulated knowledge capital across generative levels.

13.5 Heterogeneous Value Creation and Circulation

The capability account concerns what can be done. The political-economic account also requires a representation of the different values created through those activities, their recognition, and the arrangements through which benefits and burdens circulate. Monetary compensation, verified findings, technical reliability, professional recognition, language access, collective autonomy and cultural preservation can possess different evaluative structures. Aggregating these outcomes into a single scalar may conceal precisely the distributive and epistemic asymmetries under examination. The framework therefore begins with a typed family of value domains $\{\mathbf{V}_k\}_{k \in K_V}$, where each $\mathbf{V}_k$ has an interpretation and possibly its own order or measurement convention. A monetary domain might permit addition in a fixed currency and accounting period, whereas a domain of procedural contestability may be characterized by institutional relations rather than a cardinal quantity.

For a value-generating event $x \in \mathbf{X}$, let $\nu_k(x)$ be its assessment in domain k when the assessment is defined. Equation 8 records the partial nature of such valuation.

$$\nu_k : \mathbf{X} \rightharpoonup \mathbf{V}_k, \quad k \in K_V. \quad (8)$$

The partial mapping in Equation 8 allows some aspects of value to remain unmeasured, contested or resistant to the chosen scheme. Even within one domain, different participants may adopt different legitimate evaluative standpoints. The act of assigning an indicator is itself an institutional and epistemic

process requiring study. The formalism accordingly keeps the production of an outcome, its recognition as valuable, and the production of an official valuation as distinct events.

Circulation can then be represented as a typed network of relations among contributing persons, organized collectives, infrastructures, repositories, users and other institutional positions. A circulation event records its source, recipient, value type, institutional rule and relevant supporting activity. The representation can include reciprocal exchanges, public transfers, knowledge sharing, training, maintenance commitments, the imposition of costs, and forms of appropriation. Where the domain supports a meaningful flow quantity, we may write $F_{ab}^k(\mathcal{H})$ for a measured flow of type k from a to b . The same notation has no automatic quantitative interpretation for domains such as epistemic recognition or interpretive authority. These require typed relational descriptions instead.

For a conserved, additive domain with a fixed set of participants, a local balance relation may be useful. Equation 9 makes its restrictive assumptions explicit.

$$\Delta S_a^k = \sum_{b \in A} F_{ba}^k - \sum_{b \in A} F_{ab}^k + G_a^k - D_a^k, \quad (9)$$

where S_a^k is a measured stock, G_a^k and D_a^k are recognized production and depletion terms, and the equation applies only when flows, accounting boundaries and measurement units are compatible. Equation 9 is an accounting identity within a stated convention. Many forms of knowledge can be used simultaneously by multiple parties and can create additional capability through circulation. Their propagation does not obey the same conservation assumptions as a budget transfer. For such cases, the model should record transformations of accessible resources, capacities or recognition practices rather than impose an artificial stock balance.

Value conversion requires a separate institutional mechanism. Financial support may enable researchers to access instruments; publication recognition may become a grant allocation advantage; community-maintained software may contribute to commercial services that subsequently fund, partially fund, or bypass its maintainers. Let $C_{k\ell}^r$ be a partial conversion relation under institutional rule r , relating assessments in domain k to those in domain ℓ . A conversion relation may be asymmetric, conditional or non-functional. Its successful operation is a matter of documented practices, policies, negotiations or observed allocation results. The existence of a correlation between two value indicators does not establish an actual transfer or causal conversion.

The central circulation question concerns the reproduction of productive conditions. Let $M_c(\mathcal{H})$ denote the resources, work and governance capacities necessary to maintain productive component c under a specified service or research standard. Let $\text{Supp}_c(\mathcal{H})$ denote the support that can in practice be mobilized toward its maintenance. A comparison between these quantities is meaningful only after the contributions have been represented in compatible terms, and even then it constitutes one indicator rather than an exhaustive measure of sustainability. Research infrastructures also depend on forms of care, institutional trust, preservation, and responsible interpretation that may have weak monetary representation. Their omission would bias a circulation model toward activities for which price data happen to be available.

The approach therefore makes no automatic inference from observed income concentration to extraction. An institution may receive revenue and devote part of it to long-term preservation, universal access, or activities whose benefits are hard to price. Conversely, an arrangement may make extensive use of publicly contributed data and labour while externalizing correction, adaptation and continuity burdens. Evaluating the reproductive effect of a circulation pattern requires tracing both the recognized returns and the conditions that bear its continued costs. Commons-based recirculation, associated with generative justice, supplies one possible institutional orientation for this inquiry; it remains an empirical and normative proposition to assess in particular settings [26, 40].

13.6 Ownership, Access, and Power Relations

The framework represents legal rights, effective access and rule-changing authority as differentiated relations. For an actor a and component v , the relevant questions may concern the permission to inspect

or use a resource, the capacity to copy or adapt it, the authority to exclude others, the power to alter governance rules, the duty to maintain a service, and the ability to contest decisions. These relations can be represented by a typed rights-and-powers map, whose elements need not be numerical and need not belong to one actor. Equation 10 introduces the formal signature.

$$R_{\mathcal{H}} : A \times V \longrightarrow \mathcal{P}(\text{Right} \sqcup \text{Power} \sqcup \text{Duty}). \quad (10)$$

Equation 10 records a relational bundle associated with the historical configuration. The map does not make an individual’s knowledge, autonomy or personhood an alienable property object. The object v is a selected component such as a licensed dataset, institutionally maintained method, platform service or standard-setting procedure. Where actors are collectivities, the internal distribution of voice and authority remains a separate question. Formal ownership can coexist with duties, review mechanisms, non-transferable claims or constrained public mandates. The established literature on differentiated property rights provides a useful precedent for such separation [82, 43].

Practical control is additionally conditioned by capabilities and dependencies. An actor may possess a contractual entitlement without available staff to use it. An institution may lack formal title to an open standard yet influence its practical application by controlling the only widely deployed compatible service. A public organization may administer a common archive while its users retain consequential rights of review, portability and revision. The relevant relation of power is therefore contextual: it concerns what an actor can induce, prevent, permit or change in the feasible activity sets of others under prevailing institutions.

For each institutional intervention p available to actor a , one may compare feasible activities before and under the intervention. Equation 11 defines a non-cardinal profile of possible effects on an affected actor b .

$$\text{Influence}_{a \rightarrow b}(\mathcal{H}) = \{ (p, \text{Cap}_b(\mathcal{H}), \text{Cap}_b(\mathcal{H} \mid p)) : p \in P_a(\mathcal{H}) \}. \quad (11)$$

Here $P_a(\mathcal{H})$ contains the interventions or decisions the actor can actually exercise, and $\mathcal{H} \mid p$ is an explicitly specified institutional scenario. The profile in Equation 11 reveals which feasible activities could change, subject to the accuracy of the intervention model. Actual institutional power also includes bargaining responses, coalitions, legal remedies, mutual dependencies and possible reconfiguration of the system. A power estimate lacking these mechanisms may overstate the leverage of nominally central actors.

The distinction between observation and intervention is crucial for interpreting the profile. A correlation between the closure of a repository and a decline in publications might reflect changes in research funding, staffing or disciplinary priorities. A counterfactual scenario would need to identify which activities would remain feasible with an alternative repository and how agents might adapt. Causal inference requires assumptions and data beyond the representation of a dependency link, a distinction familiar from structural causal modelling [75]. The mathematical framework may support the formulation of such hypotheses without itself identifying their effects.

13.7 Generative Dependency and Extractive Leverage

Extraction at different generative levels requires an account of influence that separates upstream position from effective dependency. The relevant relation can be studied by comparing productive capabilities under an intervention affecting access to a component, while allowing feasible substitution. Let $v \in V$ be a component, let $\mathcal{B}_v(\mathcal{H})$ be the declared class of admissible replacement or adaptation plans, and let $u_{a,q}(\mathcal{H})$ be a bounded indicator of actor a ’s attainable performance of task q under specified constraints. The interpretation of $u_{a,q}$ may involve completion, cost-adjusted feasibility, reliability, or another declared task-specific property. A comparison of heterogeneous tasks requires an independently justified normalization and weight scheme.

The dependency-sensitive counterfactual loss for a task is defined in Equation 12.

$$\delta_{a,q}(v \mid \mathcal{H}) = \left[u_{a,q}(\mathcal{H}) - \sup_{b \in \mathcal{B}_v(\mathcal{H})} u_{a,q}(\mathcal{H} \ominus v \oplus b) \right]_+. \quad (12)$$

The symbols $\ominus v$ and $\oplus b$ specify a modeled restriction of access to v and a modeled replacement plan b ; they are intervention operators, not ordinary set subtraction and addition. The positive-part operator $[z]_+ = \max\{z, 0\}$ expresses a chosen focus on losses rather than compensating gains. The replacement class must be nonempty and should include a declared baseline plan, which may be the plan to proceed without replacement. A separate comparison may be needed for gains, changes in collective capabilities, or indirect institutional effects.

Given nonnegative, explicitly justified weights $w_{a,q}$ over a specified actor-task sample $\mathcal{S}$, Equation 13 defines a provisional effective dependency score.

$$D_{\mathcal{S}}(v \mid \mathcal{H}) = \sum_{(a,q) \in \mathcal{S}} w_{a,q} \delta_{a,q}(v \mid \mathcal{H}). \quad (13)$$

Equation 13 should be used only when task scores and weights support aggregation. In settings of contested values or incommensurable outcomes, the vector of $\delta_{a,q}$ values provides a more faithful description. Even a well-estimated scalar measures vulnerability under the selected restriction and substitution set. It does not measure the moral worth of a knowledge component, establish the intent of its controller, or imply that an extraction mechanism exists.

Proposition 13.2 (Monotonicity under enlargement of admissible substitutions). *Fix a configuration $\mathcal{H}$, component v , actor-task sample $\mathcal{S}$, nonnegative weights, and bounded task scores. If the admissible substitution family is enlarged while the evaluated task-score function remains the same, then the effective dependency score in Equation 13 cannot increase.*

Proposition 13.2 follows because enlarging the family over which a supremum is taken can only weakly increase the best attainable counterfactual score. The difference from the fixed baseline score therefore weakly decreases, and taking its positive part and a nonnegative weighted sum preserves the ordering. This result is a formal property of the chosen score, not an empirical claim that adding a technically available alternative necessarily improves bargaining or public autonomy. New alternatives may demand unaffordable transition costs, encounter legal prohibitions, or require scarce expertise. Their admission to $\mathcal{B}_v(\mathcal{H})$ should reflect those feasibility constraints.

The computed loss may be especially sensitive to incomplete enumeration of feasible substitutions. Suppose a verified candidate family $\hat{\mathcal{B}}_v$ is a nonempty subset of the full admissible family $\mathcal{B}_v$, with the same unrestricted baseline and task-score function. The score obtained from the verified subset supplies an upper bound on the score obtained from the full family, as formalized by Proposition 13.3.

Proposition 13.3 (Upper bound from incomplete substitute enumeration). *Fix the baseline configuration, component, sampled tasks, bounded task scores, and nonnegative weights in Equation 13. If $\emptyset \neq \hat{\mathcal{B}}_v \subseteq \mathcal{B}_v$ and the task-score function is evaluated under identical conditions, then the dependency score computed using $\hat{\mathcal{B}}_v$ is at least as large as the score computed using $\mathcal{B}_v$.*

Proof. The supremum over the smaller nonempty family is weakly below the supremum over the larger family for each actor-task pair. Subtraction from the same baseline, the positive-part operation, and aggregation with nonnegative weights preserve the reversed inequality. $\square$

Proposition 13.3 has an asymmetric evidential implication: when alternative plans are omitted, a reported score can overstate effective dependency. It is an upper bound only if the observed plans are correctly established as feasible and the baseline scores are comparable. If unknown feasibility is incorrectly coded as absence, or if the analyst's task standard changes with the intervention, the proposed numerical bound loses its evidential interpretation. Documented alternatives should therefore be distinguished from conjectured and inaccessible alternatives; the resulting interval of defensible dependency assessments is more informative than an unqualified point estimate.

Potential extractive leverage requires further information about who controls the restriction or alteration of v , whether value is appropriated under the relevant arrangement, and what burdens or capabilities are affected. One may define a descriptive profile $\text{EL}_{a,v}(\mathcal{H})$ consisting of the actor's admissible interventions, the affected tasks and participants, dependency comparisons, observed or modeled value transfers,

maintenance obligations, and available procedures for contestation. The profile is intentionally not collapsed into a product of dependency, power and revenue. A multiplicative index could be useful for a particular empirical model, but it would require independently validated cardinal scales and assumptions about interactions among its factors. The descriptive profile preserves the possibility of alternative causal interpretations.

Consider a hypothetical shared verification protocol used by several research collectives. An operator may have authority to revise its interface, but the collectives may possess interoperable implementations, rights to maintain a fork, and sufficient trained personnel to switch. The protocol could occupy a relatively deep generative position while its effective dependency score is modest under plausible substitution plans. Alternatively, a particular application interface may sit near outputs in one representation yet function as the sole route through which numerous institutions submit recognized evidence. Its operational dependence may be high, even though its apparent depth is small. These cases demonstrate why the relation between depth and extractive potential is conditional.

A stronger claim of *structural extraction* requires evidence connecting an actor's control to a sustained pathway of appropriating benefits generated through distributed contribution, together with a grounded assessment of the contributors' feasible productive conditions, mutual agreements, maintenance costs and remedies. Control can support public services, and accumulation can contribute to collective reproduction. The same technical dependency can support institutions with materially different circulation arrangements. Formal dependency analysis can identify a site for institutional inquiry; a historical and normative assessment must determine the character and consequences of the observed relation.

13.8 Recursive Capital Expansion and Structural Evolution

Capital accumulation can alter the rules and productive conditions through which additional accumulation becomes feasible. A shared method may enable researchers to construct new instruments, and those instruments may support changes in the method. An organization may use revenue from applications to strengthen a common repository, or invest the same proceeds in a controlled interface that raises users' dependence on its services. These possibilities require a description of transformation pathways whose outputs can revise components, institutional rights, and admissible productive activities.

Let $\mathcal{H}$ be a declared class of historical configurations, and let $\text{Adm}(\mathcal{H})$ be the family of specified transformations among them. A *generative continuation* is an admissible composable family of transformations from an initial configuration within that class. Composition is defined only for transformations whose interfaces, representational meanings and institutional conditions are compatible. Equation 14 specifies a two-step composition.

$$\mathcal{H}_0 \xrightarrow{\tau_1} \mathcal{H}_1 \xrightarrow{\tau_2} \mathcal{H}_2, \quad \tau_2 \circ \tau_1 \in \text{Adm}(\mathcal{H}_0, \mathcal{H}_2). \quad (14)$$

The mathematical arrows in Equation 14 signify compatible modeled transformations. Their use neither privileges a global chronological parameter nor implies that every historical transformation has a determinate continuation. Additional transformations may be admitted or ruled out as productive practices, governance arrangements, and interpretive conventions change. In particular, a productive transition may modify $\mathcal{Q}$, alter the dependency types in $\mathcal{K}$, or reshape the ways tasks and values can be compared. Under such structural changes, a comparison of the capability sets in Equation 6 requires an explicit translation between the task universes and recognition conventions.

The recursive character of capital expansion can be described through the consequences of transformations for further admissible transformations. A configuration resulting from collective research may enlarge the set of tasks that can be undertaken by participants, strengthen mechanisms of verification, and alter the arrangements for maintaining infrastructures. A private investment may enlarge productive capacity while concentrating authority to restrict a widely shared interface. A subsequent organizational or legal response may revise that authority. None of these outcomes follows from recursion alone. The relevant mechanism lies in the structure of transformation opportunities, the institutional distribution of

Table 14: Formal objects, political-economic interpretations, and evidential requirements in the proposed relational framework.

Formal object	Analytical interpretation	Evidence or limitation
$\mathcal{H}$, typed dependencies	Productive components and conditional support relations	Case boundary, practices, protocols, alternative routes
$\text{Cap}_a, \Gamma_{\mathcal{H}}$	Feasible tasks and possible transformation capabilities	Access, labour, skills, coordination, task-specific outcomes
ν_k, F_{ab}^k	Heterogeneous values and compatible circulation flows	Accounting rules, recognition practices, transfers, burdens
$R_{\mathcal{H}}$, Influence	Rights, duties and effective institutional powers	Contracts, rule changes, decisions, constraints, contestability
$D_S, \text{EL}_{a,v}$	Substitution-sensitive dependency and potential leverage	Credible interventions, switching costs, appropriation, remedies
$\text{Adm}, \text{Cont}_a$	Structural transitions and available continuations	Historical records, representational comparability, uncertainty

decision powers, and the circulation arrangements that support the continued reproduction of productive conditions.

For an illustrative formal comparison, let $\text{Cont}_a(\mathcal{H})$ be the set of admissible continuations that actor or collectivity a can effectively participate in, given declared resources and authority. Equation 15 defines a weak expansion condition for configurations whose continuation sets have a compatible interpretation.

$$\text{Cont}_a(\mathcal{H}) \subseteq \text{Cont}_a(\mathcal{H}'). \quad (15)$$

When Equation 15 holds, the representation identifies a weak enlargement of an actor's continuation repertoire, conditional on the comparison convention. This condition is not necessary for every plausible notion of productive improvement. A more reliable method may deliberately eliminate dangerous, invalid or ethically prohibited options while increasing the quality of legitimate inquiry. A structural transformation can also create novel categories of activity for which direct set inclusion is undefined. Such cases require a richer partial-order or relational comparison, including the admissibility and normative standing of the relevant activities.

Two stylized trajectories illustrate the comparative use of the framework. In a public-recursive arrangement, contributors create a dataset, develop shared validation tools, receive institutional or cooperative support for maintenance, and extend the resulting capacity to additional participants. In an extractive-recursive arrangement, a service operator builds a proprietary interface over collectively generated resources, accrues revenues or strategic advantages through users' dependency, and uses some returns to deepen restrictions on the alternative paths through which those users might pursue their work. These are hypothetical mechanisms, not empirical identifications of particular organizations. Both can coexist with valuable specialization, negotiated remuneration and productive expansion. An investigation of actual cases would need to determine the terms of consent and contestation, the practical viability of substitutes, and the burdens borne by different contributors.

Table 14 summarizes the relation between the principal formal constructions and the evidence that could support their interpretation. Its purpose is to prevent unobserved assumptions from being concealed within seemingly precise mathematical notation.

13.9 Formal Properties, Counterexamples, and Epistemic Limits

The framework yields modest but useful deductions and exposes several forms of underdetermination. Proposition 13.2 is an internal mathematical result concerning feasible alternatives. It formalizes a limited intuition: when accessible alternatives improve under a fixed performance criterion, the modeled vulnerability created by restriction of one component weakly decreases. The result does not identify the institutions that would make those alternatives available or the costs of creating them. In practice,

substitution options may themselves depend on contested licenses, specialized training, collective coordination, and continuing maintenance. These conditions should be incorporated into the counterfactual before interpreting the numerical outcome.

A second formal observation concerns the distinction between knowledge-capability expansion and capital control. Two configurations may support equal task-capability sets while differing in who can revoke permissions, alter standards, or appropriate revenue. Equality of the sets from Equation 5 therefore fails to imply institutional equivalence. Conversely, configurations with similarly concentrated decision authority may support different levels of public productive participation. The rights mapping in Equation 10 and the circulation specification provide independent dimensions with which to describe such differences. Any purported single index of the quality or justice of a knowledge-production arrangement would require a defended normative ordering of these dimensions.

A third observation concerns nonmonotonic transformations. A new shared epistemic rule may eliminate unsupported practices, improve reliability, and change the criteria under which success is assessed. Under those circumstances, an increase in raw task count could misrepresent epistemic improvement. The set comparison in Equation 6 is informative only relative to a common and adequately justified task universe. Where the relevant epistemic categories change, the appropriate representation may be a typed correspondence, a partial mapping, or an account of failed translation. Structural equivalence should be asserted only at the level at which the mapping is justified.

Remark 13.4 (Relative generative depth and institutional risk). A component's upstream position can widen its potential influence on dependent activities. The realized institutional consequences remain conditional on effective dependence, the feasibility of alternatives, the distribution of decision powers, and the mechanisms by which benefits and burdens circulate. Generative depth by itself establishes neither exclusionary power nor extraction.

Remark 13.4 clarifies the paper's central conditional hypothesis. It preserves the possibility that restrictions on widely used meta-knowledge or epistemic standards may be more consequential than restrictions on a specialized output. It also admits application-level bottlenecks, adaptive alternatives, distributed governance, and institutions where concentrated coordination supports public service. A formal model can organize these possibilities, while historical and empirical inquiry determines which mechanisms were operative and for whom.

The current proposal also has a topological limit. A directed dependency hypergraph can represent combinations of prerequisites and alternative routes, but it does not automatically supply a theory of circulation through higher-dimensional cells. A complementary two-complex representation could assign vertices to represented events, edges to couplings, and faces to explicitly specified relational or value-circulation primitives. Cellular chains and boundary operators might then support formal investigations of closed circulation, constraints, and topological reconfiguration. Such extensions require a precise declaration of cell semantics, orientation and admissible transformations. A cycle in a mathematical complex is not by itself a socially beneficial value-return pathway, and a topological obstruction is not automatically an institutional injustice. Standard constructions in algebraic topology provide the mathematical tools, while the validity of their application to public knowledge production remains to be argued [38].

An empirical programme based on the present formalism would benefit from several complementary forms of evidence: historically documented alterations in access and governance; observed technical and organizational dependencies; information about contributors' work and maintenance burdens; records of resource allocation and value circulation; and accounts of participation, meaning, authority and contestation. Comparative cases could assess whether a change in a shared standard altered the feasible task sets of different contributors, how substitution costs were distributed, and whether benefits were invested in collective maintenance or in more restrictive arrangements. Counterfactual estimates should disclose the intervention, identification strategy and uncertainty. Qualitative interpretation is particularly important for categories of epistemic value or recognition whose meaning depends on communities and their practices.

The formalism supplies a conditional language for comparing feasible activity, generative dependency, differentiated rights, and typed value flows. Its results do not identify dispossession, extractive conduct, or justice without historical, institutional, and normative premises. The documentary illustrations in Section 14 therefore test the applicability of its analytical distinctions and the visibility of required evidence; they do not purport to estimate the model's parameters or confirm its causal hypotheses.

14 Comparative Illustrations of Knowledge Capital Accumulation

This section investigates how the proposed distinctions among capital formation, generative dependency, institutional control, and heterogeneous value circulation can guide comparisons of situated knowledge-production arrangements. Its objective is illustrative and methodological: to connect the relational formalism of Section 13 with documentary evidence from scholarly publishing, public software infrastructure, research evaluation and standards, artificial intelligence, and cultural knowledge institutions. The discussion first identifies documented institutional or technical features in each domain, then considers conditional mechanisms suggested by the present framework, and finally specifies the evidence required to evaluate claims about accumulation, dependency, extraction, and public reproduction. Published studies, institutional documentation, and constructed analytical examples are distinguished throughout. The evidential weight of a bibliometric observation differs from that of a commissioned market analysis, a technical documentation page, or an institutional strategy. In particular, declared policy objectives should be distinguished from realized institutional effects, and an available interface from demonstrated reliance upon it. The cases are selected for variation in their generative interfaces rather than for representativeness, and the comparisons do not constitute a systematic causal investigation.

The comparative object is a configuration of productive activities and relations, rather than a named organization assumed to possess a single institutional character. A publisher may supply editorial coordination while operating proprietary analytical services; an open-source project may distribute code under permissive terms while concentrating the responsibility of maintenance; a public archive may circulate digitized materials while relying on legal restrictions and community protocols. In each case, knowledge resources, productive capacities, rights and responsibilities may be distributed differently across actors. The empirical question is whether those distributions permit contributors to maintain and change the conditions of production, and through what paths economic, epistemic, social, and institutional values are recognized and recirculated. For the discussion below, a *documented feature* denotes a statement supported by a cited source, a *mechanism illustration* denotes a theoretically specified conditional pathway, and a *diagnostic question* identifies an unresolved empirical issue.

14.1 Academic Publishing and Scholarly Communication

Scholarly communication provides an instructive setting because the knowledge-producing process extends across research, authorship, editing, reviewing, certification, dissemination, indexing, archiving and institutional evaluation. Different participants may supply the conditions for these activities, while control of the means of dissemination or evaluation can reside elsewhere. The accumulation of an archive of articles, a journal's reputation, stable bibliographic identifiers, editorial expertise and institutional trust may jointly increase the capacity to support additional research. These accumulated capacities are potentially productive even when the immediate transaction concerns access to a particular document.

The concentration of academic publishing has been examined through historical bibliometric evidence. Larivière, Haustein and Mongeon report that the five most prolific publishers accounted for more than half of the papers in the 2013 portion of their Web of Science-indexed corpus, assembled over 1973–2013, with substantial variation across disciplinary groupings [56]. The indexing scope and historical period delimit this finding: it establishes concentration in a specified publication corpus, while neither measuring effective control of all scholarly knowledge nor establishing a particular extractive relation. The study nevertheless identifies a relevant institutional context in which questions of bargaining,

infrastructure substitution, and allocation of publication-related revenue may arise.

A further level of inquiry concerns the integration of publication with research services. The SPARC-commissioned landscape analysis describes a transition in which some commercial scholarly communication firms offered interconnected tools for research workflow, evaluation and data analytics in addition to conventional content products [5]. This commissioned market analysis provides an attributed interpretation of industry developments and possible consequences for academic institutions; it does not itself establish the effects of any particular contract or the prevalence of coercive dependence. Whether any particular bundle yields an actual constraint on research freedom depends on contracts, interoperability, portability, governance and available competitors. A publisher may improve services through integration, and universities may obtain substantial benefits from reliable analytical infrastructure. The analytical concern is the distribution of the resulting capacities and decision powers, including the ability to withdraw from or renegotiate an integrated service.

The generative-level perspective changes the relevant unit of analysis. A restrictive contract for one article may primarily affect a bounded set of access and reuse activities. A publishing workflow, indexing convention, identity infrastructure or assessment rule used by numerous organizations may influence activities whose outputs subsequently become inputs to many other researchers. This upstream effect is relative to the specified dependency structure. For example, an institution that relies on a unique interface for deposit and compliance reporting may be operationally dependent on that interface, although the same institution could have more flexible alternatives for accessing the underlying publications. The contractual rights covering articles, repositories, metadata and downstream analytics should therefore be analysed separately.

A stylized comparison can clarify the distinction. Consider a hypothetical consortium of universities whose researchers write articles and perform peer review. In one arrangement, subscription or service fees finance stable editorial and preservation services, and participating universities can export their metadata, audit relevant rules, and maintain alternative deposit routes. In another arrangement, an operator can unilaterally modify indispensable metadata interfaces, impose charges linked to institutional switching costs, and retain exclusive control over derived analytical data. Both arrangements might create useful knowledge capital. The second also presents a plausible mechanism of extractive leverage if the associated value capture recurrently draws on distributed academic contribution and diminishes contributors' viable productive options. Documented contractual powers, observed transfers, labour requirements, switching costs and contestation mechanisms would be needed to adjudicate that possibility. It cannot be inferred from the commercial identity of the operator alone.

Recognition and circulation require equal attention. Scholarly value can accrue through access to findings, the reliability of certification, professional recognition, teaching use, reusable metadata and subsequent discoveries. These benefits are neither jointly priced nor necessarily distributed according to the institutions that collect revenue. A university may support open repositories, the public may benefit from disseminated research, and commercial intermediaries may earn returns through complementary services. A complete circulation account would trace costs of research and reviewing, receipts from subscriptions or services, preservation responsibilities, and reinvestment into research and community infrastructures. It would also examine how evaluation practices affect research directions. The illustrative issue, accordingly, is the structure of value circulation and rule-setting authority throughout scholarly communication, with the publisher's legal ownership position constituting one component of a larger historical configuration.

14.2 Open-Source Software and Shared Research Infrastructure

Open-source software offers a complementary arrangement in which the terms for inspecting, using, modifying, and redistributing code can be comparatively permissive while capacity for maintenance remains unevenly distributed. The source code of a widely reused library may facilitate research, public administration, education, and commercial products. Further productive effects emerge through accumulated documentation, testing practices, security knowledge, compatibility agreements and communities

capable of implementing changes. An initial public release is therefore one element of capital formation within a larger reproductive ecology.

In a report on public digital infrastructure, Eghbal describes the often under-recognized work of maintaining widely used public code and the institutional difficulty of sustaining that work [25]. This report supports the importance of maintenance as an analytical concern; its broad descriptions should be interpreted in the context of the projects surveyed and the 2016 software environment. The issue extends beyond unpaid volunteer contributions. Public-sector developers, firms, nonprofit foundations, research groups and independent maintainers may all contribute to repositories governed by different combinations of licence terms, funding, reputation, project rules and technical authority. The existence of publicly reusable code supplies information about formal access, while issue triage, merge permissions, release management and security responses supply information about effective control.

One mechanism of expansion is productive recombination. Researchers may reuse a numerical library, combine it with domain-specific methods, and publish further tools. Commercial users may similarly incorporate open components into paid services. Such downstream activities can create heterogeneous values: useful applications, income, scientific improvements, learning opportunities and infrastructure resilience. Their relation to the originating project depends on whether the new users provide patches, documentation, funds, security audits, interoperability tools, or other support. Downstream monetization alone does not establish extraction. Some projects deliberately provide reusable commons components without requiring financial repayment, while contributors may obtain other benefits through recognition, skills or participation. A substantive claim of structural extraction would require evidence of recurrent appropriation linked to effective control and constraints on the reproductive capacity of contributors, under a defensible account of their agreements and obligations.

A particularly instructive counterexample to a simple hierarchy of danger concerns a near-application component. A modest package occupying a narrow conceptual level may be deployed throughout numerous systems because it implements a required file format or networking interface. A failure to maintain that package could affect a large number of activities, even though its conceptual content is specialized. Conversely, a more abstract mathematical framework might be readily replaceable by independently implemented alternatives. These possibilities support the substitution-sensitive approach introduced in Section 13.7: generative depth and effective dependency should be estimated independently. In software, substitution may require technical compatibility, migration labour, security review, community coordination and rights to distribute modifications.

The relevant capital relations therefore cross several boundaries. A software licence defines certain legal permissions; repository governance assigns implementation authority; organizations contribute infrastructure and compensated work; users form dependencies through build systems and applications; and maintainers may assume ongoing obligations without equivalent control over the benefits derived elsewhere. Public or cooperative funding of maintenance can expand the continuation repertoire of a project by supporting testing, documentation and succession. It may also concentrate authority if funding conditions permit a single sponsor to determine priorities or revoke essential hosting access. Empirical comparisons should record contribution histories, decision rules, financing and in-kind support, the distribution of maintenance burdens, and the viability of forks or alternate implementations. This reveals how accumulation can be simultaneously commons-based in its accessible outputs and concentrated in its operational capacities.

14.3 Scientific Standards and Epistemic Evaluation Systems

Research standards occupy an important interface between epistemic coordination and institutional power. An agreed protocol for data description, measurement, identifiers or evidence reporting can reduce the labour of exchange and improve the composability of research. The FAIR principles identify findability, accessibility, interoperability and reusability as objectives for data stewardship, including machine-assisted discovery and use [91]. Such standards can constitute accumulated collective knowledge capital because investments in common identifiers, shared representations, metadata practices

and expertise may support numerous productive tasks. FAIR is formulated as guiding principles rather than a single technical specification, and its accessibility requirements can coexist with authentication and authorization. The generative influence of particular implementations depends on actual adoption, legally permitted uses, the range of supported activities and the availability of feasible alternatives.

Crossref supplies an operational illustration of an infrastructural interface: its public REST API exposes scholarly metadata deposited by members and trusted sources, including information concerning references, funding, licences and post-publication updates [78]. This institutional documentation establishes that the metadata interface exists and identifies some of the information it disseminates. It does not establish the accuracy of every deposited record, the degree of dependency of every research user, or the distributive effects of a particular governance decision. The generative significance of bibliographic metadata is nevertheless readily specified as a conditional mechanism. If a research tool, archival workflow or evaluation system depends on particular identifier conventions, changes in those conventions may affect the possibilities for discovery, linking and reproducibility across many downstream activities.

A separate issue concerns evaluative standards. Hicks and colleagues' Leiden Manifesto proposes principles for the responsible use of research metrics, emphasizing contextual interpretation and the importance of qualitative judgments [41]. Such guidance provides a point of comparison for institutional arrangements that assign weight to citation indicators, rankings or quantitative benchmarks. An evaluation system may alter the incentives governing topic choice, publication practices, teaching and recognition. The resulting effects involve epistemic value and institutional authority as well as resource allocation. A metric can support transparent comparison within a well-defined purpose and population; misuse or overly broad application may transform it into a gatekeeping mechanism that shapes which investigations can obtain the conditions for further development.

The possibility of deep-level extractive leverage becomes clearer when a standard is tied to mandatory participation. Consider a hypothetical certification rule that universities require for eligibility to share data with a publicly funded repository. When the rule is interoperable, revision is publicly contestable, and implementations can be supplied by multiple actors, accumulation at the standards level may enlarge collective capabilities. When one operator has exclusive permission to implement the rule and can modify certification fees or admission criteria without meaningful accountability, users may become dependent on that operator's choices. Yet this construction alone is insufficient to establish exploitation; investigators would need evidence of fees relative to costs, the processes of rule authorization, effects on legitimate research, and how the resulting benefits circulate. A rule could impose justified burdens to sustain quality, privacy or reproducibility. The normative assessment should consider these purposes alongside distributional effects.

Standards also evolve in response to applications. New instruments, data formats or scientific criticisms can reveal defects in a shared ontology or methodological convention. Revision may invalidate some old practices while improving the reliability of others. A formal comparison of task counts would be misleading if changed standards redefine what counts as sound evidence. The important historical objects include situated deliberations, translations among disciplines, participation in standard-setting, and the capacity of affected communities to appeal, revise or maintain their own implementations. These processes explain how accumulation in meta-knowledge and methods can be both productive and politically consequential without presuming a universal linear progression from basic theory to application.

14.4 Artificial Intelligence and Foundational Knowledge Infrastructures

Artificial intelligence provides a case in which the relations among datasets, model architectures, trained parameters, computing facilities, interfaces and downstream applications are both visibly interconnected and difficult to reduce to a single generative hierarchy. A substantial model can support numerous applications, while the infrastructure for data collection, training, inference and evaluation can be used by many different models. Conversely, application feedback may generate new evaluation data, influence training choices and change the distribution of investment across infrastructure. These relations include technical dependencies as well as financial, contractual and institutional connections.

Bommasani and colleagues propose ecosystem graphs that document selected foundation-model supply-chain assets, including datasets, models and applications, and their reported technical and social dependencies [10]. The resulting graph is a curated documentation framework, not an exhaustive register of all production dependencies. Its empirical graph is an observation and documentation project, not an exhaustive map of causal dependence or institutional power. The proposed graph approach is useful here because it makes explicit why a model name or a single layer label cannot describe the full productive configuration. Researchers examining capital accumulation would also require information about computing access, labour, licensing, developer tools, governance of benchmarks and the possibility of replacing a supplier while preserving required functionality.

The economic dimensions vary across components. Collecting or licensing a dataset can establish one kind of knowledge resource. Maintaining a distributed computing platform can establish another. Skilled research labour, a model's parameterization, an interoperable API and the social capability to evaluate its outputs can each become conditions for additional productive activities. Their ownership arrangements need not coincide. Publicly produced research may be incorporated into privately operated services, while proprietary models may be used to generate public educational tools or openly released research outputs. The relevant analytical task is to identify the contributions and permissions involved, together with the conditions on which recipients depend. An apparent public benefit from an application can coexist with concentrated control over the infrastructural layer, while concentration may in certain settings sustain expensive technical coordination.

Documentation contributes a further dimension of generative capacity. Gebru and colleagues propose structured datasheets covering the motivation, composition, collection and anticipated use of datasets [36]. Such practices can support more informed assessment and make some data-provenance questions more tractable. Their existence does not guarantee that training-data permissions were obtained, that affected participants could influence decisions, or that a deployed model can be meaningfully audited. Nevertheless, documentation can enable users to distinguish technical usability from justified authority over source materials and can help trace whether epistemic biases or restrictive licensing practices propagate through downstream applications.

A hypothetical service chain illustrates conditional cross-level extraction. A community supplies texts, annotations and evaluation expertise to a research corpus; a separate organization trains a model using lawful and agreed permissions; application developers integrate the model through an API. Value is created through contributions at many layers. If the service provider acquires authority to alter access terms, restrict portability and appropriate downstream analytics while communities have little effective voice over the continuing use of their contributions, dependency may provide leverage for sustained asymmetric value capture. Yet the same chain could support collective production if benefits were recirculated into annotation work, accessible evaluation resources, research training and public governance. Neither route can be inferred from the mere fact of model reuse. Claims would require documented consent terms, compensation or nonmonetary returns, technical replacement costs, governance rights, and effects on contributors' productive autonomy.

Attention to environmental and material conditions also matters. AI infrastructure relies on energy, physical equipment, data-center operations, supply chains and maintenance. These are productive conditions that generate costs and ecological implications beyond the knowledge artifacts themselves. Allocation of these burdens is part of value circulation, although environmental effects require independent physical measurements and suitable boundaries. The conceptual framework can represent the dependence of an activity on energy or computing resources; it cannot derive energy consumption, ecological harm or the justice of its distribution from a dependency graph alone. Comparative research should combine technical system accounts with environmental evidence and socially situated assessments of benefit and burden.

14.5 Humanities, Public Archives, and Cultural Knowledge Production

The study of cultural archives expands the comparative scope beyond conventional scientific publication and digital engineering. Historical records, literary works, oral histories, museum collections, community archives and interpretive scholarship participate in knowledge production through preservation, translation, description, criticism, teaching and reinterpretation. Their value includes epistemic understanding, cultural continuity, institutional memory and the ability of communities to develop new interpretations. These activities can create durable knowledge-producing conditions even where saleable outputs are peripheral. In such settings, the relation between a preserved artifact and the right to use or reinterpret it may involve copyright, cultural obligations, custodial responsibilities and legitimate community claims that have different bases.

The Europeana Foundation's institutional guidance describes machine-readable instruments communicating copyright status and reuse conditions for digitized cultural objects supplied by diverse cultural heritage institutions [79]. These instruments include Creative Commons licences and public-domain tools as well as informational statements issued through the Rights Statements Consortium. The latter describe rights status and do not themselves grant permissions; the distinction matters where an archive communicates permissions that it cannot independently confer. The European Commission and Europeana Foundation's strategy for the common European cultural heritage data space sets objectives concerning accessibility, interoperability and the governance of shared digital foundations [87]. The strategy appears in the European Union Publications Office catalogue as a 2025 publication, while the Commission announced it on 8 January 2026. The rights guidance documents a functioning descriptive procedure, whereas the strategy articulates prospective institutional aims whose effects require subsequent evaluation. A distinction is particularly important: standardized rights metadata makes permissions more intelligible, while the underlying authority to authorize use remains governed by the applicable rights and legal conditions. A metadata aggregator does not necessarily own the works to which its records refer.

Collective knowledge production also raises questions about culturally situated authority. The CARE principles for Indigenous data governance emphasize collective benefit, authority to control, responsibility and ethics, especially where historical power asymmetries shape the collection and secondary use of data [14]. Their presence alongside the FAIR principles demonstrates that machine-readable accessibility and the legitimacy of a particular reuse may require distinct assessments. A collection can become more findable while communities retain justified restrictions over contextual interpretation, sensitive material or culturally governed forms of circulation. Maximizing the total number of downloads therefore supplies an incomplete measure of public generativity. Sustaining participatory capacity may depend on community deliberation, language preservation, trusted custody and the resources needed to maintain archives.

A possible capital formation mechanism begins with public and community investment in digitization, cataloguing, translation and preservation skills. Such investments can create infrastructural capital supporting scholarship, education and cultural creation across several generations of participation. A second mechanism arises through commercial reuse, where a service may contribute search and presentation tools and earn revenue from access or complementary services. An investigation of value circulation would ask whether that revenue contributes to preservation and community capacities, whether archives retain viable alternatives, and how the cultural knowledge embodied in collections is recognized. Restrictions need to be evaluated contextually: a limitation intended to protect culturally sensitive knowledge may support collective autonomy, whereas exclusive downstream control over otherwise reusable archival metadata may create an obstacle to research without a corresponding legitimate justification.

The humanities case also exposes a difficulty for the generative-level metaphor. Classification and description systems can alter the categories through which materials become intelligible. Curatorial decisions may influence future recognition of people, practices and events; interpretive communities can contest those classifications and produce revisions. Some changes affect the epistemic interface through which numerous inquiries become feasible, while others alter the meaning or legitimacy of the apparent knowledge objects themselves. A graph of computational dependencies may record that users call a catalogue API; historical interpretation is needed to understand what the catalogue names, omits or

Table 15: Illustrative cross-domain interfaces of knowledge capital, potential dependencies, and evidence needed for value-circulation analysis.

Domain	Generative interface and possible dependency	Circulation, control and evidence questions
Publishing	Certification, metadata, evaluation and workflow integration	Contracts, portable records, academic labour, service fees, preservation and reinvestment
Public software	Shared code, compatibility, release and maintenance practices	Contribution records, sponsor power, forks, support, security and maintenance costs
Research standards	Identifiers, interoperable representations and evaluative rules	Revision rights, adoption, substitutes, contested metrics and support for standard upkeep
AI infrastructure	Dataset–model–application dependencies, compute and APIs	Licensing, compute access, developer substitution, labour, environmental burdens and benefit sharing
Cultural archives	Rights metadata, cataloguing, preservation and cultural authority	Stewardship rights, interpretive participation, reuse permissions, community benefit and preservation funding

misconstrues. The resulting account of capital expansion must preserve such interpretive remainders. Technological reuse, cultural recognition and ethical stewardship are related but cannot simply be converted into one numerical measure of accumulated value.

14.6 Cross-Case Comparison of Generative Dependencies and Value Circulation

Across the five domains, a recurring pattern is the joint production of useful shared conditions and unequal ability to modify those conditions. A publisher can combine certification with analytics; an open-source library can enable many applications while relying on a small maintenance community; a common research standard can improve interoperability and also serve as a gatekeeping rule; an AI model can supply reusable capabilities through restricted computational interfaces; and a public archive can improve access while retaining duties toward cultural source communities. These parallels specify an analytical family of mechanisms. They do not demonstrate that one institutional form is intrinsically more extractive or more productive than another.

Table 15 summarizes the distinctive dependency and circulation questions in each illustration. The table deliberately lists candidate interfaces and required observations instead of assigning extractive scores. An institution's legal status or a component's assigned generative level would supply insufficient evidence for such a ranking.

A disciplined comparison begins by specifying an activity and its feasible productive conditions. The activity could be publishing a reproducible article, maintaining an open library, reusing interoperable research data, developing an AI-assisted application, or translating a historical archive. Next, one would record the contribution history and distinguish rights to own, access, alter, govern, withdraw and redistribute different components. A further step maps which transformations remain feasible when a selected component or institution changes its terms. Only after identifying the credible alternatives can the analyst evaluate effective dependency. Evidence of monetary transfers, unpaid labour, reputation, reciprocal support and maintenance obligations would then support a heterogeneous account of value circulation.

The relevant counterfactuals must be situated. In publishing, a university might be able to replace a single journal subscription while lacking an affordable alternative to an integrated analytical workflow. In public software, a permissive right to fork may have little practical force without expertise and sustained funding. In standards, the possibility of a different measurement procedure may be irrelevant if public grant rules recognize only one institutional format. In AI, a technically interoperable model may require unattainable computational resources or unavailable evaluation data. In cultural archives, alternative dissemination channels may fail to respect cultural protocols or may lack the resources needed for preservation. Each example concerns a different kind of feasibility limitation; they therefore resist comparison through one generic measure of monopoly or openness.

The cases also expose distinct forms of value-recognition bias. Citations may understate review

and maintenance work; repository popularity may obscure the collective effort of infrastructure caretakers; numerical indicators may privilege certain kinds of scholarship; application visibility may obscure upstream annotation and data-production labour; and cultural heritage metadata may inadequately recognize communities' continuing interpretive authority. These biases influence attribution and subsequent allocation of institutional support. The influence may be recursive when recognised contributions affect funding, credentials, representation in governance and the ability to set standards. Historical and qualitative research is needed to determine who experiences these processes and how their productive agency changes.

A comparison of institutional alternatives can be structured around functions rather than labels. Public financing, subscription services, cooperative governance, open licensing, community stewardship, and commercial investment can each contribute to the formation of useful productive conditions. Their relative adequacy depends on which tasks require coordination, who bears maintenance burdens, how revision decisions are made, and whether affected participants possess feasible means of contestation. In one setting a funded central operator may be necessary to ensure safety and continuity; in another, interoperability and distributed maintenance may better preserve productive autonomy. Even when knowledge outputs circulate freely, decisions about classification, evaluation and access to computational resources may remain concentrated. Conversely, privately operated infrastructures may coexist with enforceable portability, public oversight and substantial support for shared research.

The illustrations expose differences among five things that are sometimes conflated: the relative position of a generative component, the feasibility of replacing it, authority over relevant access gates, actual pathways of value appropriation, and the capacity to maintain productive conditions. The documented examples do not supply representative causal estimates. They instead identify case-specific records needed to adjudicate claims of dependency or extraction, including instances in which public availability coexists with difficult-to-replace infrastructure. The normative question of whose productive autonomy and participation warrant protection is addressed separately in Section 15.

15 Public Generativity, Ethics, and Justice

The ethical significance of knowledge-capital accumulation concerns the conditions under which persons and communities can create, interpret, employ, sustain, and revise knowledge-producing arrangements. This section develops a provisional normative interpretation of the preceding political-economic and relational analysis. Its objective is to clarify the objects of ethical assessment, identify relevant claims of recognition and participation, and examine institutional responsibility for the reproduction of shared generative conditions. The discussion proceeds through collective productive capabilities, contribution and distribution, participation and autonomy, generative justice, accountable power, and sustainable circulation. It draws on capabilities theory, epistemic justice, structural responsibility, knowledge-commons governance, and generative justice as partly complementary resources whose differences remain relevant. Normative propositions in this section are offered as explicit evaluative commitments and possible institutional design principles; the dependency formalism of Section 13 supplies neither a proof of their validity nor a complete procedure for deciding among them.

The central ethical object is a historically situated relation among contributors, beneficiaries, infrastructures, and rules. A research archive might increase access while transferring custodial work to an inadequately supported community; a proprietary laboratory might charge for specialized services while maintaining reliable quality controls and contributing to public capabilities; and an openly governed software project might allow unrestricted copying while concentrating practical maintenance and release authority. Such combinations illustrate why legal form, price, and the numerical quantity of publicly available outputs offer incomplete accounts of ethical performance. A normative assessment must identify the affected parties, the opportunities available to them, the benefits and burdens they bear, and the extent to which they can participate in altering the arrangements that shape their activities. The assessment also requires attention to historical exclusions, epistemic and representational biases, and the legitimate plurality of interests among communities connected to the same production system.

15.1 Public Knowledge Capital and Collective Generative Capabilities

Public knowledge capital, in the present inquiry, denotes a configuration of resources, practices, institutions, and effective capacities that supports knowledge production with a public dimension. The public dimension may arise through accessibility, public funding, collective stewardship, social benefits, or meaningful participation in the conditions of production. These characteristics can coexist in different combinations. The ethical inquiry therefore concerns the actual capabilities supported by the configuration and the distribution of opportunities to exercise them. The capabilities approach developed by Nussbaum evaluates development in terms of substantive opportunities and human dignity rather than relying solely on aggregate economic indicators [69]. The present paper adapts the distinction between a nominal resource and an effective opportunity for the narrower task of examining knowledge production. This is a proposed application of the approach, with its own domain limitations.

Consider a repository containing open research datasets and software. Its entries are resources; the ability to inspect a file, verify a result, conduct an independent analysis, and participate in maintaining the relevant standards are different practical capabilities. A participant's feasible activity depends on equipment, technical literacy, language, accessible documentation, computing capacity, time, institutional permissions, and the stability of supporting services. These conditions vary across communities. For this reason, the extent of a shared repository should be evaluated alongside the feasible set of productive activities it supports for differently situated participants. The comparison may reveal that an increase in released materials accompanies a widening or narrowing of substantive participation, depending on the distribution of complementary conditions.

Collective capability also has a relational aspect. A knowledge-producing community may possess capacities that emerge through coordination among members and cannot be assigned to an isolated individual. A maintained citation infrastructure, for instance, depends on curators, developers, registrants, librarians, researchers, funding arrangements, standards processes, and contractual relationships. Their coordinated activity may make certain forms of cumulative research feasible at a scale unattainable through disconnected efforts. This observation motivates the analysis of joint capabilities without treating a community as a single person possessing a unitary preference. The coexistence of common production with internal disagreement requires attention to membership, voice, unequal workloads, and mechanisms for resolving contestation.

The significance of generative levels follows from the range of activities dependent on shared conditions. Improvements in metadata semantics or foundational methodological training may support several disparate research programmes, while improvements to a specialized application may support a narrower set of tasks. Such patterns are conditional on effective dependency and available alternatives, as analyzed in Sections 4 and 13. The normative importance of a generative level does not derive from depth alone. Its relevance is mediated by whose opportunities depend on the component, what those opportunities mean for persons and communities, and the costs associated with preserving or changing the dependency. A deeply situated rule that can be readily replaced may pose fewer ethical constraints than a comparatively applied service that constitutes the only feasible access route for a marginalized research community.

One proposed evaluative practice is to compare capability profiles across affected groups and institutional configurations. Such profiles would document feasible research tasks, opportunities to criticize dominant interpretations, access to maintenance knowledge, and practical avenues for institutional change. Where a configuration generates benefits through collective capacities, the distribution of those benefits should be examined alongside the reproduction of the collective conditions on which they depend. A capability profile remains an analytical aid: its relevance, category selection, measurement and interpretation require situated deliberation. Its construction can itself exercise power over what counts as productive activity or valuable knowledge.

15.2 Contribution, Recognition, and Distributive Justice

Knowledge production frequently combines identifiable authorship with contributions whose causal significance is distributed across technical support, review, curation, translation, maintenance, teaching,

5495 preservation, and infrastructural work. The allocation of income, authorship credit, research opportuni-
5496 ties, and institutional authority can therefore diverge from the history of contributions. Distributional
5497 justice requires a theory of the relevant entitlements and needs; a descriptive record of labour or depen-
5498 dencies cannot establish a unique just allocation. In particular, the heterogeneity of created value restricts
5499 the usefulness of any procedure that attempts to convert epistemic, cultural, social, and economic effects
5500 into a single undifferentiated share.

5501 At least four distributive concerns merit separation. One concerns compensation and material support
5502 for labour required by a knowledge-producing activity. Another concerns attribution and recognition for
5503 intellectual, technical, organizational, and custodial contributions. A third concerns access to the benefits
5504 generated by collective production, including training, research opportunities, useful information, and
5505 the continuation of shared services. A fourth concerns the allocation of costs, risks, and ongoing obli-
5506 gations, including labour for maintenance, privacy protection, archival care, and corrective work. An
5507 arrangement may provide generous access to outputs while placing recurrent burdens on a small group
5508 of contributors. Conversely, a collective may reserve resources for maintenance and participant support
5509 even when this constrains immediate free provision of every service.

5510 Recognition introduces an independent ethical dimension. Fricker's account of testimonial and
5511 hermeneutical injustice examines wrongs associated with credibility and the resources through which ex-
5512 perience can be understood [33]. Dotson's analysis of testimonial quieting and smothering further draws
5513 attention to relations that prevent or constrain contributions to shared knowledge [24]. In the setting of
5514 public knowledge capital, these analyses suggest that a system's evaluative categories, publication con-
5515 ventions, standards, and attribution practices may influence who can contribute recognized knowledge.
5516 The conceptual extension should be empirically investigated in each context rather than inferred from
5517 the existence of a formal evaluation process. Differences in assessment may reflect warranted evidential
5518 standards, institutional bias, unequal access to preparation, or some combination requiring contextual
5519 discrimination.

5520 Distributive arrangements also interact with future productive capacity. Payment to an individual
5521 contributor may remedy a discrete uncompensated task, while stable support for a shared facility may
5522 enable an entire community to undertake further research. These are related but distinguishable goods. A
5523 recurrent circulation mechanism might therefore reserve resources for contributor livelihoods, maintain
5524 common infrastructures, provide independent access to research methods, and support efforts to rem-
5525 edy historical exclusions. A decision about the distribution among these purposes involves substantive
5526 normative judgment as well as operational constraints. The promise of a larger future knowledge stock
5527 cannot by itself justify present violations of consent, dignity, or legitimate rights.

5528 The political-economic meaning of extraction remains an evidential question. A private actor can
5529 earn revenue from a collectively enabled service without thereby establishing a case of injustice. An ex-
5530 traction claim requires analysis of the value appropriated, available alternatives, affected parties' capaci-
5531 ties, and the institutional terms through which gains and burdens are distributed. Ethical assessment adds
5532 considerations that may exceed the structural extraction criteria developed in Section 12. An arrangement
5533 might be authorized by contract and remain open to criticism on grounds of unequal bargaining power
5534 or compromised substantive agency. Conversely, apparent concentration may support a service whose
5535 operational risks or coordination requirements make some delegated authority defensible, provided its
5536 scope and accountability are specified.

5537 15.3 Access, Participation, and Productive Autonomy

5538 The public character of a knowledge system can be examined through several separable opportunities:
5539 obtaining resources, understanding their operation, employing them in productive activity, contributing
5540 to their improvement, contesting decisions, and taking part in revising governing rules. Access to a pub-
5541 lished artifact occupies one place within this broader set. A licence can permit copying while high tech-
5542 nical barriers, restricted computing environments, costly certification procedures, or opaque governance
5543 limit productive autonomy. The opposite configuration can also occur: a service with restricted redistri-

bution may nevertheless provide substantial access, clear review procedures, and reliable opportunities for affected parties to challenge operating decisions. Ethical interpretation depends on the justification and combined consequences of these arrangements.

Productive autonomy here denotes the situated capacity to pursue and revise knowledge-producing activities under conditions that give participants meaningful agency. It does not imply freedom from interdependence. Shared research depends on interoperable methods, collective review, standards, and negotiated institutional commitments. Autonomy can be supported by dependable collective structures when participants retain credible opportunities for voice, movement between arrangements, and revision of the conditions that constrain them. Effective exit may require exportable records, transferable skills, viable alternative services, and resources sufficient to make departure feasible. Effective voice may require accessible deliberative procedures, transparent explanations, and protection against retaliation or disciplinary exclusion.

Governance of public knowledge systems involves choices about who is eligible to participate and in which capacity. A researcher, software maintainer, archivist, data subject, cultural source community, public funder, and downstream user may have distinct claims that cannot be collapsed into a homogeneous category of stakeholder. Fraser's analysis of the scale and framing of justice directs attention to disputes over whose standing is recognized in the relevant decision space [30]. An analogous problem arises when decisions about a knowledge infrastructure affect communities absent from its formal membership or funding jurisdiction. The connection is interpretive: Fraser's theory does not itself determine the membership of any particular data trust, open-source governance board, or university research consortium.

Participation also presents conflicts. Broad participation can improve the legitimacy and informational quality of deliberation, while unrestricted disclosure of culturally sensitive records, personal information, or research vulnerabilities may compromise legitimate interests. A public-knowledge institution may need carefully differentiated governance procedures that preserve rights of affected communities, research integrity, privacy, and the possibility of independent criticism. Such differentiation is compatible with a commitment to public generativity when the reasons for restrictions are reviewable, their scope is proportionate to the relevant interests, and affected parties have suitable avenues of representation. The conditions are proposed governance criteria, not features that can be assumed from a commons designation.

A further challenge concerns the practical costs of participating. Formal rights to attend meetings or propose amendments may be hollow when deliberation requires unpaid time, specialized technical language, travel resources, or institutional sponsorship. Independent participation can therefore depend on remuneration, accessible communication, translation, procedural assistance, and supported technical training. These investments are themselves forms of capital formation: they enlarge the capacity to take part in generating and revising shared knowledge conditions. Their value cannot be assessed exclusively by counting direct outputs, since some of their effects concern agency and the resilience of collective decision-making.

15.4 Generative Justice and the Reproduction of Creative Conditions

Generative justice provides a useful starting point for examining the connection between value creation and the continuing capacities of its producers. Eglash emphasizes the circulation of value toward its generators and their capacity to shape the conditions of further generation [26]. Applied to knowledge production, this orientation invites investigation of whether institutions support the reproduction, improvement, and transformation of shared creative conditions. The present analysis extends the inquiry to different generative levels and to heterogeneous kinds of value, while retaining the need for historically situated ethical interpretation. The resulting conception of public generativity is a proposed framework for institutional evaluation, not an empirical law of commons production.

A regenerative circulation arrangement can sustain several mutually dependent functions. Direct returns can support contributors' material circumstances. Collective investment can support libraries,

laboratories, software maintenance, community archives, reproducibility infrastructures, and accessible education. Governance resources can sustain deliberation, rights review, independent audit, and conflict resolution. Epistemic resources can support alternative approaches, minority perspectives, and revisions to entrenched classifications. The significance of a return depends on whether it actually strengthens relevant productive conditions and agency. A monetary transfer to an institution may increase its balance sheet while leaving precarious contributors or essential custodial activities without support.

Relations among generative levels complicate the normative assessment of value return. Revenue obtained from an application might be invested in foundational methods used by many communities. Such reinvestment could produce widespread benefits, although a monopoly over the resulting methods might also expand institutional command. Alternatively, a research consortium might return resources directly to contributors while neglecting a shared repository whose deterioration threatens continued inquiry. The appropriate balance among individual benefits, collective infrastructure, and independent alternatives depends on the history and vulnerability of the system. An institution's announcement that it reinvests profits in research provides an initial accounting claim; evaluation should examine what capacities the investment produces, for whom, and under whose control.

The relevant idea of reproduction includes continuity and transformation. Sustaining an inherited research practice may require maintaining equipment, preserving records, mentoring new participants, and updating compatible formats. Responding to limitations or emerging evidence may require substantial revision of methods, recognition standards, or governance institutions. These changes can alter the topology of dependencies that made earlier production possible. A justice-oriented analysis should therefore consider both the ability to maintain valued practices and the ability to challenge or transform the structures within which those practices operate. This interpretation maintains the distinction between an observed continuation of activity and assumptions about a privileged temporal direction or universally desirable growth.

A possible diagnostic distinguishes four outcomes of circulation. First, a system may support the immediate continuation of established activities while distributing little control over their renewal. Second, it may diversify participants' capacities while increasing recurrent operational burdens. Third, it may intensify dependent production by accumulating resources at a central interface. Fourth, it may combine material support, effective access, institutional accountability, and opportunities for revision, thereby widening feasible paths of collective production. These categories are interpretive possibilities; evidence could reveal mixtures and movements among them. They also help explain why high apparent openness, high aggregate output, and generous funding do not uniquely identify a just arrangement. Normative performance depends on the relations those indicators leave unmeasured.

15.5 Institutional Responsibility and Power Accountability

Institutions that regulate knowledge production exercise multiple forms of power. Funding decisions influence which research programmes have resources. Editorial and scientific-review procedures influence public recognition. Platforms and standards bodies govern interoperability, discoverability, and practical dependency. Data custodians and infrastructure operators determine access, privacy safeguards, maintenance priorities, and possible discontinuation. The ethical issue concerns how authority is justified, how its effects are made intelligible, and what mechanisms permit correction when burdens are displaced onto parties who have limited influence over the relevant decisions. Responsibility may be distributed across actors whose roles differ markedly in legal obligation, knowledge, capacity, and effective control.

Young's social-connection model analyzes political responsibility for structural injustice as a shared responsibility to address collective processes, distinguishing it from individual liability [93]. The distinction is pertinent to knowledge infrastructures built and reproduced by interconnected organizations. A university, publisher, repository, public funder, software supplier, and research community may each participate in arrangements that generate undesirable effects, while their legal duties and practical powers differ. The proposed application is to identify feasible forms of participation in correction, including changes to contracts, attribution practices, evaluation criteria, portability requirements, and financing.

Table 16: Provisional ethical dimensions of knowledge-capital governance, their evidential requirements, and potential institutional responses.

Dimension	Relevant evidence and affected capacities	Illustrative governance response
Material support	Labour, remuneration, maintenance costs and re-current burdens	Stable support, fair contracts and maintenance funding
Recognition	Attribution, credibility, classification and omitted contributions	Reviewable credit rules, documentation and appeal procedures
Productive access	Feasible use, training, technical barriers and alternative pathways	Accessible tools, training, portability and appropriate safeguards
Participation	Membership, standing, deliberation costs and influence over revision	Representative procedures and supported participation
Accountability	Authority, conflicts of interest, contestability and corrective capacity	Reason-giving, independent review and enforceable remedies
Reproduction	Viable continued capabilities, stewardship and adaptability	Reinvestment, preservation and resources for institutional change

Such a model does not erase questions of misconduct, liability, negligence, or the particular obligations that arise from contractual and legal relations.

Accountability should be calibrated to the kind of power exercised. Authority over a particular dataset can call for data governance, consent review, documentation, and audit. Authority over an infrastructure used by many downstream systems can call for transparency concerning interoperability, notice of major changes, viable migration pathways, and deliberation on discontinuation. Authority over epistemic standards or classification rules can call for reason-giving, independent criticism, and opportunities for underrepresented constituencies to submit evidence and participate in revision. The systemic approach to deliberation developed by Mansbridge and colleagues offers one conceptual resource for examining deliberative functions distributed across sites rather than concentrated in a single forum [59]. Institutional design must nevertheless consider confidentiality, expertise, administrative feasibility, and the unequal capacities of participants to use formal procedures.

The dimensions in Table 16 connect proposed ethical concerns to observations and possible institutional responses. Their selection remains contestable and requires contextual justification.

Table 16 collects these dimensions as a non-exhaustive research instrument. It connects a normative concern to evidence that would help determine whether the concern arises and to possible institutional mechanisms for addressing it. The columns do not prescribe a single institutional constitution. A privately owned service, a public agency, and a commons association may meet particular requirements through different combinations of enforceable contracts, user councils, professional duties, community governance, public oversight, and market alternatives. The effectiveness and legitimacy of these arrangements require evaluation in their respective legal and social contexts.

Accountability further requires attention to the ways evaluation itself can redistribute power. Metrics describing participation, citations, reproducibility, service uptime, or benefit sharing may aid oversight, but their adoption can change incentives and marginalize outcomes that the metrics fail to represent. Responsible evaluation therefore entails transparency about normative choices, opportunities to contest indicators, and periodic review of their effects. The ethical significance of a metric cannot be read directly from its apparent technical objectivity. Where assessment standards become foundational dependencies for many research activities, their governance may have consequences across multiple generative levels.

Institutional responsibility also includes protection for epistemic dissent and correction. Retractions, security disclosures, appeals against misclassification, community challenges to culturally inappropriate uses of archives, and competing methodological approaches can impose short-run costs while improving the capacity for legitimate collective revision. A system oriented to durable public generativity has reasons to support credible channels for these activities, subject to procedural rights and the integrity of the underlying evidence. The justification of any particular remedy should remain proportionate to the nature of the harm, the rights of affected parties, and the institution's effective capacity to act.

15.6 Sustainable Value Circulation and Knowledge Commons Governance

The sustainability of public knowledge production is a relational and institutional question. A system may exhibit rapid growth in publications, software adoption, or dataset downloads while its maintenance resources, contributors' capacity to participate, or public oversight arrangements become fragile. Other systems may expand more slowly while maintaining resilient alternatives, diverse sources of support, and procedures for correcting institutional decisions. Neither growth rate provides a sufficient ethical criterion. The analytic task is to examine the reproducibility of valued activities, the burdens of continuation, and the feasibility of institutional adaptation under changing conditions.

Knowledge-commons research provides a basis for attending to the particular resource, community, and governance arrangements of a shared knowledge system [40, 70]. The 2021 UNESCO Recommendation on Open Science adds an institutional normative reference emphasizing equitable access, participation, openness, and the enabling conditions of open scientific practice [89]. These sources do not prescribe an identical allocation of property rights, access rules, or decision authority in every domain. Their significance for the present framework is that sustainable shared production depends on more than release of outputs. Maintenance, collective-choice procedures, suitable safeguards, skills, and material infrastructures constitute productive conditions that require recurrent resources and legitimate coordination.

Value circulation may take direct monetary forms, such as infrastructure subscriptions, public grants, cooperative contributions, or remuneration for maintenance. It can also involve nonmonetary transfers through mentoring, reciprocal software contributions, public documentation, technical review, mutual assistance, and shared institutional knowledge. Such heterogeneous contributions differ in convertibility, temporality, and normative significance. A funding programme that rewards visible novelty while neglecting essential repair work may undermine a core condition of production even as measured publication output increases. A community that relies exclusively on uncompensated voluntary effort may experience shortages in particular capabilities or unequal participation burdens. Sustainable circulation requires attention to the work that keeps shared arrangements usable and to the agency of those who perform it.

Institutional pathways must also preserve legitimate diversity. A public system may sustain research through taxation and professional administration; a cooperative may combine member contributions with collective control; a commons may use voluntary contributions and rules developed through its participants; and a private enterprise may provide specialized infrastructure under enforceable public obligations or interoperable standards. Each arrangement can accumulate and expand knowledge-producing capital. The comparative ethical question concerns the conditions under which productive capacities, valuable outputs, decision rights, and burdens circulate in ways that participants can justify, challenge, and modify. Public governance is a substantive achievement requiring ongoing inquiry into those relations, rather than a guarantee attached to a designation of ownership.

Durability also involves competing values. Open publication can foster scrutiny and reuse, while research involving sensitive records may call for restrictions, consent, or community governance. Interoperable standards can lower switching costs while requiring costly coordination. Funding shared foundations can support numerous activities while diverting resources from specific urgent needs. The ethics of knowledge production must therefore address trade-offs among legitimate aims with attention to who bears costs and who possesses decision-making authority. Vallor's account of technological ethics emphasizes the importance of cultivated judgment under complex and changing technological conditions [90]. In the present context, institutionalized practices of deliberation, accountability, and revision are possible supports for such judgment. They remain open to substantive disagreement about desirable ends.

The proposed synthesis is a criterion of *revisable public generativity*: institutional arrangements can be evaluated partly by the degree to which they sustain meaningful opportunities for diverse persons and communities to produce, understand, maintain, and transform knowledge under contestable governance conditions. This criterion treats generative capacity as one important normative object alongside dignity, rights, recognition, material security, cultural stewardship, and other irreducible values. It remains pro-

visional and requires explicit specification of the affected population, protected interests, burdens, and decision procedures in each application. An empirical study could examine how access terms, maintenance funding, attribution, migration costs, and participation rights change across selected knowledge infrastructures; it would still require a normative argument for interpreting those observations as just or unjust.

Evaluating public generativity requires a declared account of the affected public, legitimate restrictions on access, acceptable maintenance burdens, and rights to participate in revising productive conditions. Deep-level dependencies can increase the reach of governance decisions, while a specialized application bottleneck may have comparable practical significance when substitution is difficult. These observations specify questions for institutional ethics; they do not settle the relevant distributive or procedural judgments. Section 16 identifies the conceptual and empirical uncertainties that a defensible application must address.

16 Theoretical Boundaries and Open Research Problems

The present inquiry has proposed a relational account of knowledge-capital formation, recursive expansion, and differential control across generative levels. Its conceptual scope is wider than the evidence presently assembled, and its formal representations specify relations whose empirical estimation remains largely an open research task. This section identifies the boundaries of those claims and articulates an agenda for cumulative inquiry. The discussion proceeds through the historical meaning of primitive accumulation, plural representations of generative levels, measurement of heterogeneous capital and value, identification of power and extraction, institutional comparison, structural transformations and long-range dependencies, and a set of research problems that connect these topics. The method is methodological and critical: it evaluates the assumptions needed to move from political-economic concepts to representational models, from models to observations, and from observations to defensible causal and normative judgments. Its aim is to make the framework revisable without collapsing distinct historical, empirical, formal, and ethical questions into a single criterion.

Three forms of limitation guide the analysis. A *conceptual boundary* concerns the meaning and scope of a category, such as the historical distinction between initial capital formation and primitive accumulation through separation. An *epistemic boundary* concerns what can be learned from the available documents, measurements, historical records, and interpretive accounts. A *practical and normative boundary* concerns the authority of an investigator to rank or redesign productive arrangements whose participants may understand value, ownership, recognition, and legitimate governance differently. These boundaries interact. A formal calculation may be internally correct while its input categories inadequately describe a community's productive relationships; a documented transfer of revenue may be economically measurable while its relation to collective capability remains contested; and a governance proposal may be ethically appealing while its causal effects remain unknown. Maintaining these distinctions is therefore a condition of responsible theoretical development.

16.1 Historical Specificity of Primitive Accumulation

The concept of primitive accumulation carries a historically specific political-economic argument. In Marx's account, separation of producers from the means of production is central to the establishment of capitalist production relations [61]. Enclosure, dispossession, coerced reorganization, and transformations of property relations are therefore more than illustrative events associated with an otherwise neutral acquisition of an initial capital stock. Their place in the concept concerns the constitution of a particular relation between capital and productive labour. Treating primitive accumulation as a synonym for the appearance of any new productive resource would obscure that relation and make the historical claim difficult to test.

The present paper accordingly retains two linked research categories. *Initial knowledge-capital formation* refers to the emergence or stabilization of productive resources and capabilities within a specified

relational and historical boundary. *Primitive accumulation*, in its Marxian register, concerns a transformation in the organization of production, especially when control of productive conditions is consolidated through separation or dispossession. A public archive established by cooperative labour may instantiate initial formation; a contractual or legal restructuring that deprives its contributors of effective access to indispensable means of continued production may invite inquiry into separation and appropriation. The second characterization requires evidence of a changed relation, its historical mechanism, and its material consequences. Its applicability remains a proposition to be investigated, rather than a label supplied by the identity of an institution.

This distinction raises a problem of historical scale. What is initial relative to a particular organization may be inherited relative to a longer social history. The funding, language conventions, legal institutions, scientific methods, and labour capacities mobilized in a newly founded research project arise within existing networks of production and transmission. A study that chooses the founding date of a firm as its opening boundary may assign the resulting productive capacity to that firm, while a longer study may show substantial prior contributions by publicly financed laboratories, education systems, voluntary maintainers, and communities of practice. The boundary can be defensible for a particular investigation, yet conclusions concerning who created, financed, or controls productive conditions are conditional upon it.

A further distinction concerns the institutions within which accumulation takes place. Capitalist production, public administration, cooperatives, commons-based production, and communist conceptions of collective production may each involve historically accumulated knowledge and expanding productive capacities. Their forms of control, allocation, and circulation can differ considerably. An investigation of capitalist appropriation may require an account of property, contracts, wage labour, and revenue claims; an investigation of collectively governed production may focus on membership, custodial obligations, contribution, and decision rights. The same vocabulary of capital formation can assist comparison when its units are specified, while its Marxian interpretation requires sensitivity to the historically particular organization of social relations. An open research problem is whether distinct processes of separation can be compared without presupposing that they all reproduce the same mode of production.

For empirical work, historical process tracing would need to establish when rights or productive capacities were acquired, how the relevant arrangements were justified and contested, what alternatives existed, and whether access to productive means changed. Contract histories, institutional records, funding agreements, labour accounts, interviews, legal materials, and documented technical transitions provide partly complementary evidence. Retrospective judgments should be cautious about assigning a single originating event to cumulative structures that emerged through prolonged social cooperation. The conceptual value of primitive accumulation lies in its ability to direct attention to historically constituted separation and control; its explanatory value depends on identifying such mechanisms in particular cases.

16.2 Generative Levels and Representational Pluralism

The relative generative levels developed in Section 13 are a representation of productive dependence, functional scope, and recurrent transformation. They offer an analytical vocabulary for locating accumulated resources and rules within a partially ordered system. Their construction depends on what is counted as a productive activity, which dependencies are observed, which alternatives are considered feasible, and what institutional or historical boundary is chosen. The same research infrastructure may occupy a comparatively deep position for one set of experiments while functioning as a replaceable application tool for another. A level assignment should therefore include its task domain and evidential warrant.

A generative dependency can take several forms. A mathematical method may be necessary for a specified derivation; a dataset may support training without being uniquely indispensable; a technical standard may enable coordination even when several implementations exist; a peer-review procedure may confer a recognized form of epistemic authority; and an archive may allow future reinterpretations that participants cannot enumerate in advance. These relations have different modalities. Logical deriv-

ability, material necessity, learned convention, institutional authorization, and historically contingent coordination should be represented with typed relations where possible. A single unqualified edge can hide differences that become decisive when interpreting dependency or control.

Representational pluralism follows from this diversity. Directed hypergraphs are useful for modeling activities whose feasibility depends jointly on several inputs. Partial orders are useful where a restricted dependency relation satisfies the relevant order conditions. Networks with feedback or changing vertices can express mutual influence, infrastructural learning, and the alteration of rules through applications. Relational two-complexes may help represent event couplings and higher-order constraints, provided their vertices, edges, and faces have explicit domain-specific interpretations. Such constructions may be related through information-preserving maps over limited domains, but their use does not establish that an observed production system possesses a uniquely privileged mathematical structure.

The selection of a model is itself a knowledge-producing act. Bowker and Star show that classification systems influence social and informational practices, and that their consequences can become embedded in infrastructures [12]. The present framework should therefore examine the politics of its own categories. Who decides that a practice is an “application” rather than a method? Which actors’ tacit knowledge disappears when productive activities are encoded as measurable outputs? What is treated as a substitute when researchers have distinct obligations to a community or to a research tradition? These questions make classification accountable to affected practices. They also caution against representing disciplinary disagreement as a deficiency to be eliminated by imposing a common hierarchy.

A useful methodological exercise is *representation sensitivity analysis*. Investigators can construct alternative dependency maps for the same bounded case: one based on technical prerequisites, another on contractual access conditions, and a third on contributors’ experienced constraints. If a proposed high-leverage dependency persists across defensible representations, the conclusion becomes more robust within the studied domain. If the ranking changes sharply, the disagreement may identify distinct forms of dependence requiring separate treatment. Discrepancy among maps is therefore potentially informative evidence about a plural system, rather than simply modeling error.

16.3 Capital Measurement and Heterogeneous Value Incommensurability

Measuring knowledge-capital accumulation requires clarity about the object being counted. Publications, datasets, software releases, trained researchers, laboratory instruments, preserved collections, institutional recognition, and enforceable access rights can participate in production, but their numerical totals have different meanings. Growth in the number of outputs is compatible with declining interoperability, loss of key maintainers, rising acquisition costs, or a narrowed range of credible research paths. Conversely, a relatively stable archive may become much more productive when documentation, translation, or accessible tools permit new communities to use it. Measures of stock, accessibility, effective capability, and control should consequently remain differentiated.

An operational account could specify a domain of productive tasks and evaluate which activities different participants can perform under observed conditions. Such an account can draw on the capability-set representations in Section 13, but practical measurement must acknowledge that many activities are only partially observable, that feasibility depends on skill and context, and that a reported capability set can change when an investigator revises the task ontology. A count of feasible activities may convey local changes in access; it cannot serve as a universal magnitude of knowledge capital. Further, capabilities may have complementarities: possessing two interfaces together can make a previously inaccessible activity possible, so the productive consequence of each resource need not be additive.

Heterogeneous value adds a second difficulty. Economic income, epistemic reliability, cultural continuity, learning opportunities, institutional authority, preservation, and collective autonomy are evaluated through partly different standards. Some are exchangeable within established contractual or market arrangements; others are experienced as obligations, practices, or public goods whose significance is undetermined by a simplistic common denominator. The value-circulation formalism can keep typed records of transfers, recognition, and transformations; its nodes and conversion rules are nevertheless selective

representations of lived and institutional relations. The existence of a formal map between two types of value does not prove their normative equivalence or the legitimacy of the exchange.

A measurement strategy can combine domain-specific indicators with explicit judgments about their scope. For example, a shared research platform might be assessed through service continuity, documented maintenance labour, data-export feasibility, researcher access, the cost of feasible alternatives, and users' capacity to challenge decisions. Recognition might be assessed through attribution records and interviews alongside bibliometric descriptions. Decisions about which indicators matter should be documented, contestable, and revisable with contributors and affected communities. Aggregation may be suitable for a bounded institutional decision when participants have authorized a purpose and method, while preserving component-level information for scrutiny. Divergent valuations can be reported directly rather than forced into an unexplained composite score.

Uncertainty should be presented as a property of the investigation. Manski's analysis of policy decisions under uncertainty is pertinent because it highlights the risks of presenting uncertain estimates as determinate inputs to collective decisions [60]. In the present setting, missing financial data, unrecorded maintenance, contested attribution, and uncertain substitutes may support ranges, scenario comparisons, or conditional findings rather than precise totals. Measurement protocols should record the observer, unit, period or partial order, excluded contributions, and assumptions concerning valuation. An important open problem is to determine which comparisons remain invariant when relevant participants apply different yet defensible valuation conventions.

16.4 Causal Identification of Power and Extraction

An explanatory theory of extraction needs evidence about mechanisms and their consequences. Observed concentration of rights, high revenue, a dominant technical standard, or disagreement among participants can motivate inquiry, yet none alone establishes that value is being extracted from contributors in the sense developed in Section 12. The proposed concept joins appropriation and control to a recurring relation of asymmetric value capture and constraints upon the reproduction or transformation of productive capabilities. Each component presents evidential demands. The identities and contributions of actors must be reconstructed; access and decision powers must be documented; and the effects of the arrangement require comparison with credible alternatives.

The counterfactual challenge is substantial. A platform that charges a high access price might be necessary to finance reliable preservation and security, or it might exploit substantial switching costs to collect returns disconnected from reproductive contribution. A repository that restricts data access might impose an arbitrary barrier, or it might fulfill legal, ethical, or culturally authorized duties. Observed prices or restrictions cannot resolve these possibilities without contextual analysis. Statistical causal inference, including the potential-outcomes tradition discussed by Holland, emphasizes the assumptions required to interpret differences as effects of particular interventions [44]. Here, interventions on ownership, licensing, interoperability, or governance may alter the set of participants, their strategies, and even the system of productive tasks being measured.

Causal identification is further complicated by selection and simultaneity. Productive organizations may attract users because their infrastructure is valuable, while higher usage can in turn strengthen the organization's capacity to invest and its bargaining position. The institution may select a proprietary standard after attracting substantial participation, or growth may follow a regulatory mandate. A cross-sectional correlation between market concentration and a dependency indicator cannot determine the direction of causation. Historical records, natural experiments, staggered rule changes, contractual discontinuities, and carefully chosen comparison cases may identify particular mechanisms when their assumptions are defensible. Qualitative evidence about the reasons for participation, exit, compliance, and contestation is also necessary to distinguish formal rights from practical choices.

The proposed dependency measures invite a specific methodological caution. In Section 13, a substitution-sensitive measure represents the change in specified feasible activities when a resource or relation is removed under an identified counterfactual scenario. Its interpretation depends on the admis-

sible alternatives, maintained conditions, and task weights. Estimating a large change may establish a form of infrastructural criticality within that scenario. To infer extractive leverage additionally requires evidence about who can control access or conditions, whether value is appropriated through the dependence, whether contributors are constrained, and how resulting benefits and burdens circulate. This sequence preserves the analytical separation between systemic importance, power, and justified claims of extraction.

Interventions may also have heterogeneous effects. Making a dataset publicly accessible can help some researchers, expose others to privacy risks, and change the value of maintenance work. Replacing a proprietary interface may reduce price while increasing reliability burdens for a small public team. A contractual change can increase aggregate output while restricting the ability of a minoritized research community to shape epistemic standards. Identifying a causal effect on one indicator does not settle the associated ethical judgment. Cartwright and Hardie stress the importance of contextual support factors when considering whether evidence from one setting can inform action in another [15]. For public knowledge production, claims about institutional reform should specify the conditions under which a mechanism is expected to operate and the groups for whom its consequences are assessed.

16.5 Institutional Comparison and Empirical Validation

Comparative study is needed to evaluate whether the framework identifies distinctions that are empirically useful across forms of knowledge production. The documentary illustrations in Section 14 establish plausible sites of inquiry, while remaining selective examples. A comparative research design would sample configurations of rights, productive functions, and governing practices rather than infer outcomes from familiar organizational names. A publicly funded laboratory can rely on proprietary instruments; a commercial publisher can maintain open metadata; a cooperative may delegate technical authority to a small team; and a knowledge commons may impose justified restrictions to protect participants or cultural materials. Institutional variation therefore occurs within as well as between nominal types.

One approach is a nested design in which selected cases are studied at several levels. At an infrastructural level, researchers could document inputs, interfaces, maintenance requirements, interoperability, and available substitutes. At an institutional level, they could examine legal rights, funding, contracts, accountability, and mechanisms for revising rules. At a participatory level, they could investigate productive autonomy, epistemic recognition, skills, labour burdens, and the practical possibility of exit or collective voice. The levels are methodological perspectives rather than permanent partitions of the studied system. Analyses should allow one observable mechanism, such as a metadata standard, to connect all three perspectives.

Comparability is a distinct issue from uniform measurement. Certain variables, such as documented costs of migrating datasets or the existence of formal appeal procedures, can be defined comparably across several settings. Other phenomena, including trusted custody of culturally sensitive records or recognition of situated expertise, require interpretation within specific practices. Ostrom's diagnostic approach to complex institutional arrangements cautions against universal institutional prescriptions and encourages systematic attention to interacting conditions [72]. In the present inquiry, that orientation motivates case-specific mechanisms within a common comparative protocol. The protocol should preserve the substantive distinctions that make a practice meaningful to participants.

A prospective study might record an institution's contractual access arrangements, repository infrastructure, contributor labour, and governance procedures before and after a documented rule revision. It could then examine whether changes in portability, research activity, maintenance capacity, and users' perceived agency align with the proposed mechanisms. Such observations require a credible explanation of contemporaneous changes in funding, staffing, technology and demand. A complementary historical comparison could trace how a widely used standard emerged, acquired authority, was contested, and was revised. A third study might reconstruct heterogeneous value circulation among research contributors, public funders, intermediaries and downstream users. These designs would test different parts of the framework and allow some proposed mechanisms to fail independently of others.

Research protocols should be attentive to ethics and positionality. Interviews with workers or research participants may reveal contractual obligations and power imbalances that limit what can be disclosed. Participation in a knowledge commons can create community expectations concerning confidentiality, attribution, and ongoing access to findings. Investigators should consider consent, data security, interpretive review, and the return of useful results to participants, subject to their research design and legitimate confidentiality obligations. The framework's concern with public generativity is itself a reason to examine whether its empirical implementation distributes burdens and authority responsibly.

16.6 Generative Transformation and Long-Range Dependencies

The evolution of knowledge-producing conditions complicates both measurement and causal explanation. A resource that appears deeply embedded in an observed dependency structure may lose importance when a new method makes its function substitutable. A minor application may reveal flaws in a foundational classification system and precipitate substantial methodological revision. A previously marginal community archive may become central to a line of inquiry following a change in research questions, public needs, or interpretive practice. Consequently, an analysis of capital expansion should consider transformations in what counts as a productive condition, a meaningful output, and an admissible continuation of activity.

The distinction among structural change, representational revision, and new observation is crucial. Investigators may redraw a dependency network because newly available documents reveal an older relation, while the underlying production arrangement remains substantially stable. Alternatively, participants may alter a standard, create a new institution, or reorganize their division of labour; those changes can modify the set of feasible transformations itself. A model might also change because scholars refine the semantic categories used to describe an activity. Each situation warrants a different evidential account. Treating every changed graph as evidence of generative transformation would conflate the development of knowledge about a system with the system's own transformation.

Long-range dependence also involves questions of temporal ordering. Research histories may include branching projects, delayed reuse of archived materials, concurrent collaborations, retrospective reinterpretation, and innovations that redefine their apparent precursors. The formalism allows histories and continuation relations to be specified for the task at hand; it does not posit a universal global present or assume that every productive relation is ordered by a single clock. An empirical study may use chronological dates for contractual changes or funding disbursements while employing partial orders to describe dependencies among research activities. The choice should be justified by the mechanism under investigation, and where appropriate, by participants' accounts of how historical continuity is constituted.

Questions about "deep" and "shallow" accumulation therefore concern a moving domain of possible paths. Meta-knowledge may have many downstream uses within one historically situated system, yet novel applications can establish new conceptual categories, eliminate a dependency, or redirect research priorities. An application-level bottleneck can at times be more consequential for an immediate public capability than an abstract principle near the root of an analyst's representation. Moreover, the effect of replacing a resource can be discontinuous when multiple complementary infrastructures must be changed together. In such circumstances, a local measure of substitutability may underestimate coordinated transition costs and overestimate the stability of an incumbent's leverage when collective replacement is feasible.

Formal analysis of changing dependency structures could begin with a family of relational configurations linked by specified continuation or revision maps. Such a family might record changes in feasible activities, stakeholder rights, and value-circulation paths without presupposing that elements persist unchanged. More ambitious models could investigate the appearance or disappearance of dependency cycles, the splitting or merging of productive institutions, and the reconfiguration of higher-order couplings. These extensions should have explicit interpretation and observational tests before topological or dynamical terminology is used to explain a social event. The capacity to draw a changing complex

provides a representational possibility; claims about the causal importance of a topological transition require separate argument.

16.7 Open Problems in Public Knowledge Capital Research

The preceding limitations identify a programme of interconnected research problems. The initial priority is to develop comparable historical accounts of the formation of knowledge-producing conditions. Such accounts would distinguish inherited public contributions, new investment, cooperative creation, legal appropriation, and changes in productive dependence. Their aim would be to determine how the same resource can participate in different accumulation processes, and when the historical concept of primitive accumulation adds explanatory specificity. A second priority concerns mapping generative dependencies across disciplines and institutions without erasing locally meaningful differences. Both tasks require explicit sampling boundaries and records of uncertainty.

A third problem concerns the evaluation of heterogeneous capital and value. Researchers need methods that retain economic, epistemic, cultural, social and institutional dimensions while supporting intelligible comparison. Partial orderings, multi-criteria descriptions, counterfactual capability sets, and participatory evaluation provide possible starting points. The theoretical challenge is to clarify when transformations between valuation domains preserve relevant meanings and when the translation changes the practical interests at stake. An associated empirical challenge is to recover maintenance and reproductive labour whose contributions may be omitted from public financial accounts or conventional output metrics.

A fourth problem concerns extraction. The central task is to establish a diagnostic sequence linking contribution, dependency, access control, appropriation, value circulation and changes in productive agency. Comparative evidence should distinguish fees supporting legitimate joint maintenance from rents sustained by contestable barriers; it should also clarify how benefits can accrue to users who did not directly contribute to the underlying resource. Such distinctions may require a combination of account-level observations, contract analysis, participant interviews, infrastructure tests, and causal designs based on documented interventions. Where competing interpretations remain compatible with the evidence, the conclusion should retain that ambiguity.

A fifth problem concerns institutional change and governance. Which combinations of common access, differentiated stewardship, paid coordination, public investment, cooperative authority and rights of contestation can support the reproduction of productive capabilities? How do such combinations respond to scarcity, privacy, scientific reliability, long-term preservation and cultural obligations? The inquiry should compare arrangements under similar constraints while allowing institutional purposes to differ. The value of a general framework lies in helping investigators discover situated trade-offs and possible reforms, not in predetermining a single organizational ideal.

A sixth problem concerns reciprocal generative change. Empirical research could trace cases where application-level activity modifies a methodology or an epistemic standard, changing the dependency position of accumulated capital. Equally important are instances where the concentration of a foundational resource fails to generate effective control because substitutes, collective governance, or institutional checks remain available. Identifying such counterexamples would refine the proposed relation between generative depth and extractive leverage. It would also help separate the historical stability of a productive system from the persistence of a particular analyst's categories.

The empirical agenda is organized by research domain in Table 17; the table separates unresolved distinctions from candidate evidence and methods.

The distinctions in Table 17 make the evidential scope of each proposal explicit. A chosen research technique cannot substitute for identifying the question it is meant to answer. Some parts of the programme may support statistical causal estimates; others may remain historical reconstructions, formal possibility claims, or participatory normative inquiries. The contribution of a common conceptual framework is to coordinate these investigations while allowing their evidential standards and conclusions to differ.

Table 17: Research boundaries, evidential requirements, and candidate validation strategies for knowledge-capital analysis.

Research domain	Principal unresolved distinction	Candidate evidence or validation practice
Historical formation	New productive capacity; separation and dispossession	Archival process tracing, property changes, funding and labour histories
Generative levels	Posited dependency; observed substitutability; participants' interpretations	Typed dependency mapping, alternative representations, substitution tests
Capital and value	Resource stock; feasible capabilities; heterogeneous valuation	Multidimensional indicators, cost and maintenance records, participatory interpretation
Power and extraction	Systemic importance; effective control; recurrent asymmetric capture	Contracts, switching costs, transfer records, interventions and counterfactual comparison
Institutional comparison	Organizational category; operative governance mechanism	Nested case studies, matched mechanisms, qualitative and quantitative triangulation
Historical transformation	Change of system; change of model; change of evidence	Versioned records, revision histories, longitudinal dependency maps

Finally, the relation between public generativity and justice remains a substantive open question. The provisional criterion of revisable public generativity in Section 15 directs attention to contributors' and communities' capabilities to maintain and transform the conditions of production. Its application requires decisions concerning the relevant public, legitimate restrictions, justified inequality, distributional burdens, and institutional responsibility. These decisions warrant explicit normative debate and may remain contested after empirical effects have been estimated. In that sense, the proposed theory is intended to sustain further historical, mathematical, empirical and ethical work. Its development will depend on careful examination of cases where the framework succeeds, cases where it needs alteration, and cases whose meanings resist its categories.

17 Conclusion

The present paper has examined the historical formation, accumulation, and expansion of knowledge-producing capital as processes constituted through changing relations among resources, persons, institutions, generative rules, and productive capabilities. Its primary objective has been to articulate a comparative theoretical vocabulary with which capital formation can be investigated across institutional configurations and across relative generative levels. The inquiry has combined political-economic interpretation, knowledge-commons research, considerations of heterogeneous value, a provisional relational formalism, documentary illustrations, and an explicit account of evidential and normative limits. This concluding section brings these arguments together, specifies the scope of their contribution, and identifies the main requirements for further inquiry. Its claims concern an analytical proposal rather than a demonstrated general law of knowledge production.

A central result of the conceptual analysis is the distinction between the formation of productive knowledge capital and the historically specific process of primitive accumulation. Within a defined field of investigation, productive conditions may emerge from inherited knowledge, collective labour, public investment, maintained infrastructures, and institutional coordination. Such formation can take place within capitalist enterprises, public research systems, cooperatives, knowledge commons, and arrangements informed by communist conceptions of collective production. The Marxian category of primitive accumulation, by contrast, requires inquiry into transformations of productive relations, particularly separation, dispossession, and the constitution of control over the conditions of production [61]. The broader

phenomenon of initial formation supplies a comparative object; historical claims about primitive accumulation require more specific evidence. Preserving both categories makes it possible to recognize collective and public processes of accumulation while identifying occasions on which newly concentrated power depends upon exclusion or dispossession.

The accumulation of productive knowledge capital likewise requires specification beyond an increasing quantity of stored information or an increasing valuation of intellectual property. A growing archive may contain more records while leaving the ability to interrogate and maintain them fragile. A scientific group may acquire equipment that raises its feasible research capabilities without owning the knowledge it uses. A commonly governed infrastructure may develop new productive capacities through coordinated maintenance even where monetary surpluses remain modest. Conversely, a resource may become a valuable object of exclusive control while its contribution to wider knowledge creation is constrained. These observations motivate separate descriptions of knowledge resources, feasible capabilities, reproducible productive conditions, capitalized positions, and effective control. Relations among these dimensions should be investigated empirically, with the boundary of the producing system and the relevant participants made explicit.

The generative-level perspective adds a further structural dimension. Meta-knowledge, epistemic standards, theoretical resources, methods, shared infrastructures, and application-level outputs can occupy different positions in the dependencies through which knowledge production becomes feasible. Accumulation at a level with many dependent activities may influence the conditions under which diverse kinds of knowledge can be created, verified, represented, or circulated. A resource's position, however, is relative to the production arrangement, its available alternatives, and the analytical purpose of the model. A generative grammar offers a useful analogy for nested dependencies, although knowledge systems may exhibit reciprocal revision, multiple foundations, distributed authorship, heterogeneous standards, and overlapping or cyclic relations. Applications can reorganize methods and epistemic assumptions; an ostensibly foundational resource can lose practical significance through successful substitution. Generative depth thus acquires explanatory value through a specified relation to effective dependency, replacement costs, historical transformation, and institutional authority.

This distinction has direct consequences for the analysis of power. A legal right to exclude use of an output, custody of a dataset, authority to amend an evaluation standard, access to a computing service, and a participant's effective ability to conduct research are different relations. These forms of ownership, permission, custody, and practical control can be allocated to distinct actors or combined within a single organization. Their effects depend on the productive tasks at stake, the enforceability of rights, the distribution of alternatives, and the capacity of affected parties to challenge a decision. Concentration at an apparently foundational generative level may create considerable leverage where downstream activities depend on a controlled and difficult-to-substitute condition. The same concentration may have limited leverage where viable alternatives, interoperable systems, shared governance, or countervailing institutions remain available. The manuscript therefore treats generative depth as one possible determinant of structural significance, rather than as an automatic index of power or harm.

A related contribution is the differentiation of value creation from recognition, attribution, capitalization, appropriation, circulation, and reproduction. Knowledge production can generate economic resources alongside epistemic, educational, cultural, relational, and institutional goods. The processes that generate these goods can involve dispersed contributors, long-standing public infrastructures, inherited concepts, care and maintenance, interpretive labour, and resources that receive little visible credit in conventional output accounts. Recognition systems help make some contributions legible while leaving others difficult to record. Markets, funding systems, professional organizations, public agencies, and knowledge commons provide different channels through which value may be transferred, translated, redistributed, or reinvested. Since these forms of value may be incommensurable or only locally comparable, the analysis is better served by plural accounts of valuation than by an unqualified aggregate of knowledge capital. Such an account follows the concerns of plural value theory and social epistemology while maintaining the political-economic question of who controls the conditions of subsequent production [2, 57].

Value circulation matters to capital expansion because it participates in the reproduction of the system that generates value. An income stream can maintain a shared repository, support contributors, finance research equipment, or accumulate under an actor who controls a critical service. Nonmonetary circulation can support further production through mentoring, documentation, transferable expertise, reciprocal review, and mutual maintenance. Each arrangement can create new capabilities, redistribute burdens, or alter the authority to decide how productive conditions are organized. The appropriate unit of inquiry is therefore a trajectory of connected productive arrangements rather than a transaction isolated from the work that enabled it. The concept of circulation becomes analytically substantive when the investigator can specify the value concerned, the actors and conditions implicated in its production, the mechanism of transfer or conversion, and its effects on the capacity for further creation.

The comparative institutional analysis supports a related clarification. Capitalist, public, cooperative, commons-based, and communist-conceived arrangements admit practices of capital formation, reinvestment, and expansion, although their rights, purposes, authority structures, and means of distribution may differ. A commons is a governed social and institutional arrangement concerning shared resources and collective rules; it does not define a comprehensive political-economic regime. Public ownership similarly leaves open the allocation of practical decision authority, access, maintenance responsibilities, and the possibility of institutional exclusion. Privately organized systems can provide valuable shared services under enforceable duties or interoperable arrangements, while commonly governed systems may face unequal voice, insufficient support for maintenance, and concentrated informal authority. Theoretical comparison should consequently specify operative arrangements rather than infer productive or ethical outcomes from organizational names. The commons literature provides analytical resources for studying these rule configurations, their participants, and their changing relations to shared knowledge [40, 71].

Extraction occupies a distinctive place within this account. An unequal distribution of economic returns, a high level of institutional centrality, a proprietary licence, or an asymmetrical relationship of expertise supplies an object for investigation but does not, on its own, determine whether an extractive structure exists. The proposed diagnosis examines contributions to production, the formation and control of dependencies, institutional restrictions on participation, mechanisms of recurrent value capture, the allocation of maintenance and risk, and the consequences for the productive capabilities of those whose efforts help sustain the arrangement. The distinction between extraction and exploitation also requires attention to the relevant political-economic and normative standards. Where empirical records leave rival explanations open, the conclusion should remain conditional. This caution is especially important in research concerning epistemic and infrastructural power, where a formal network model may identify centrality more easily than it identifies a legally and socially situated relation of appropriation.

The proposed connection between extractive leverage and generative levels is thus a conditional hypothesis. When a productive resource supports many consequential activities, substitutes are costly or unavailable, effective control is concentrated, and the governance of transfers permits recurrent appropriation, a control position may propagate its effects through extensive portions of a knowledge-producing system. Such propagation can influence the feasible activities of downstream contributors and the capacity to maintain or revise the foundations on which those activities depend. In some settings, captured returns may further strengthen the controlled position through investment, standard-setting authority, contractual lock-in, or the acquisition of complementary resources. In other settings, adaptation, collective action, interoperability, or the reconfiguration of dependencies can attenuate or reverse the concentration. These possible processes should be investigated as historically situated mechanisms. Neither their direction nor their magnitude follows from the level assigned to a resource in an analyst's diagram.

The relational formalism developed in Section 13 was designed to make several such distinctions inspectable. Its typed dependencies distinguish productive requirements from other connections; its capability relations concern feasible activities rather than undifferentiated output counts; its valuation representations permit heterogeneous measures and partial comparisons; and its rights and power components represent differentiated authority. Counterfactual dependency measures incorporate the availability of admissible substitution pathways. Under the stipulated assumptions, Proposition 13.2 establishes a re-

stricted monotonic relation between the enlargement of admissible alternatives and the modeled loss caused by removing a resource. This is a mathematical consequence of specified feasible sets, not an empirical theorem that increased openness necessarily reduces social extraction. The formalism offers a language for constructing testable accounts and locating modeling assumptions. It leaves open the identification of actual causal relations, the legitimacy of competing valuations, and the institutional interpretation of modeled authority.

The documentary illustrations show the range of questions such a language can organize without establishing a universal pattern. Scholarly publishing highlights relations among access, scholarly labour, evaluative institutions, and control of dissemination services. Open-source production raises questions of maintainers' burdens, free use, practical governance rights, and contributions that sustain common technical foundations. Scientific standards show how rules that facilitate coordination can also become sites of consequential authority. Artificial intelligence infrastructures draw attention to the conjunction of models, data, computation, labour, access interfaces, and evaluation regimes. Archives and humanities institutions show that cultural stewardship, interpretive legitimacy, provenance, and the rights of affected communities may alter what counts as beneficial circulation. Comparative analysis across these domains should therefore concern specified mechanisms and evidentially supported contrasts, while retaining the distinctive legal, epistemic, and cultural purposes of each institution.

The ethical analysis introduces a provisional criterion of *revisable public generativity*. It concerns the extent to which persons and communities have meaningful opportunities to participate in creating, understanding, maintaining, and transforming the conditions of knowledge production under arrangements they can question and help revise. This criterion directs attention to capacities that conventional distributions of finished outputs may overlook. It also requires material support, recognition, safeguards for vulnerable contributors, appropriate forms of access, credible routes of appeal, and institutional mechanisms for correcting erroneous or unjustified decisions. Its application has to coexist with other legitimate ends, including dignity, privacy, scientific reliability, cultural stewardship, security, and the protection of rights. It therefore functions as one evaluative standpoint within a plural field of ethical and political-economic concerns. An empirical finding of reduced substitutability, for instance, warrants investigation of governance and burden; the conclusion that the resulting arrangement is unjust requires a further argument concerning duties, affected interests, and available alternatives.

The present study also leaves important matters unresolved. It provides neither a fully operational definition of a knowledge-capital stock applicable across disciplines nor an empirically identified causal estimate of extraction. The boundary of a knowledge-producing system can itself be disputed; its generative levels may change as participants develop new tasks or revise their epistemic practices. Different valuations may remain incompatible without making the investigation incoherent. The evidence necessary to determine who creates a resource, who maintains it, and who benefits from it may be incomplete or subject to legitimate confidentiality restrictions. Moreover, an account of historical transformation should distinguish observed changes in production from revisions to the investigator's representation and from changes in the accessibility of evidence. These limitations are substantive components of the research agenda, particularly where apparently precise indicators risk concealing unresolved interpretive judgments.

Further research can proceed through carefully bounded comparisons. Historical process tracing could reconstruct the emergence of productive conditions, public contributions, institutional enclosure, and changes in participants' access. Longitudinal records of funding, maintenance, standards, licences, and technical interfaces could help distinguish initial investment from a continuing power to dictate access terms. Mixed methods could compare feasible substitution paths and migration costs while eliciting the experiences of contributors whose capabilities depend on a shared service. Participatory evaluation could test whether proposed indicators capture what relevant communities regard as valuable and whether measured improvements are accompanied by new forms of exclusion. Where circumstances permit, credible interventions and appropriate counterfactual designs could help estimate causal effects. The methodological programme will benefit from cases in which seemingly deep control produces little effective dependency and cases in which an application-level resource becomes indispensable across

many forms of production. Such counterexamples can refine both the dependency concept and the scope of the extraction hypothesis.

Several questions consequently remain available for further theoretical development. How can an evolving family of generative structures be compared when its constituent activities, rules, and concepts are transformed? How should the distribution of authority be represented when rights to access, maintain, interpret, revise, and exit are held by overlapping groups? Under which institutional conditions does value recirculation replenish publicly useful generative capacities, and under which conditions does it reinforce a dependence on concentrated productive resources? What ethical responsibilities arise when a resource becomes broadly foundational through many unrelated contributions, even though its legal title is held by one institution? What alternatives to exclusion preserve incentives for care, scientific reliability, and sustained investment? These questions invite connections between historical political economy, relational mathematics, organizational research, institutional design, and public deliberation. The relevant relations should be examined in their situated contexts rather than reduced to a universal design formula.

The framework's central contribution is therefore a shift of analytic attention toward the conditions under which knowledge production is reproduced and transformed. Capital accumulation includes the formation of resources and capabilities; expansion concerns their capacity to support further productive activity; political-economic analysis examines who is empowered to mobilize and govern those conditions; and investigation of heterogeneous value asks how benefits and burdens circulate through the relations that sustain them. Generative levels add a relational account of differential influence without imposing a fixed hierarchy. Taken together, these distinctions permit the study of shared knowledge creation and asymmetric capitalization within the same evolving system. They also provide a way to ask whether an accumulation process expands the substantive capacity of diverse contributors to continue producing knowledge and to participate in changing the arrangements under which that production takes place.

The future value of this account depends on its capacity to be corrected by historical records, counterexamples, participant interpretations, mathematical scrutiny, and ethical disagreement. Its intended contribution is an open analytical foundation for studying knowledge-capital accumulation across heterogeneous generative structures and institutional forms. Decisions about how to allocate productive conditions, circulate value, and govern the development of knowledge remain historically specific and publicly consequential. A theory of public knowledge capital can assist such decisions by clarifying the resources, dependencies, authority relations, and reproductive conditions at stake, while leaving the justification and revision of concrete arrangements to evidence, accountable institutions, and the persons and communities affected by them.

A Terminology, Notation, and Analytical Conventions

The present appendix supplies a consolidated vocabulary and notation guide for the framework developed in Sections 13 and the preceding political-economic analysis. Its objective is to make comparisons across generative levels reproducible in their declared scope and to preserve distinctions that might otherwise be obscured by the common language of capital, value, ownership, and dependency. The appendix proceeds from the principal political-economic terms to generative-level descriptions, differentiated rights and value relations, the formal symbol inventory, conventions for comparing historical configurations, and an illustrative protocol for applying the vocabulary. The entries establish analytical usages within this paper. They are proposals for disciplined inquiry rather than claims that the same terminology bears an identical meaning across traditions or institutions.

A.1 Capital Formation, Accumulation, and Expansion

Knowledge resource denotes a recorded or otherwise transmissible object, practice, or relationally maintained body of knowledge that can contribute to productive activity. Examples include documents, corpora, experimental results, methods, public records, and shared conventions. The term does not presuppose property ownership, a monetary price, or complete representation in a digital artifact. Some resources depend upon living interpretive and institutional practices for their continued usefulness.

Productive condition designates a requisite or enabling circumstance under which a specified activity may be undertaken. The condition can be material, cognitive, technical, organizational, legal, ecological, or epistemic. Its scope is task-relative: a verification protocol might be essential under one disciplinary standard and optional under a different practice. Conditions may be jointly necessary within a specified plan while individually replaceable through another plan. Accordingly, a claimed productive dependency should identify the activity, population, institutional setting, and practical alternative routes on which the claim rests.

Productive capability denotes an actor's or organized collectivity's feasible ability to perform activities under specified resources, relations, permissions, skills, and coordination. The capability concept is practical and relational. Individual learning contributes to productive capability, yet persons and their learning do not thereby become alienable capital objects. An inquiry may distinguish personal capabilities, organizational capabilities, and capabilities sustained through a public infrastructure without assuming that these are interchangeable or transferable. Section 13 supplies a task-relative feasible-set representation for this purpose.

Initial capital formation refers to the establishment or consolidation of productive conditions capable of supporting a continuing process of knowledge production. The term is relative to a declared analytical boundary and does not posit a first moment of knowledge production or an absolute beginning of capital. An initiative may establish its first maintained archive, method, research workforce, or institutional arrangement while drawing upon extensive inherited resources created elsewhere. Initial formation may occur through private investment, collective cooperation, public support, charitable contributions, or several arrangements in combination.

Primitive accumulation, in the historically specific Marxian discussion adopted as a point of reference in the main body, concerns the formation of capitalist relations through processes that include dispossession and the separation of producers from productive means. Applying this historically specific term to a knowledge-production case requires evidence of the relevant processes and relationships. An initiative's initial formation of a research capacity is therefore a broader comparative object than primitive accumulation in that specific sense. The paper keeps the two objects in dialogue because formation of a new research infrastructure and reorganization of command over an existing public knowledge base may occur together in the same historical episode.

Accumulation denotes a historically constituted buildup or stabilization of productive resources, capabilities, institutions, or strategically relevant relations. The inquiry should state the accumulated object and the relation that makes its continued use possible. Accumulation of publications, accumulation of

reproducible methods, accumulation of shared technical capacity, and accumulation of legally enforceable claims over access all describe different phenomena. Their effects may diverge even when a single administrative measure reports an increase in each.

Capitalization denotes the organization of resources, rights, capabilities, or institutional positions as objects of prospective economic or strategic claim, valuation, investment, or command. A commercial platform may capitalize privileged control over a public knowledge interface while the underlying knowledge remains formally accessible. Capitalization may also occur through financial expectations attached to future revenue or through the consolidation of strategically valued institutional positions. The concept therefore requires identification of the claim-holder, the resource or position, the valuation convention, and the process through which prospective benefit can be appropriated.

Capital expansion refers to an enlargement or transformation of capital-relevant conditions and claims under an explicitly specified comparison. An increase in the number of usable tools, the variety of feasible research activities, the stability of a shared infrastructure, and an enterprise's control over a vital interface can each constitute a different kind of expansion. The paper does not assume that these changes are equivalent or that each increase is publicly beneficial. Where a transformation improves quality while deliberately restricting unsafe activities, the change can be significant despite a smaller raw count of feasible activities. *Recursive expansion* is the more specific case in which accumulated resources or capabilities alter the conditions and rules governing subsequent accumulation.

Institutional configuration denotes a historically situated arrangement of production, governance, entitlement, obligation, and coordination. Capitalist enterprise, publicly maintained research, cooperative practice, commons governance, and communist conceptions of production are analytically distinguishable configurations or traditions. Commons-based production denotes specified shared-resource and governance relations rather than a synonym for communism. A label alone gives insufficient information about an institution's effective access rules, decision authority, or circulation of benefits and burdens. The comparative unit remains the observed institutional arrangement.

A.2 Generative Levels and Dependency Structures

A *generative component* is a represented condition, method, object, rule, institution, or infrastructure participating in the production or transformation of other specified components or activities. The model can assign a component more than one role. A research repository, for example, may operate as an output of archival labour, a prerequisite for later studies, a site of value circulation, and an object of governance. Its location within a knowledge-production structure depends upon the relation being analysed.

A *generative level* expresses a model-relative position in a specified dependency structure. Meta-knowledge, methodological rules, standards, shared infrastructures, applications, and concrete outputs can serve as useful descriptive families. These families need not form a fixed universal ranking. A method can support applications; applications can generate evidence that revises the method. Such reciprocal influence may be represented by cycles, typed interdependencies, or several partially ordered projections of the same system. Generative position therefore refers to relational support within a model, with a declared task scope and chosen granularity.

Meta-knowledge denotes knowledge concerning the conditions, practices, criteria, and limits through which knowledge claims are generated, interpreted, assessed, represented, or translated. Some meta-knowledge can be formally articulated in inference rules or evaluation protocols; other forms depend upon historically developed judgment, tacit practices, or institutional norms. The resemblance between a knowledge-producing system and a generative grammar is a modelling analogy. It does not imply that the system possesses one stable grammar or that linguistic derivation provides a complete account of human inquiry.

Generative depth is a positional descriptor relating an element to other represented components and activities through dependency pathways. Operationalizations may use path length, level sets, condensation orders, or a partial ranking. These measurements need not agree. An upstream component may have broad downstream reach while remaining easily replaceable; a near-output interface may occupy a

single indispensable gate for many users. Depth should consequently be reported separately from reach, effective dependency, substitution cost, and institutional control.

Downstream reach describes the set of represented components or activities connected to a selected component through declared support pathways. *Effective dependency* concerns the consequences for feasible activity when access to that component is restricted under realistic, accessible alternatives. Reach is structural; effective dependency additionally requires assumptions about substitution, resources, rights, and adaptation. The same graph may support different dependency estimates for distinct actors because the alternatives available to them differ.

Substitutability refers to the availability of technically and institutionally feasible replacement or adaptation plans relative to a specified productive task. Credible substitution may require skills, additional funding, compatible interfaces, licensing permissions, and maintenance commitments. A technically demonstrable alternative does not necessarily constitute an accessible substitute for the actor being assessed. Substitutability can change after collective investment, legal amendment, or new epistemic practices. It is therefore a property of a situated comparison rather than a fixed attribute of an object.

Cross-level interaction is the support, restriction, conversion, or reconfiguration of productive conditions among relatively distinguished generative positions. Downstream applications may produce resources for methodological development, while methodological standards may influence the evaluation of downstream outputs. A *structural transformation* changes the represented productive dependencies, institutional rights, or generative conditions themselves under an empirically supported interpretation. An analyst's revision of the categories used to describe an unchanged practice is recorded separately as a representational transformation.

A.3 Value, Property Relations, and Institutional Power

Heterogeneous value denotes the plurality of potential benefits, burdens, capabilities, understandings, recognitions, and institutional consequences arising through knowledge production. The paper distinguishes economic, epistemic, social, cultural, technical, and institutional dimensions as potentially useful analytical categories. Their meanings and measures depend on context. Some values admit agreed cardinal accounting; others are ordinal, relational, contested, or only partially describable. Heterogeneity gives a reason to preserve typed descriptions even when selected monetary or performance comparisons remain useful.

Value creation concerns processes through which a contribution or coordinated activity generates outcomes of a specified kind. *Value recognition* concerns practices by which some outcomes are identified, evaluated, and rendered institutionally legible. *Value attribution* concerns the allocation of credit, authorship, responsibility, or contributory standing. *Value circulation* concerns the relations through which value-bearing resources, benefits, obligations, knowledge, recognition, or support become available, are transferred, are converted, or alter further production. These processes can occur in overlapping configurations while distributing benefits differently. A value-transfer observation should identify the value domain and its accounting or interpretive convention.

Value conversion means a documented institutional or relational process linking different value domains, such as financial resources supporting research time or recognized research activity influencing an allocation decision. Conversion may be partial, contested, conditional, or mediated by rules that benefit participants unequally. A statistical association between recognition and grant funding is one possible clue to such a relation; causal conversion requires evidence of a mechanism. *Value recirculation* refers to circulation that contributes to the continuation, repair, accessibility, or transformation of productive conditions. An arrangement can produce economically valuable outputs while leaving maintenance labour and preservation costs elsewhere in the system.

Ownership denotes a historically and legally situated set of claims over specified objects, with details supplied by the governing jurisdiction and institutional rules. *Access* concerns permission and effective opportunity to inspect or use a resource. *Control* concerns the practical or legally supported capacity to alter its availability, permitted uses, requirements, or governance. *Authority* concerns recognized

Table 18: Configuration and dependency notation used in the relational formalism.

Notation	Declared role	Interpretive qualification
$\mathcal{H}$	Historical knowledge-production configuration	Context- and boundary-relative representation
V, E	Generative components; typed dependency hyperedges	Components and relations selected for an inquiry
$A, Q, \mathcal{Q}$	Actors or collectivities; represented tasks; comparison task universe	Task universes require compatible criteria
P, R, X, I	Practices; rights/powers; value events; interpretive context	Distinct analytical fields with interacting referents
$\mathcal{K}, \kappa_e$	Dependency-type set; type of a hyperedge	Informational, methodological, institutional, or other typed supports
S_e, y_e	Prerequisite family and target of hyperedge e	Joint support and alternatives require interpretation
$[v]_{\mathcal{H}}, \preceq_{\mathcal{H}}$	Condensed dependency class; relative precedence relation	Partial order only after justified condensation and projection
$\phi_{\mathcal{H}}, W_a$	Binary feasibility predicate on actor-task-arrangement triples; admissible productive arrangements	$w \in W_a$ contains component inputs and applicable constraints; unknown evidence is separately flagged

competence to make a rule, interpret a criterion, certify a result, or resolve a dispute. The four terms can overlap, yet their distributions may differ. A public archive may be held by one institution, used by many others, and subject to review rules that distribute consequential decision powers.

Productive autonomy refers to an actor's practicable scope to pursue, maintain, and change knowledge-producing activities, including through cooperation and collective voice. In this usage, autonomy can be evaluated without treating people, their personhood, or their embodied knowledge as objects to be owned. *Contestability* denotes institutional and practical opportunities to challenge decisions, seek reasons, propose changes, and obtain review or remedy. Formal rights of appeal provide one element of contestability; effective capabilities to exercise those rights remain an additional matter.

Power designates a relational capability to influence the options, decisions, understandings, or outcomes of other actors within specified institutional and productive configurations. It may operate through resource allocation, access requirements, evaluative standards, agenda-setting, recognized authority, or the feasibility of alternatives. *Appropriation* describes the taking or allocation of benefits, claims, or control positions, without by itself determining legitimacy. *Extraction* is an analytically stronger description of a sustained arrangement in which control or dependency enables recurrent appropriation of value arising through others' contributions under identified conditions. *Exploitation* involves a further political-economic or normative judgment whose criteria should be made explicit. The investigation must identify contributions, burdens, agreements, alternatives, institutional responsibilities, and available remedies before evaluating those descriptions in an empirical case.

Public generativity refers provisionally to collective capacity for creating and reproducing shared knowledge-producing conditions. The more demanding normative expression *revisable public generativity* places attention on effective opportunities to understand, participate in, contest, and transform those conditions. Neither expression is intended as a single universal welfare index. Their operational relevance varies with the community, its activities, and the justified distribution of responsibilities.

A.4 Core Mathematical Notation

The symbol inventory is anchored in the main formal definitions of Section 13. Symbols identify types of represented information and locally defined operations; they need not denote mutually disjoint historical substances. Tables 18 and 19 collect the central names so that a reader can interpret the formal model without guessing the types of objects or their empirical meanings. The conventions apply to this paper and should be restated whenever an empirical application materially changes a definition.

A hyperedge in the model joins a finite prerequisite family to a component or task under a declared

Table 19: Capability, valuation, intervention, and continuation notation.

Notation	Declared role	Use conditions
$\text{Cap}_a, \Gamma_{\mathcal{H}}(a)$	Feasible tasks; generative reconfiguration repertoire	Actor-relative under stated productive conditions
$\text{Gain}_a, \text{Loss}_a$	Changes of capability sets across a transformation	Fixed or explicitly translated task criteria
ν_k, V_k, F_{ab}^k	Typed valuation; value domain; compatible circulation flow	Quantitative balance only for suitable domains
$C_{k\ell}^r$	Institutionally mediated value-conversion relation	May be partial, non-functional, or contested
$R_{\mathcal{H}}, \text{Influence}_{a \rightarrow b}$	Rights/powers map; counterfactual influence profile	Nominal entitlements and effective options separated
$\mathcal{B}_v, \delta_{a,q}, D_S$	Admissible substitutions; task loss; dependency score	Fixed comparison scheme; feasible alternatives included
$\text{EL}_{a,v}$	Descriptive potential extractive-leverage profile	Requires additional control, circulation, and remedy evidence
$\text{Adm}, \tau, \text{Cont}_a$	Admissible transitions; transformation; feasible continuations	Compatible interfaces and declared histories

dependency type. The directed-hypergraph representation in Equation 2 specifies the formal type of the relation. Multiple support routes to the same target can be represented, and conjunctive prerequisites should retain their meaning in any graph projection. The precedence relation in Equation 3 refers to reachability among condensation classes. Consequently, a reported precedence rank should specify the graph projection, treatment of reciprocities, granularity, and the activities for which it is interpreted.

The signs $\ominus v$ and $\oplus b$ used in Equation 12 specify modeled restriction and replacement interventions. They are separate from ordinary set subtraction and arithmetic addition. The positive-part notation $[z]_+$ records only the selected nonnegative loss in a task-specific comparison. Likewise, an arrow between two configurations denotes an admissible modeled transformation; it makes no claim that the ontology of historical becoming is exhausted by the diagram. A partial valuation arrow indicates that the declared mapping may be undefined for some events. The quantifier over substitution plans refers to a researcher-specified, feasible class of plans rather than an unlimited universe of imaginable substitutes.

Where a descriptive profile uses several domains, its appropriate output may be a tuple, relation, partial ordering, or narrative account. A scalar is justified only after units, normalization, aggregation rules, and the relevance of weighting have been defended. This convention applies equally to production-capability comparisons, value circulation, power, and the proposed effective-dependency score. The proposition on substitution enlargement in Section 13 concerns the behaviour of a selected mathematical score under fixed assumptions; its empirical interpretation depends on which substitutes are practically accessible.

A.5 Historical Comparison and Modal Interpretation

A *historical configuration* is an analytically delimited state of productive and institutional relations, recorded with whatever temporal and documentary structure is justified by the inquiry. A *represented history* is a structured family of configurations and relations supported by particular traces or reconstruction rules. A *continuation* is a composable admissible family of transformations from a selected configuration. These conventions separate a documented transformation from a hypothetical alternative and from an available, but unrealized, productive possibility. A chosen temporal coordinate may be useful for an empirical data series without constituting a universal or privileged ordering of all relevant processes.

This distinction matters for discussions of capital expansion and path dependence. Describing one infrastructure as inherited from another requires historical and institutional evidence, including mechanisms of transfer, adaptation, preservation, or learning. The mere appearance of a later date in a record need not establish productive dependence. Likewise, the set of admissible continuations may include pathways generated by revised rules or newly imagined possibilities. An analytical possibility should

Table 20: Claim-status conventions for theoretical and empirical extensions of the paper.

Status	Permitted interpretation	Further justification
Conceptual distinction	Terms are separated for an articulated analytical purpose	Coherence, scope, comparison with rival concepts
Formal definition or proposition	Result follows within the declared mathematical representation	Assumptions, proof, validity of definitions
Historical interpretation	Account reconstructs situated practices and relations	Sources, contextualization, alternative readings
Empirical association	Observed variables vary together in a specified sample	Measurement validity, sampling, uncertainty
Causal hypothesis	Proposed mechanism links interventions and outcomes	Identification strategy, counterfactual assumptions
Normative assessment	Institutional arrangements are judged using declared ethical criteria	Justification, affected standpoints, contestation
Exploratory analogy	One structural vocabulary suggests questions for another domain	Boundary conditions, remainders, failed mappings

not automatically be characterized as an event waiting to be realized. It is a modal status within a specified representation and its practices of validation.

Comparison compatibility denotes sufficient agreement of object types, task criteria, valuation conventions, and institutional meanings to interpret differences across configurations. Compatibility can be partial. A scientific field might revise what counts as a valid outcome, making an earlier list of feasible tasks incomparable to a later list without a translation. A repository might move from unrestricted access to a membership model while preserving its underlying documents; comparison then requires attention to changed access and governance rather than only to the documents' count. Where a meaningful translation is unavailable, the research record should present a discontinuity in comparability instead of an artificial common score.

Counterfactual intervention refers to a specified alteration in represented conditions whose implications are assessed under explicit assumptions. The restriction of an interface and the availability of substitute implementations form one such intervention. Its credibility depends on the accessibility of alternative hardware, labour, permissions, coordination, and institutional remedies. An observed association does not identify the causal effect of that intervention. In studies of public knowledge production, policy changes, natural experiments, process tracing, oral histories, records of institutional decisions, and technical dependency tests may each illuminate different parts of the causal question. Their evidential reach should be stated in the case-specific study.

The distinction between *system transformation* and *representation change* should be documented explicitly. A revised graph or measurement method may alter description without altering practice; changed official classification rules may alter both description and actual opportunities. Evidence should identify the processes linking a revised representation to any change of productive conditions.

A.6 Evidential and Normative Status of Claims

The manuscript combines political-economic interpretation, conceptual distinctions, preliminary mathematical representations, comparative illustrations, and normative proposals. Each bears a different burden of justification. Table 20 records practical conventions for assigning a claim's epistemic status. The categories may overlap in a research programme, while their specific justifications remain distinguishable. An interpretation grounded in an archive can motivate a mathematical model, for instance, but the model's internal consistency does not turn the interpretation into a demonstrated causal finding.

Model adequacy is assessed against the question pursued. Dependency graphs can identify technical alternatives while leaving moral authority unresolved; legal records can establish entitlements while leaving practical access unknown; interviews can identify perceived dependence while leaving resource flows undetermined. Conflicting evidence and incomplete translations across disciplinary vocabularies

should remain visible.

Normative neutrality of the formal syntax means that notation supplies no verdict on institutional justice. Task selection, weights, represented actors, and value categories nevertheless embody epistemic judgments. Studies should disclose these choices and omitted standpoints. Extraction claims additionally require evidence of recurrent appropriation, control mechanisms, contributors' work and burdens, feasible alternatives, and available remedies.

A.7 Application Protocol and Illustrative Case Specification

A case-specific application can follow a sequence of analytic commitments. First, declare the knowledge-production activity and the boundaries of its institutional setting, including which groups of contributors, users and maintainers are represented. Second, identify the knowledge resources and conditions supporting the activity, allowing for collective contributions and inherited public infrastructures. Third, specify generative dependencies, jointly required prerequisites, alternative routes, and possible reciprocal interactions. Fourth, record differentiated rights, duties, governance responsibilities and actual access constraints. Fifth, describe the values created, recognized and circulated, preserving incompatible value types. Sixth, state the counterfactual interventions and substitutability assumptions. Finally, separate observed changes, formal consequences, causal hypotheses and normative assessments. These commitments can be implemented iteratively as evidence revises the initial boundary.

Consider a hypothetical public research archive maintained through a consortium. Researchers contribute records and methods; librarians and engineers provide preservation, accessibility and validation; several institutions supply financing. An external platform organizes an application interface around the archive and offers search, analytics, and evaluation services. An inquiry can represent the archive and interface as separate components of V , together with the maintenance practices that make each usable. Activities in Q might include independent replication, cross-disciplinary search, and preservation review. Actors in A include the consortium, contributing teams, a platform operator, and user organizations; collectivities can be disaggregated where internal voice or benefit allocation is material.

At the knowledge-resource level, the archive may remain publicly accessible. At a methodological level, its validation procedures may be maintained by a narrower professional community. At an application level, the external platform may possess control over an interface used by many institutional users. A generative-level characterization records these positions without imposing a general hierarchy of worth. To study effective dependency, the inquiry would ask whether users can access the underlying records, reproduce the relevant analytics with other tools, retain the required expertise, and exercise the rights necessary to change interfaces. If these substitution plans are practical, the modelled loss resulting from restriction of one service may be modest even when the service is widely used. If alternatives are legally unavailable or prohibitively expensive, the same technical topology may yield a different assessment.

The case also permits separate accounts of heterogeneous value. Archive contributions may yield verification benefits, public accessibility, professional recognition and financial savings; platform services may yield revenue and additional capabilities; maintainers may absorb preservation, correction and migration costs. A payment to the platform documents one circulation event. It does not reveal the full history of public support, the allocation of maintenance burdens, or the public benefits supplied by the platform. A finding of structural extraction would require further evidence of recurrent appropriation connected to effective control, an analysis of the contributors' productive conditions, and assessment of the operative agreements and alternatives. An arrangement that returns resources to the consortium could support collective reproduction, while other value pathways might remain concentrated. Several mechanisms may coexist in the same institution.

The hypothetical archive illustrates why the proposed framework uses multiple analytical records. A graph of technical prerequisites can reveal potential bottlenecks. A rights map can identify who may revise or withdraw a service. A circulation account can identify which work and costs sustain the arrangement. A historical record can describe how these relations emerged and changed. A normative inquiry can examine whether participants have meaningful opportunities to understand, contest and transform

conditions governing their work.

B Political-Economic Foundations of Accumulation and Reproduction

This appendix elaborates the political-economic distinctions upon which the paper's account of knowledge-capital formation depends. Its role is to clarify the historical specificity of primitive accumulation, the reproduction of productive conditions, and the institutional diversity through which collective knowledge-producing capabilities may be accumulated. The inquiry is principally conceptual and historically interpretive. It draws selectively on Marxian accounts of capitalist accumulation and reproduction, scholarship on the background conditions of production, and institutional analyses of collectively governed resources. The appendix does not claim that a common vocabulary eliminates the disagreements among these traditions. Its objective is to render their respective questions explicit, then identify conditions under which a comparative investigation of knowledge production becomes analytically defensible.

The discussion proceeds through eight components: the historical relation between primitive accumulation and separation; the distinction between productive stocks and capital relations; reproduction and expanded production; the labour and maintenance of knowledge; the circulation and appropriation of heterogeneous value; institutional forms of collective accumulation; the position of generative levels in the reproduction of dependence; and a comparative diagnostic protocol. The resulting distinctions complement the definitions in Appendix A, while supplying historically grounded qualifications to the more abstract relational representation in Section 13.

B.1 Historical Separation and the Specificity of Primitive Accumulation

Marx's treatment of primitive accumulation in Part VIII of the first volume of *Capital* identifies a historical question about the constitution of capitalist relations of production. In the formulation preceding the chapters on enclosure, coercive legislation, and the development of capitalist agriculture and industry, the appearance of accumulated resources as a prior condition of capital is itself presented as something requiring explanation. His analysis concerns the historical production of conditions under which the means of production can be concentrated in particular hands while producers become dependent upon selling their labour power. The analytical centre is a transformation of social relations, including access to the means of subsistence and production, rather than the mere temporal priority of a stock of resources [61].

That distinction matters when the object of inquiry is knowledge. A research library, a technical vocabulary, a shared observational practice, or a public database can become a condition for subsequent knowledge production through processes that involve donation, state investment, public education, cumulative labour, or mutually agreed cooperation. Such processes can create substantial new productive capabilities without reproducing the particular historical separation analysed by Marx. The present paper therefore uses *initial formation* to describe the establishment of such conditions within a declared analytic boundary. It reserves *primitive accumulation*, in its historically specific sense, for inquiries that reconstruct how the relations of production were transformed through separation, dispossession, coercive appropriation, and related mechanisms. This discipline prevents the vocabulary of primitive accumulation from functioning as a generic synonym for investment or initial construction.

A knowledge-producing institution may also undergo a process bearing relevant similarities to enclosure. Consider a previously shared scientific archive whose governing body transfers exclusive control of essential preservation, indexing, or access systems to a new operator. Whether the transfer amounts to dispossession requires evidence about the preceding entitlements, the effective opportunities of contributors and users, the authority by which those entitlements changed, and the enforceability of alternatives. Mere adoption of a commercial interface establishes an organizational change; a historically supported account of separation requires more. The knowledge resource may remain readable even as some participants lose meaningful control over its maintenance or further transformation. Consequently, inquiries

should examine the particular conditions from which producers are separated, including infrastructural, legal, interpretive, and institutional conditions, rather than infer enclosure from a change in nominal ownership alone.

The historical category also raises a problem of repetition. A transfer of control can become a continuing mechanism through renewals of exclusivity, migration costs, contractual restrictions, or repeated conversion of collective work into privately controlled services. The concept of *ongoing dispossession* is used in later critical scholarship to capture such dynamics. Fraser, for example, places expropriation alongside exploitation in a broader account of capitalism's conditions of possibility [31]. Such accounts are interpretive developments, and their application to a contemporary research institution should establish a causal history of the arrangement at issue. The possibility of recurrent separation does not make every institutional asymmetry an instance of primitive accumulation.

B.2 Productive Stocks, Capital Relations, and Capitalization

Accumulated productive resources can be described under several analytical vocabularies. A technical instrument can be inventoried as an asset; a trained research team can be described through its capabilities; an institutional repository can be understood as a collectively maintained knowledge resource; and particular controls over these conditions may form part of a relation through which value is appropriated or command over labour is exercised. Each description identifies a different aspect of the same historical configuration. In a Marxian account, capital is constituted through determinate social relations of production and valorization. The present paper's broader expression *knowledge-producing capital* is an explicit comparative extension, denoting historically accumulated conditions that can support further production. Where analysis turns to capitalist capital in the stricter sense, the additional relations of ownership, labour, commodity exchange, and appropriation have to be reconstructed [61].

The difference can be illustrated through a university-built scientific instrument. Physical equipment, calibration knowledge, labour routines, and a maintained research environment support experiments. These conditions may contribute to collectively accessible inquiry under a public mandate. They may equally become components of a fee-based service, or enable an enterprise to acquire exclusive research advantages. An identical device can therefore participate in different capital relations. Conversely, a firm may possess a legal title to a device while lacking the practical knowledge required to use it. Productive capability cannot be inferred from an asset register alone. It depends on the viable coupling of physical conditions, people, practices, institutional permissions, and historically acquired competence.

Capitalization is another distinct process. A knowledge resource may be valued as a source of expected future revenue, licensed access, reputational advantage, or a strategically important institutional position. Capitalization in this sense can alter resource allocation and the distribution of claims on future returns, even when the material knowledge content remains unchanged. A valuation or financial claim, however, provides limited evidence about the actual capacity of a group to create new knowledge. Empirical work therefore needs at least three separate records: the productive conditions available, the rights and obligations governing these conditions, and the valuations or capitalized claims associated with them. A study that collapses the records risks equating market worth with social productive capacity.

The concept of accumulation likewise requires a specified object. A repository can accumulate records while losing maintenance staff; a laboratory can improve throughput while narrowing its research agenda; a corporation can expand the scale of licensed data without increasing the community's independent capacity to reproduce the associated method. These changes differ in kind. The paper's distinction among resources, feasible productive activities, and power over the conditions of activity helps articulate why accumulation in one dimension may accompany contraction in another. Such divergence is especially consequential when knowledge capital is distributed across different generative levels.

B.3 Simple Reproduction, Expanded Reproduction, and Productive Continuity

Reproduction concerns the continued availability of the conditions that allow production to proceed. In the first volume of *Capital*, Marx distinguishes simple reproduction from accumulation that converts

surplus value into additional capital. The second volume develops circuits and the reproduction of aggregate social capital, including the mutual dependence of production, replacement, and circulation. Its analyses of simple and expanded reproduction direct attention to the compatibility of productive arrangements and to conditions for renewed activity, rather than to the isolated output of one undertaking [61, 63]. These analyses refer to specific capitalist value relations. The present paper draws from them a comparative question about the requirements for renewing knowledge production, without treating the Marxian reproduction schemas as numerical measures of plural epistemic or social values.

Consider a publicly supported research infrastructure. The archive's continued usefulness may require preservation, software updates, data migration, correction, training, and institutional stewardship. A new article or dataset represents one generated output. The work required to keep the archive credible, accessible, and interpretable belongs to a different accounting category: it contributes to the reproduction of its productive conditions. An institution can report rising publication counts while deferring the costs of preservation. Expansion of observable outputs in such a case may coincide with deteriorating conditions for further reliable production.

A useful distinction is that between *replacement*, *maintenance*, and *transformation*. Replacement restores a condition whose useful service has been consumed or lost. Maintenance sustains the continuing operation of a configuration through skilled activity and routine correction. Transformation reorganizes productive conditions or produces an additional capability. The boundaries overlap in practice: migrating an archive to a new technical standard can both maintain access and create new forms of interoperability. An empirical study should document which functions are preserved, which are extended, which disappear, and for whom these changes matter. The familiar expression *expanded reproduction* may then be used as an analogy for an enlargement of feasible knowledge-producing activities, provided the study states which capacities have expanded and which burdens have accompanied that expansion.

Reproduction is also distributed across organizations and domains. A commercial analytics service may rely upon publicly financed repositories, unpaid peer review, educational training, open-source dependencies, and professional standards. Its reported operating margin does not describe the complete arrangement of labour and support on which its activities depend. Conversely, public laboratories can depend on market-produced equipment and specialized private services. Neither form of organization is analytically self-sufficient. A reproduction inquiry therefore traces the interdependencies through which the conditions for an activity are renewed, including the possibility that an apparent gain within one organizational boundary is sustained through costs displaced beyond it.

Changes in reproduction conditions need not follow a single development trajectory. A new instrument can enlarge one task repertoire while making an existing skill difficult to retain. An institutional reform can make a method easier to reproduce while weakening the ability to question its assumptions. In the present framework, the continuity of a productive system is evaluated relative to specified practices, relevant participants, and admissible transformations. Such an account provides a historical description of reproductive relations, without assuming that the reproduction of an institution is equivalent to the reproduction of its legitimacy or public benefit.

B.4 Collective Labour, Maintenance, and Social Preconditions

Knowledge production ordinarily draws upon numerous forms of labour, some of which are easily represented by discrete publications or products and others of which persist through maintenance, interpretation, and care. Researchers may formulate a theory; technicians maintain instruments; librarians preserve records; teachers transmit skills; administrators coordinate permissions; programmers repair computational dependencies; and communities make interpretive or observational knowledge available. The boundaries of particular contributions depend upon institutional history and research design. A political-economic reconstruction needs to identify labour and productive responsibility beyond the contributors most visible in final outputs.

The classical problem of cooperation remains instructive. In Marx's account of capitalist production, cooperation, machinery, and the division of labour transform productive organization and the relation

between individual labour and collective productive powers [61]. For knowledge production, cooperative activity can generate results that are unattainable through isolated contributions. Shared concepts, calibration practices, stable standards, and a trusted institutional setting can alter what subsequent contributors are capable of doing. These effects are often associated with a durable organization or technical artifact, even where their formation depended on distributed and partly unrecorded work. Attribution to a principal inventor or publisher consequently describes only a selected relation within the broader production process.

A further layer concerns the conditions under which labour capacities themselves can be sustained. Education, health, care, time for inquiry, and stable material circumstances shape participation in knowledge production. Fraser's work on the relation between capitalist accumulation and social reproduction identifies the importance of background activities and institutional divisions through which productive labour becomes possible [31, 32]. The application to public knowledge production is an analytical extension: a research system's ability to renew its human and institutional capacities may depend on activities funded or performed outside the research budget. The absence of a budget line for this work is insufficient grounds for treating it as costless.

Knowledge labour also involves questions of agency and practical understanding. A trained researcher is a participant capable of interpretation, resistance, innovation, and cooperation. A model of productive capability should therefore avoid portraying the person as a transferable asset controlled in the same manner as a server or laboratory instrument. Contracts, wages, and managerial authority can shape what the researcher is permitted or economically able to do; they do not establish proprietary title over the researcher's personhood or entire knowledge repertoire. Productive autonomy is best examined through actual opportunities to choose activities, retain skills, access necessary resources, contest institutional rules, and participate in decisions about the reproduction of the workplace.

Maintenance and training can also be sites of innovation. A librarian's change to a classification practice or an engineer's adjustment of a data-validation procedure may alter the generative conditions of subsequent inquiry. Such contributions may appear institutionally as overhead, support, or routine service. Their productive significance depends on the tasks and dependencies they affect. The label assigned by an organization is thus evidence about recognition and accounting conventions, while the consequences for knowledge production require separate inquiry.

B.5 Appropriation, Value Circulation, and Extraction

An analysis of knowledge-capital accumulation is incomplete without tracing where generated benefits, costs, and control rights move. Monetary revenue provides one description of circulation, yet knowledge-producing arrangements also generate epistemic reliability, technical competence, recognition, bargaining capacity, educational opportunity, and durable public access. These value descriptions may overlap, conflict, or remain incommensurable. The framework therefore treats circulation as a collection of institutionally mediated processes through which different valued effects are allocated, translated, recognized, or reinvested. It does not assume that a common scalar magnitude can exhaust their significance.

At least four questions arise within a political-economic account. The first concerns *origination*: whose work, resources, and historical investments supported the production of the relevant benefit? The second concerns *appropriation*: who acquired rights, revenues, privileges, or decision authority associated with the resulting activity? The third concerns *recirculation*: what resources, knowledge, and opportunities returned to those who contributed to and maintain the productive conditions? The fourth concerns *reproduction*: what effect did the resulting arrangement have on the capacity of participants to continue or transform their work? A complete answer may require organizational records, contracts, historical accounts, interviews, and task-specific measures, as well as explicit recognition of disputed valuations.

A recurrent asymmetry becomes especially significant when an actor can claim returns associated with a condition whose reproduction depends on others. For example, a private service may receive income from a publicly maintained repository, while the repository's preservation costs remain borne by

a dispersed community. This description suggests a possible mechanism of asymmetrical circulation. An extractive finding needs further analysis: the nature of the operator's contribution, the terms of agreement, the availability of alternatives, the distribution of risk and maintenance burdens, and the consequences for contributors' continued productive capabilities. A service that helps finance preservation can form part of a mutually sustaining arrangement. A service that repeatedly captures returns while weakening feasible alternatives may create a different dependence. The evidential burden cannot be resolved by the private or public label alone.

The distinction between *appropriation* and *exploitation* is particularly important. A benefit can be appropriated lawfully, contractually, collectively, or by coercive means, and its legal form does not determine the complete ethical analysis. Exploitation theories introduce further criteria concerning relations between labour, value, entitlement, and power. The present paper uses *extraction* as a provisional mechanism-oriented category whose application requires evidence of recurrent appropriation associated with asymmetric control over productive conditions. Its use is narrower than a general complaint about unequal outcomes, while remaining distinguishable from a fully specified Marxian account of surplus-value extraction. Interpretations of injustice also require normative premises that the historical and formal descriptions alone cannot supply.

B.6 Capital Accumulation Across Institutional Arrangements

Knowledge-producing capacity may grow within capitalist firms, public universities, cooperatives, community archives, and commons-based infrastructures. These settings can share certain material requirements: instruments must be maintained, skilled participants must be supported, work must be coordinated, and accumulated resources must remain usable. Their institutional relations can nevertheless differ substantially. A comparative political economy should investigate the distribution of rights, the purposes guiding investment, the terms of access, the mechanisms of collective decision-making, and the return of benefits to participants and wider publics.

Under capitalist organization, capital accumulation can be related to private ownership of productive conditions, wage labour, investment, and the appropriation of returns under market and contractual relations. The significance of these features varies by sector and jurisdiction. In knowledge production, a commercial publisher, an instrument manufacturer, and an open-source service provider may occupy different positions even when each operates as a private enterprise. A firm may enable broad use of knowledge while maintaining concentrated control over financing, interfaces, or strategic choices. The specific relation is therefore assessed through rights and dependencies rather than through a uniform prediction based on enterprise type.

Commons-based organization concerns resources and activities governed through rules of shared access, contribution, maintenance, and collective choice. Hess and Ostrom's analysis of knowledge as a commons offers a vocabulary for distinguishing resource characteristics from governance arrangements, while Ostrom's broader institutional work cautions against universal design prescriptions [40, 70, 72]. Commons may depend on membership rules, licenses, public financing, dedicated maintenance teams, and enforceable obligations. The presence of sharing does not imply an absence of institutions or asymmetric responsibilities. It invites examination of how the community can reproduce its conditions and how meaningful the participation of affected contributors becomes.

Communist conceptions of collective production represent a broader political-economic question about common production conditions and the allocation of the social product. In his *Critique of the Gotha Programme*, Marx discusses deductions for replacing means of production, expanding production, and meeting common needs before individual distribution [62]. The text offers a conceptual reminder that common production also requires reserves and deliberate allocation for reproduction. It supplies neither a ready-made governance manual for contemporary knowledge commons nor empirical evidence that collective ownership will resolve coordination or power asymmetries. The institutional translation requires explicit specification of authority, responsibility, participation, and remedies. Commons governance and communism should accordingly remain distinct analytical categories.

Public institutions and cooperatives create additional configurations. A publicly funded research institution may operate under statutory obligations while relying on privately supplied infrastructure. A cooperative may distribute formal voting rights yet face external financial constraints or unequal technical participation. Hybrid arrangements may place ownership, access, maintenance, and rulemaking authority in different hands. The relevant comparative unit is the concrete configuration of productive conditions and enforceable rights, not a single classification assigned to the organization.

This diversity permits a reciprocal comparison. A capitalist system may expand a public knowledge commons through funded production, open dissemination, and maintenance contributions; a commons-based system may develop gatekeeping, unequal recognition, or dependence on specialized maintainers. Both assertions describe possibilities, and particular instances require evidence. The distinction between *accumulation* and *appropriative organization* therefore serves an empirical purpose. It enables inquiry into the conditions under which productive capacity increases and into the separate question of whose capacity, control, and opportunities increase as a result.

B.7 Generative Position and the Reproduction of Dependence

The political-economic relevance of generative levels follows from the fact that knowledge capital can support further production in different ways. A specialized application can improve a bounded activity, while a validation method, scientific standard, language of description, or shared training infrastructure may support many activities. Such breadth does not establish an invariant hierarchy. Knowledge systems often contain substitute paths, reciprocal adaptation, cross-disciplinary transfer, and dependencies that change with institutional conditions. Generative depth is therefore treated as a relation within a declared model of production, and its significance is evaluated against actual feasible alternatives.

The mechanisms of accumulation and appropriation can travel across these positions. Revenue from applications may finance fundamental research and the maintenance of shared methods. A common method may expand opportunities for diverse downstream innovations. Control over a method can also provide leverage over how results are validated or made legible to other institutions. In an educational setting, authority over curricula, credentials, and research evaluation may affect the acquisition of productive knowledge long before an identifiable product is made. In each example, capital expansion changes the conditions for other activities; the source of the effect may be financial, organizational, epistemic, legal, or technological.

This perspective clarifies a possible amplification mechanism. Where a widely used generative condition has few workable substitutes, control of the condition may influence numerous dependent activities. The magnitude of influence also depends on the ability to exclude, vary quality, alter rules, or redistribute access; on the costs borne by dependent participants; and on those participants' capacity to contest or reorganize the relation. A technical dependency graph describes possible channels of influence. A historical political-economic account determines which channels were actually activated, by whom, and under which institutional arrangements. A normative judgment examines the legitimacy and consequences of the resulting allocation of authority.

The opposite effect is also possible. An innovation initially developed for one application may become a general method, altering inherited standards and reducing previously concentrated dependencies. A public repository may introduce interoperable tools that distribute effective capability more widely even while increasing the aggregate volume of commercial use. The analytical challenge is to follow the transformations themselves. The fact that a condition appears foundational in a diagram does not demonstrate enduring control; its reproductive position can be changed through collective work, new knowledge, law, governance, and technical substitution.

B.8 Comparative Diagnosis and Historical Evidence

The preceding distinctions suggest a comparative method that preserves both political-economic specificity and the plurality of knowledge-producing institutions. Table 21 separates six questions that are often conflated in accounts of knowledge accumulation. The table is an interpretive aid: its evidence

Table 21: Political-economic dimensions of knowledge-capital formation and reproduction. The evidence column describes possible inquiry targets rather than exhaustive indicators.

Analytical dimension	Principal question	Potential evidence
Formation	Which inherited or newly assembled conditions support production?	Resource histories, labour records, public investments, technical dependencies
Separation	How did producers' access and authority change?	Historical entitlements, contracts, governance changes, feasible alternative paths
Reproduction	Which contributions renew productive capability?	Maintenance work, training, replacement costs, preservation and repair activities
Expansion	Which feasible activities and capacities became available?	Task repertoires, capability assessments, organizational changes, observed constraints
Circulation	Where do differentiated values and burdens travel?	Revenue, non-monetary benefits, recognition, transfers, costs, reinvestment
Appropriation and control	Who can claim returns or alter productive conditions?	Rights bundles, exclusion power, decision authority, contributor accounts, remedies

examples identify possible observation strategies and are not jointly sufficient conditions for any single normative verdict.

A case inquiry can begin by identifying a productive arrangement and constructing a trace of the conditions on which it depends. The trace should include inherited contributions, current participants, maintenance activities, and institutional relations. It should then reconstruct changes in rights and capacities without assuming that calendar succession alone supplies a causal explanation. Alternative histories and competing actor accounts can reveal different interpretations of apparent discontinuities. Qualitative interpretation, documentary analysis, quantitative estimation, and formal dependency modelling each address different aspects of this reconstruction.

The analysis of primitive accumulation requires especially careful historical evidence. Relevant materials include documentation of earlier use rights, the authority behind their alteration, the resources or capabilities lost, and the mechanisms through which the changed relation was maintained. Evidence of increasing market concentration can help identify a research site, yet a concentration statistic alone does not establish coercive separation or exploitation. Likewise, a resource's open license supplies information about formal permissions while leaving unresolved its technical availability, the financial conditions of use, and the ability of contributors to revise its governance.

Reproduction requires an account of what an institution must renew to sustain particular forms of knowledge production. Such an account benefits from distinguishing the finance of a service from the collective costs of preparing knowledge, supporting researchers, maintaining tools, caring for participants, and preserving interpretive continuity. Comparisons across institutional forms should make these boundaries explicit. A costly arrangement may provide valuable shared capacity, while a nominally inexpensive arrangement may externalize maintenance obligations. The effects can be assessed using several non-equivalent criteria, with contested valuations and evidential uncertainty documented rather than hidden within a composite score.

Finally, the political-economic analysis connects to the paper's account of justice by specifying the historical and material conditions upon which normative reasoning depends. Questions about distribution concern returns and burdens; questions about recognition concern whose contributions count; questions about participation concern who exercises authority over common productive conditions; and questions about generative opportunity concern whether individuals and collectives can sustain and transform their activities. These questions can yield divergent assessments within a single institution. A responsible account states the disagreements and the evidence required to pursue them. It thereby preserves the central research possibility of this paper: knowledge-capital formation and expansion can take place in several institutional arrangements, while their consequences depend on the historical configuration of production, reproduction, circulation, and power.

C Generative Dependency Graphs, Hypergraphs, and Partial Orders

This appendix develops the dependency representation used in Section 13. Its purpose is to distinguish the existence of an inferred productive connection, the joint conditions needed to perform an activity, the effective availability of alternative routes, and the relative ordering that can be constructed from these relations. The analysis proceeds from typed hypergraph semantics to closure and conjunctive prerequisites, graph condensation and relative levels, substitution-sensitive bottlenecks, interdependent failures, and changes of representational scale. A hypothetical research-infrastructure example supplies a common reference case. The final subsection sets out requirements for interpreting these constructions as historical and political-economic evidence. The mathematical definitions are conditional on a declared case boundary and on the represented rules of feasible production; they do not posit an invariant ontological hierarchy of knowledge.

C.1 Typed Generative Components and Representational Boundaries

A finite research model begins with a typed component set V , a represented task set Q , and a family E of dependency assertions. The object $\mathcal{H}$ retains the additional practices, actors, rights, circulation events and interpretive context specified in Equation 1. A component may be a research protocol, accessible dataset, interpretive vocabulary, software package, institutionally maintained index, or available laboratory service. It is an element of the research representation rather than a claim that these materials share a single social or physical substance. Productive tasks in Q may involve creating an output, verifying a finding, reproducing a method, maintaining a service, or transforming a shared standard. A task's satisfactory performance must be specified with the participating community and its material conditions in view.

An ordinary directed edge $u \rightarrow v$ can record that one component contributes to another. In many productive activities, however, several prerequisites must be present together, and there may be several distinct ways of meeting the same task. Directed hypergraphs provide an established formal language for systems with conjunctive and alternative pathways, including their paths and cuts [35]. The present use adopts a particular *support hyperedge* $e = (S_e, y_e, \kappa_e)$, with $S_e \subseteq V$ finite and $y_e \in V \sqcup Q$, in agreement with Equation 2. Its type $\kappa_e \in \mathcal{K}$ records whether the assertion concerns a technical, informational, legal, organizational, methodological or evaluative relationship. Multiple types may be required to interpret one historical dependence; a typed edge records the selected aspect under examination.

A support hyperedge is read provisionally as follows: within a declared production context, the joint availability of the components in S_e contributes a specified sufficient support route to the represented target y_e . The claim of sufficiency is relative to separately declared background conditions and quality criteria. A dataset and algorithm, for instance, may permit computation only if compatible equipment, trained personnel, and required permissions are also available. These conditions may be encoded as explicit components, captured through a feasibility predicate, or left as identified omissions. Each strategy has different evidential costs. Technical execution success cannot be inferred from a hyperedge extracted only from documentation of intended use.

In particular, a relationship of *historical influence* differs from an operative dependency. A publication may have inspired a later method without remaining a prerequisite for present performance; a software dependency declared by a package manager may be technically optional; a standard may be formally public while remaining costly to implement. A well-formed representation records which interpretation is being asserted and which observation, document, or participant account supports it. Where evidence conflicts, parallel representations or uncertainty annotations may be warranted. A larger number of recorded arrows can reflect improved documentation rather than actual growth of dependence.

The analyst's boundary also determines whether the same object is an input, a task, or a transformed result. A validation protocol can be modeled as a component supporting an experiment, and its revision can be modeled as a task that generates a modified protocol. This distinction is particularly important when the paper describes meta-knowledge as a generative level: the model can represent the reproduction and transformation of a rule without declaring the rule permanently foundational. The granularity of the

component set should be appropriate to the causal and institutional question being asked, with alternative decompositions reported where they could alter the findings.

C.2 Conjunctive Support, Alternative Routes, and Closure

Joint necessity and alternative sufficiency require separate logical operators. Consider two hyperedges $e_1 = (\{d, m\}, q, \kappa)$ and $e_2 = (\{d, m'\}, q, \kappa)$ for a task q . Within the stipulated context, each route requires the dataset d together with one analysis method; the second route substitutes m' for m . Two ordinary paths, one from d and another from m , do not record the required conjunction. Conversely, treating m as an unavoidable predecessor of q would erase the alternative m' . This small example motivates a closure construction that respects the complete source sets of productive rules.

For clarity, suppose that E contains a finite subfamily of rules with targets in V , that a set $B \subseteq V$ of components is made directly available, and that the declared background and permissions remain fixed. Define the support-update operator by Equation 16.

$$F_{\mathcal{H},B}(Z) = B \cup \{y_e \in V : e \in E, S_e \subseteq Z\}, \quad Z \subseteq V. \quad (16)$$

The operator in Equation 16 is monotone under set inclusion for this finite, fixed rule family. Its least fixed point is a closure of provisionally supported components. Equation 17 specifies the computation from the directly available seed set.

$$Cl_{\mathcal{H}}(B) = \bigcup_{n \geq 0} F_{\mathcal{H},B}^n(B). \quad (17)$$

In Equation 17, finite V ensures that iteration stabilizes. A dependency cycle without a supported initiating route adds no components solely by asserting reciprocal support. This is an important convention: a diagrammatic cycle can describe coordination, iterative refinement, or circular documentation, yet the least-fixed-point reading requires usable seeds or independently specified resources. Other semantics, such as a greatest fixed point for coinductive constraints or a dynamic model of mutual maintenance, may be appropriate for different questions. Choosing among them is substantive modeling work.

Tasks are assessed by checking their hyperedge source sets against the supported closure. For a given actor, the analyst can restrict available seeds and admissible rules according to skills, licensing, costs, governance, and coordination; the resulting task supports can then inform the feasibility predicate in Equation 5. This relationship is conditional: support closure supplies a necessary modeling layer, while empirical task performance may involve uncertainty, reliability thresholds, and norms of acceptable evidence not captured by the binary rule structure.

The distinction between *potential support* and *effective access* also matters for capital accumulation. A public archive can increase the family of technically executable tasks while an institutional change makes some of those tasks practically inaccessible to certain researchers. Modelled growth in $Cl_{\mathcal{H}}(B)$ is consequently neither a sufficient indicator of productive autonomy nor a direct index of distributive benefit. Comparison should include both the technical rules and the actor-specific context that makes them usable.

C.3 Strongly Connected Components and Relative Partial Orders

Knowledge-producing practices often contain reciprocal support. An experimental instrument enables a measurement, while a series of measurements informs revised instrument calibration; a classification rule supports a public archive while disputes over archived materials contribute to the revision of the rule. A directed representation can display cycles without treating them as paradoxes. Cyclic support, however, complicates the use of conventional hierarchical diagrams. The construction of a partial order requires a further abstraction.

For a selected task scope, form a *support projection* $G_{\mathcal{H}}$ whose vertices include V and, where useful, task terminals in Q . For each hyperedge e , draw ordinary arcs from each $s \in S_e$ to y_e . This projection

is convenient for describing reachability. Crucially, it relaxes the conjunctive semantics of the original hyperedge: a path from one source to its target records potential participation in a support route, even if other required sources are unavailable. Structural reachability in the projected graph can therefore overestimate effective productive dependence. Retaining the original hyperedge list alongside the projection is essential.

Define mutual reachability among projected vertices in the usual way and partition the projection into its strongly connected components. Contract each class to a single vertex; the resulting condensation graph is acyclic. Standard topological-order procedures apply to such finite acyclic graphs [48]. Equation 18 defines a reachability order on condensation classes consistent with Equation 3.

$$[C] \preceq_{\mathcal{H}} [D] \iff \text{a directed path in the condensation connects } [C] \text{ to } [D]. \quad (18)$$

The notation $[C]$ in Equation 18 denotes a condensation vertex associated with an equivalence class of components; the empty path establishes reflexivity. Antisymmetry follows from acyclicity, and path concatenation establishes transitivity. Hence the relation is a partial order on the selected quotient, even though the uncontracted graph may contain cycles. A topological *listing* is a linear extension chosen for display or computation; it does not imply that the underlying generative order is total. Incomparable classes can represent independent activities, incomplete information, or genuinely distinct domains of practice.

Remark C.1 (Interpretation of condensation). A strongly connected class represents mutual reachability in an analyst-defined projection. Its members need not be economically equivalent, contemporaneous, institutionally interchangeable, or jointly controlled. Condensation can obscure internal power asymmetries and distinct labour contributions. Any political-economic inference should return to the uncontracted relations.

Remark C.1 prevents a particularly consequential overinterpretation. A technical cycle that joins a foundational method and a commercial service may be a useful computational component, yet the two participants may possess radically different rights to revise standards or discontinue access. Their placement in one mathematical class does not settle the question of authority over that class. Furthermore, a cyclic projection may be created by edges whose conjunctive requirements cannot jointly be realized. The order is accordingly a structural analytical object, not a verified account of feasible reproduction.

For task-oriented inquiries, a *relative level* can be introduced by choosing a family $T \subseteq Q$ of terminal tasks and measuring longest directed paths from condensation classes to the designated terminals, when such paths exist. This produces an ordinal layering of the finite projected acyclic graph. Other conventions may use shortest distance, branching depth, or dependency cut sets. These choices answer different questions. A component can be distant from outputs in one projection, close to them in another, and irrelevant to a third task set. Distances can also change if a researcher combines several protocols into one modeled component. Consequently, purported differences of generative depth require disclosure of the selected tasks, graph projection, granularity and level convention.

C.4 Substitution, Feasible Routes, and Effective Bottlenecks

Structural reachability provides a useful index of potential influence. Effective dependence calls for a richer comparison: which productive activities lose feasibility or quality if one condition becomes inaccessible, given the realistic alternatives available to affected actors? The distinction is central to the paper’s conditional account of extraction. An apparently deep method may have many usable substitutes, while a near-output infrastructure can be difficult to replace because of permissions, specialized expertise, switching costs, accumulated coordination or exclusive access to complementary data.

Let $\mathfrak{F}_{a,q}(\mathcal{H})$ denote the nonempty family of feasible complete component-support sets under a fixed actor, task and performance criterion. For the present finite-component model, assume *availability monotonicity*: if a complete support set is feasible, making additional components available does not render its previously executable plan infeasible, since unused components may be ignored. This assumption

concerns available components, not mandatory use, conflicting licences, or the resources consumed to acquire them. Let $\mathfrak{R}_{a,q}(\mathcal{H}) = \text{Min}_{\subseteq} \mathfrak{F}_{a,q}(\mathcal{H})$ be the family of inclusion-minimal feasible complete input routes. Each route in this family enables actor a to perform task q under the reference performance criterion. In the simplified component-level definition below, each route is a subset of V containing the complete component inputs of a feasible support plan; permission, skills, and institutional conditions enter the test of whether that route is admissible. The feasible support family need not be upward closed when adding a component incurs a compulsory cost or legal restriction; in such cases the availability-monotonicity assumption must be replaced by an explicitly costed or constrained plan universe. This typing convention is important: institutional gates or obligations are included as separate typed requirements only in an explicitly extended route universe, as used in Appendix F. Redundant component inputs are excluded relative to the declared criterion. Minimality is model-relative and does not require a unique route. In a binary model with fully enumerated feasible routes, Equation 19 defines an unavoidable component.

$$\text{Ess}_{a,q}(\mathcal{H}) = \bigcap_{R \in \mathfrak{R}_{a,q}(\mathcal{H})} R, \quad \mathfrak{R}_{a,q}(\mathcal{H}) \neq \emptyset. \quad (19)$$

Equation 19 identifies components common to all recorded minimal feasible routes. An unavailable or infeasible task has an empty route family and is deliberately excluded from this intersection definition. The computation also depends on correctly expanding indirect dependencies, so that a route's stated inputs represent a complete support plan rather than an incomplete list of immediate parents. Institutional commitments and indispensable skills can determine route feasibility without becoming components of the intersection in Equation 19. For inquiries in which they are explicit requirements, the analyst should construct an augmented typed route universe and report component and institutional projections separately. Neither representation turns human abilities into alienable property.

Under the stated finite-universe assumption, the intersection of all feasible complete supports equals the intersection of their minimal supports: every feasible support contains a minimal feasible support, and a component present in every minimal support is consequently present in every feasible one. This equivalence is useful when a new support can render an old minimal route nonminimal. The essential-set construction gives a binary description under a fixed performance threshold. The graded counterfactual loss $\delta_{a,q}$ in Equation 12 allows a different inquiry: performance may degrade without a complete loss of feasibility; adaptation may be costly; and replacement plans may change relative quality. It is possible for a component to be absent from $\text{Ess}_{a,q}$ while its restriction causes a substantial practical burden because alternative routes exist only with expense, delay or unreliable performance. Equally, a component may appear essential under a narrow model even though a collective can develop a previously unrepresented alternative. An observed dependency score should therefore disclose the candidate substitute set and explain why the performance criterion is appropriate.

Proposition C.2 (Feasible-support expansion and unavoidable components). *Fix a finite component universe, actor, task, and performance criterion. Let $\emptyset \neq \mathfrak{F} \subseteq \mathfrak{F}'$ be two families of feasible complete support sets, and let $\mathfrak{R} = \text{Min}_{\subseteq} \mathfrak{F}$ and $\mathfrak{R}' = \text{Min}_{\subseteq} \mathfrak{F}'$ be their nonempty inclusion-minimal subfamilies. Then $\bigcap \mathfrak{R}' \subseteq \bigcap \mathfrak{R}$. The result does not require $\mathfrak{R} \subseteq \mathfrak{R}'$.*

Proof. Finiteness ensures that each feasible support contains at least one inclusion-minimal feasible support. Hence $\bigcap \mathfrak{F} = \bigcap \mathfrak{R}$ and $\bigcap \mathfrak{F}' = \bigcap \mathfrak{R}'$. The inclusion $\mathfrak{F} \subseteq \mathfrak{F}'$ gives $\bigcap \mathfrak{F}' \subseteq \bigcap \mathfrak{F}$, proving the assertion. $\square$

Proposition C.2 concerns the enlargement of the family of feasible *complete support sets*, rather than assuming that the family of minimal routes itself expands by set inclusion. For instance, if $\{d, m\}$ was minimal and the newly feasible support $\{m\}$ makes it nonminimal, the original minimal family need not be a subfamily of the new one even though feasible supports have expanded. This correction matters for interpreting the addition of substitutes. Its use is conditional on a common support universe and feasibility criterion; a change of the applicable rules, obligatory costs, or the meaning of the task requires a separate comparison. It complements Proposition 13.2, which concerns weakly decreasing modelled performance loss when the admissible replacement class enlarges. Neither proposition implies

that producing and maintaining new substitutes is costless. In many cases, a potential substitute is a public good requiring collective financing or negotiated interoperability.

C.5 Joint Restrictions, Nonadditive Losses, and Dependency Concentration

Analyzing components in isolation can miss dependencies created by their combination. Suppose a task admits two sufficient alternatives, one using component r and another using component s , with all other prerequisites held accessible. Restricting r alone preserves the second route, and restricting s alone preserves the first. Restricting both prevents the task within this model. Thus the joint vulnerability of the two-component set can exceed the sum of the separately measured vulnerabilities. The example formalizes a concern that often arises when legal rights, interoperability constraints and complementary infrastructures are distributed among several organizations.

For a fixed binary task criterion, let $\chi_{a,q}(B)$ be the feasibility indicator when the components in $B \subseteq V$ are unavailable and the remaining background is fixed. Define the corresponding restriction loss in Equation 20.

$$\Delta_{a,q}(B \mid \mathcal{H}) = [\chi_{a,q}(\emptyset) - \chi_{a,q}(B)]_+. \quad (20)$$

Under the two-route scenario, the value in Equation 20 is zero for each individual restriction and one for their union. This establishes a simple counterexample to additive decomposition of vulnerability. More generally, shared prerequisites, switching sequences, coordination costs and network feedback can create complementarities or partial offsets. A summary measure assigning the full joint effect independently to each input would double-count the same productive loss; a scalar allocation of that loss would require an explicit attribution convention and a justification for its use.

A structural cut in a directed graph or hypergraph may indicate a candidate bottleneck; the correspondence between graph cuts and actual intervention losses depends on the support semantics and feasible substitute plans. Directed hypergraph paths and cuts have substantial computational traditions [35]. For social analysis, a cut constructed from technical components may ignore the possibility of a new license, a collective migration effort, a change in evaluation rules, or the provision of an alternative public service. Conversely, a graph with abundant nominal paths can hide a common licensing authority or a shared energy and compute constraint across the supposedly distinct routes. The appropriate cut family should therefore include, or at least report, shared institutional dependencies that are empirically material.

These distinctions complicate the interpretation of accumulation across generative levels. A controller may gain strategic importance through a set of complementary services, even if none is individually indispensable. Multiple organizations might jointly control the last feasible alternatives to an important public research capability. A common standard might generate widespread benefits while remaining contestable because several communities can revise or replace it. The number of actors, edges, or nominal alternatives alone yields no normative ranking. An analysis of recurrent appropriation requires the further account of rights, bargaining, contribution, value circulation and remedies developed in Sections 13 and 12. Inferences about power must be attached to interventions that identifiable actors can actually exercise.

C.6 Multiresolution Models and Cross-Level Transformation

Knowledge production can be examined at multiple resolutions. A research platform may be represented as one node in a university-wide model, a cluster of software and governance components in an organizational model, or an array of protocols, work processes and interfaces in a detailed study. Each view serves a different purpose. In the computational setting of VLSI circuit partitioning, multilevel hypergraph methods use successive coarsening and refinement [49]; the present framework adopts this representational analogy while retaining the difference between algorithmic partition quality and empirical adequacy in social inquiry.

Let a fine-grained component model be indexed by V_f and a coarser one by V_c . A declared map $\pi : V_f \rightarrow V_c$ associates fine components with coarse aggregates. It may merge an archival database, an

authentication system and a validation service into a single institutional interface. The map can simplify the view of cross-system dependencies, but it also removes information about which specific component is controlled, maintained or substitutable. A useful comparison therefore includes an explicit account of the properties preserved by π . It may preserve the existence of some pathways while failing to preserve feasible alternative routes, rights distributions, individual maintenance burdens or causal effects of restrictions.

The distinction can be exhibited without assuming categorical equivalence between models. A projection that sends several fine components to one coarse node can make a composite service appear essential even if users can replace one of its fine-grained parts. Conversely, a coarse model may omit a common prerequisite shared by apparent alternatives, yielding the opposite error. Effective dependence is therefore not generally invariant under aggregation. An analyst who reports a generative hierarchy should provide a sensitivity analysis across credible resolutions, particularly when making claims about deep-level extractive power. Apparent growth of a downstream dependency set may be a consequence of changing granularity rather than a change in the productive world.

Historical transformation introduces another complication. A public archive may move to a more interoperable format, thereby changing the feasible routes without changing its nominal owners. An application may generate a method that is reused as a new foundational procedure. A field's evaluative standards may shift, altering the meanings and quality criteria of its tasks. Each case can require a new hyperedge family, revised types or a changed task universe. The history relation τ of Equation 4 can record such changes, while comparisons of tasks and components may require partial correspondence rather than literal identity. A previously upstream component can become redundant or be reclassified under revised productive practice; an apparently specialized application can become a crucial shared infrastructure.

A transition in the graph model and a transition in the represented system must remain distinguishable. Discovery of a previously undocumented dependency can change the formal diagram with little institutional alteration. A formal change of licensing rules can be practically inconsequential if access had already been restricted by technical barriers; in another setting it can substantially expand feasible activity. The researcher needs historical traces of changed practices, effective permissions and participants' available options. A mathematically clean hierarchy supplies a representational convention for the chosen inquiry, while judgments about public generativity require a broader account of collective reproduction and authority. Figure 1 offers a concrete illustration of this distinction through a research archive with two alternative validation routes and shared prerequisites.

C.7 Illustrative Research Archive with Alternative Validation Routes

Consider a hypothetical research archive that permits contributors to publish independently verified datasets. The modeled components are an underlying archive d , an open validation method m , a commercial validation method m' , a shared interoperability specification s , and an editorial registry r . The intermediate component z denotes a validated record; the represented terminal task q_p is registered public dissemination. The example stipulates that either validation method can generate z when available together with d and s , and that dissemination requires z together with access to r . These are assumptions of the demonstration, rather than claims about a particular scientific institution.

Figure 1 presents a schematic of the designated support routes. Hyperedge junctions represent conjunctive source sets, and the paired branches to the validated record z represent alternative sufficient routes. The figure excludes detailed licensing and cost constraints, which are discussed in the interpretation.

Under this model, restriction of m leaves the method m' route available, provided that its licenses, cost, required labour and standards compatibility satisfy the actor's feasibility criteria. The corresponding reverse statement holds for restriction of m' . Restriction of both methods removes the two specified validation routes; restriction of the shared archive or specification can have an even broader effect. Yet a claim about effective dependency must acknowledge additional routes that may be built through col-

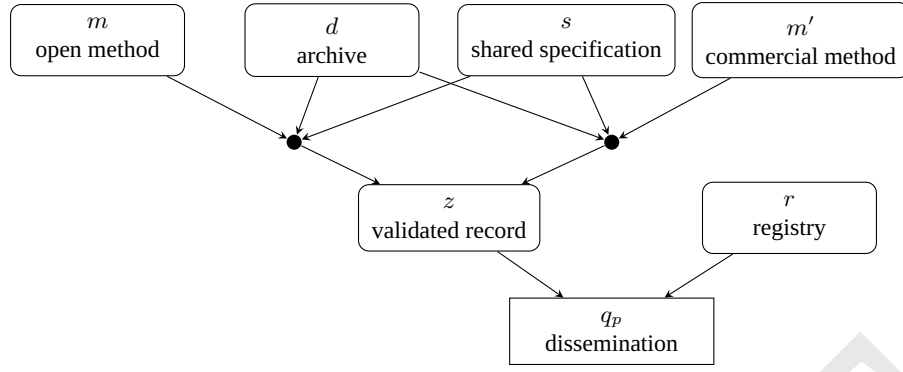


Figure 1: Illustrative conjunctive and alternative support routes for a hypothetical archive. Filled junctions denote conjunctive hyperedge sources; the two junctions supply alternative routes to the component z . Technical support paths alone do not establish legally or economically feasible access.

lective action or remain outside the selected case boundary. A public consortium might finance a third validation implementation, or the technical community might revise s to reduce dependence on an otherwise costly service.

The distinction between source position and institutional control is decisive. The open method might appear broadly upstream in the model yet be independently maintained by several communities. The commercial method might occupy a comparable structural position while being managed under exclusive service contracts. The shared specification might be nominally public but revised by an authority that excludes substantial contributors. Likewise, an editorial registry near the output layer could be an effective bottleneck if publicly recognized dissemination depends on registration and substitutes are institutionally unavailable. The representation can locate candidate dependencies; documentary inquiry must establish control, fee structures, maintenance contributions, contestation rights and available remedies before characterizing any arrangement as extractive.

A comparison of institutional forms may also alter the meaning of the same graph. In a publicly financed arrangement, recurrent payments to a method provider may be compensation for continued maintenance. In a cooperative arrangement, the provider might be accountable to contributing users. In a capitalist service arrangement, the provider may invest revenue in both service improvements and proprietary expansion. An arrangement conceived under collective or communist principles might distribute control over the archive and methods through common institutions while encountering its own coordination challenges. These institutional differences concern rights, distribution and reproduction; the support paths in Figure 1 do not predetermine their political-economic evaluation.

C.8 Evidence Protocol, Robustness, and Open Mathematical Questions

A dependency analysis becomes informative through a documented protocol connecting formal objects to situated knowledge-producing activities. Table 22 summarizes the main choices to report. The table is designed as a compact audit instrument rather than a universal standard for causal inference. It keeps structural properties separate from interpretive, institutional and empirical claims.

The data collection procedure should distinguish declared technical dependencies, observed task performance, legal permissions, organizational capacity and participant interpretations. Package declarations, repository metadata, institutional documents and interviews offer different views of the same structure. Where appropriate, technical interventions or reproducibility tests can probe substitution routes under reproducible conditions. Such tests may establish a local operational dependence, while broader causal claims about investment, opportunity and exploitation require additional designs and evidence. Publicly available inputs do not automatically provide a complete account of the people and relations maintaining them.

A robustness analysis should vary task selection, quality thresholds, representation scale, omitted

Table 22: Evidence and sensitivity requirements for a multilevel generative dependency inquiry.

Model decision	Documentation requirement	Principal failure mode
Components and tasks	Scope, participant categories, task quality thresholds	Omitted labour or conflated objects
Conjunctive routes	Joint prerequisites, alternatives, rule type and context	Treating a projected path as sufficient
Cycles and levels	Projection, condensation, terminals, chosen rank convention	Inferring a universal epistemic hierarchy
Substitution	Licenses, skills, cost, compatibility and adaptation plans	Counting nominal but unusable substitutes
Institutional control	Enforceable rights, practical discretion and remedies	Equating structural centrality with power
Historical comparison	Evidence of productive change and translation of task criteria	Mistaking a redescription for system change
Extraction assessment	Contributors, circulation, maintenance, recurring appropriation	Deriving a normative verdict from topology

background constraints and feasible substitute plans. In one sensitivity case, the analysis might treat standards-compliant implementations as mutually substitutable; in another, it might incorporate observed switching costs and an organizational inability to migrate. Both may be meaningful under different purposes. Reporting divergent results is preferable to collapsing them into a single apparently precise indicator. Structural metrics can be used as search devices for possible institutional vulnerabilities while preserving uncertainty about the actual relations of power.

Several mathematical extensions remain open. Context-dependent rule activation may require probabilistic hypergraphs or constraint systems that represent resource depletion and uncertainty. Recursive maintenance can be represented through dynamic or game-theoretic structures rather than a purely static least-fixed-point closure. Joint control of substitute routes poses questions of coalitional power and the allocation of complementary bottleneck effects. Historical comparison may require typed morphisms between changing component universes and partial translations between changing task criteria. Relations among knowledge dependencies, heterogeneous circulation and higher-dimensional cells may motivate a complementary two-complex representation reserved for Appendix D. Those extensions demand their own semantics and justification. A graph cycle does not supply evidence that value actually recirculates, and a computed path does not establish social causality.

The appendix therefore establishes a disciplined use of graphs, hypergraphs and partial orders for inquiry into multilevel knowledge capital. Its strongest conclusions are internal: under defined rule semantics, support closure and condensation are well formed; feasible route enlargement weakly reduces the set of unavoidable components; and joint restrictions can produce nonadditive losses. The historical and normative significance of these findings depends on the credibility of the represented productive practices, the availability of substitutes, the distribution of effective power, and the ways heterogeneous benefits and burdens circulate. These qualifications allow the formal account to serve comparative inquiry without converting a provisional generative hierarchy into an assumed structure of reality.

D Relational Two-Complex Representations of Knowledge Production

Appendix D develops a complementary cellular representation for historically constituted relations in knowledge production. Its role is to describe event couplings, locally specified relational primitives, and the boundaries of circulation records that are only partially represented by the task-support hypergraphs of Appendix C.1. The objective is to identify what information a finite relational two-complex can preserve, which mathematical properties follow from its incidence structure, and which political-economic interpretations require independent evidence. The discussion proceeds from typed cellular semantics and chain complexes to value annotations, relative boundaries, historical transformations, and a worked ex-

ample. All constructions are conditional representations of a selected history and observational boundary. They do not posit that social reality has a privileged cellular decomposition.

Two distinct sources of mathematical motivation should be kept separate. Cellular homology studies incidence, boundaries, and topological features of spaces assembled from cells [38]. Spin-foam models supply an example of higher-dimensional combinatorial complexes with faces and edges carrying physically interpreted labels [6]. The present account borrows the possibility of attaching typed information to a two-dimensional complex. It does not import quantum-gravitational dynamics, spin representations, state sums, transition amplitudes, or physical causal claims into the analysis of knowledge production. Its substantive social interpretation is developed through independently specified event records and institutional histories.

D.1 Event Primitives, Couplings, and Typed Two-Cells

Let K denote a finite, oriented, two-dimensional CW complex associated with a declared historical and institutional case boundary. Write $K^{(0)}$, $K^{(1)}$, and $K^{(2)}$ for its sets of open cells of dimensions zero, one, and two. The modeling interpretation assigns an observed or reconstructed *event* to a zero-cell and a relevant *coupling* between events to a one-cell. Events may include a recorded dataset deposit, a documented validation act, a committee decision, a release, a negotiated license revision, or an identifiable transfer of maintenance responsibility. A coupling records an analytically specified relationship among selected events. Its direction is an orientation chosen for incidence calculations; causal direction, temporal precedence, and normative authority are additional claims requiring evidence.

A two-cell denotes a *primitive relational configuration* whose semantics is fixed for the particular inquiry. Candidates include a documented multilateral validation arrangement, a legally defined reciprocal maintenance obligation, or a specific arrangement connecting the production, recognition, and reinvestment of a research contribution. The precise meaning of a face is part of the model specification. Faces need not represent value, actors, agreements, or a universal type of interaction. The same recorded situation may legitimately admit different cell decompositions under different questions; comparisons should identify the differences rather than silently equate them.

The semantic typing function in Equation 21 makes the minimum commitments explicit.

$$\sigma = (\sigma_0, \sigma_1, \sigma_2), \quad \sigma_i : K^{(i)} \longrightarrow \mathcal{T}_i, \quad \mathcal{T}_0 = \mathcal{E}, \mathcal{T}_1 = \mathcal{C}, \mathcal{T}_2 = \mathcal{P}. \quad (21)$$

Here $\mathcal{E}$ is the case-specific collection of event descriptions, $\mathcal{C}$ is the selected vocabulary of couplings, and $\mathcal{P}$ is the declared collection of relational primitives. The symbols are semantic type sets rather than a claim that every event or relation is already observable. The incidence data and the meanings assigned through σ form different parts of the representation. Mathematically identical complexes can receive different social interpretations, and different complexes can encode aspects of the same historical process.

Institutions, enterprises, research groups, archives, and individual researchers may be recognized through historically constituted patterns of events and relations. They are *not* identified with single zero-cells by default. A model may designate a connected subcomplex, a family of related subcomplexes, or a changing interpretation of event histories as the support for an actor or institutional position. Such an assignment calls for evidence about organizational continuity, legal identity, agency, and membership. It also permits a collective producer to appear through distributed coordination rather than being compressed into an assumed primitive vertex.

The selected CW structure should satisfy the ordinary attaching-map requirements. A one-cell may have coinciding endpoints; a two-cell is attached along a continuous loop in the one-skeleton, potentially traversing edges multiple times. This extra structure is substantive: a mere list of participants in an arrangement does not determine an attaching loop. For a social inquiry, the analyst should report the documentary or interpretative rationale for each face boundary and preserve unresolved ambiguities in the supporting record.

D.2 Cellular Boundaries, Cycles, and Homological Classes

Choose an abelian coefficient group A suitable for the mathematical question, initially $A = \mathbb{Z}$ for oriented integer incidence. Cellular chains $C_i(K; A)$ are generated by the oriented i -cells with coefficients in A . The boundary maps are induced by the attaching structure. Equation 22 states the two-dimensional chain-complex condition.

$$C_2(K; A) \xrightarrow{\partial_2} C_1(K; A) \xrightarrow{\partial_1} C_0(K; A), \quad \partial_1 \circ \partial_2 = 0. \quad (22)$$

For an oriented edge e whose chosen tail and head are v_- and v_+ , $\partial_1 e = v_+ - v_-$. For a two-cell f , the boundary $\partial_2 f$ is the signed edge chain determined by its attaching map and incidence degrees. The identity $\partial_1 \partial_2 = 0$ expresses the elementary fact that the boundary of a cellular boundary vanishes. The identity is a mathematical property of the construction; it does not assert that a particular social or material flow is conserved.

The first homology group in Equation 23 distinguishes closed one-chains from those filled by represented two-cells.

$$H_1(K; A) = \frac{\ker(\partial_1 : C_1(K; A) \rightarrow C_0(K; A))}{\text{im}(\partial_2 : C_2(K; A) \rightarrow C_1(K; A))}. \quad (23)$$

A one-cycle is a chain c satisfying $\partial_1 c = 0$. Two cycles represent the same homology class when their difference is the boundary of a two-chain. A nonzero class identifies a closed pattern in the chosen cell structure that is not filled by its represented faces. Depending on the model, such a feature could indicate a missing primitive relation, an intentionally unfilled coordination loop, or simply an arbitrary limitation of the coding scheme. Its mathematical status does not determine the social explanation.

The same care applies to two-dimensional chains. Since a two-complex has no three-cells, $H_2(K; A) = \ker \partial_2$ in this finite model. A two-cycle may register a formal closed surface of attached primitives. It is not intrinsically an institution, a consensual agreement, or an economically self-sustaining system. The observation that a collection of cells forms a cycle cannot establish its legitimacy, durability, or distributive consequences without the meanings and history of those cells.

A further distinction concerns a *geometric* hole, a missing observation, and an institutional exclusion. The first is specified mathematically through the represented complex. The second concerns the completeness of evidence. The third involves enforceable rules and practical capability. These categories may bear on one another, but they require different justifications. For example, an unrecorded reciprocity arrangement might be present in actual practice despite being absent from $K^{(2)}$; adding its record may change homology without any change to the institution itself.

D.3 Relation to Task-Support Hypergraphs and Generative Levels

The support hypergraph of Appendix C.1 organizes productive components, tasks, conjunctive prerequisites, and substitutable routes. The two-complex developed here organizes events, couplings, and two-dimensional relational configurations. These are complementary representational choices. A dependency hyperedge (S_e, y_e, κ_e) does not canonically determine a two-cell: its source set records a conjunctive support relation, whereas a CW two-cell requires an attaching map around a one-dimensional boundary. Translating between these structures therefore requires additional information about recorded acts, event incidence, and relational closure.

One possible construction starts from an observed execution of a feasible production route. The analyst identifies distinct acts of contribution, validation, maintenance, and use as events; selects documented couplings among them; and specifies particular multilateral configurations whose incidence and interpretation are sufficiently established to warrant faces. Different realizations of the same hypergraph route may produce different event complexes. Conversely, distinct task-support descriptions may collapse to a similar event diagram when institutional or methodological differences are not represented in the two-complex. Consequently, a proposed correspondence should record what it forgets and what it adds.

Generative levels may be assigned to clusters or selected subcomplexes as a relative metadata structure, for example to distinguish the reproduction of a methodological standard from its downstream application. An apparent upstream/downstream ordering cannot generally be derived from homological dimension: dimension zero denotes event cells, not application-level knowledge, and dimension two denotes relational primitives, not a privileged epistemic foundation. The dimension of a cell and the generative level of the activity are separate axes of analysis. A face may concern a local application decision, while a family of event couplings may concern broad epistemic standards.

This separation matters for capital accumulation. Suppose that a standard-setting organization influences many activities. A support hypergraph may represent the organization's standard as a high-dependency component, while the event complex can represent recorded decisions, negotiations, and revisions through which its authority is formed and contested. Neither graph reachability nor homology proves that the organization extracts value. The ownership and power relations developed in Sections 8 and 11 supply additional categories for investigating effective decision authority, and the heterogeneous circulation framework specifies which benefits and reproduction burdens are relevant.

D.4 Heterogeneous Value Annotations and Circulation Records

The proposed complex can carry heterogeneous annotations without collapsing values into a universal scalar. For each selected dimension of valuation α , introduce a measurement or interpretive domain M_α together with a case-specific assignment to relevant events, couplings, or faces. Epistemic reliability, maintenance time, remuneration, recognition, productive autonomy, and ecological burdens may call for different domains and evidential procedures. Where M_α lacks an additive group structure, its annotations remain labels or typed observations; standard cellular-chain arithmetic is then inappropriate without an explicitly justified translation.

For a particular additive measurement domain modeled over a commutative coefficient ring A_α (for example, $\mathbb{R}$ for an appropriately justified quantitative indicator), an observed oriented edge-flow record can be represented as a one-chain $j_\alpha \in C_1(K; A_\alpha)$. A signed coefficient expresses the value recorded relative to the chosen orientation. The boundary $\partial_1 j_\alpha$ is its algebraic event-level imbalance within the selected representation. Equation 24 defines an optional closure criterion for a case whose observation boundary has been declared.

$$\text{Closed}_\alpha(j_\alpha \mid K) \iff \partial_1 j_\alpha = 0. \quad (24)$$

The condition may be useful for a complete and properly measured flow account. It is inappropriate as a default empirical assumption. A research community can receive funds from an outside institution, produce public knowledge, and carry unresolved maintenance obligations that cross the case boundary. The modeled chain may then have a nonzero boundary precisely because inputs, outputs, and obligations extend beyond the observed event network. Multiple dimensions of value also may circulate through partially disjoint couplings with distinct attribution practices.

A complementary annotation is a one-cochain $\omega_\alpha \in C^1(K; A_\alpha)$ that evaluates a one-chain and records an analytically defined measurement, pricing convention, or other additive assessment. The cellular coboundary $\delta^1 \omega_\alpha$ evaluates the boundary of a face. Equation 25 states the finite-dimensional duality of boundaries and coboundaries.

$$\langle \omega_\alpha, \partial_2 b \rangle = \langle \delta^1 \omega_\alpha, b \rangle, \quad b \in C_2(K; A_\alpha). \quad (25)$$

This equality follows from the definition of δ^1 as the dual of ∂_2 . A bounding one-cycle can have nonzero evaluation under a cochain whose coboundary is nonzero. A closed cochain with $\delta^1 \omega_\alpha = 0$ vanishes on boundaries, but may assign a nonzero value to nonbounding cycles. These facts concern the selected additive representation. They neither establish physically conserved capital nor imply that an unbalanced social value flow is normatively extractive.

A distinctive advantage of keeping value annotations separate from incidence is that multiple circulation accounts can be compared on the same event skeleton. One record might measure an expenditure on

storage, another the volunteer hours spent in curation, and a third the formally attributed credit attached to publication. A numerical comparison between storage expenditure and credit is meaningful only if the analyst specifies a conversion convention and the institutional practice that warrants it. The distributions can also be assessed through separate statistical or documentary procedures. The topology does not determine which accounts deserve weight, whether a conversion rate is legitimate, or who is entitled to decide among them. In particular, circulation in one domain may sustain a productive capability in another domain without constituting a numerically conserved transfer between the two.

A public knowledge arrangement can exhibit circular reinforcement even when none of its individual value records is a closed cellular chain. Application revenue may finance infrastructure maintenance; infrastructure quality may support further participation; and participants may contribute new methods to a shared repository. Some relations here are practical dependencies, others are transfers, and others concern changed capacities or opportunities. A valid empirical analysis may accordingly need a task-support hypergraph, an event complex, several circulation ledgers, and participant accounts. The algebraic object $H_1(K; A)$ summarizes one limited aspect of the joint representation: which recorded one-cycles are filled by the selected primitive faces. It is not a sufficient statistic for public generativity or exploitative leverage.

Face annotations can provide a separate account of the relational conditions under which a recorded flow occurs. A maintenance pact might specify shared obligations even when its actual financial payments are recorded along selected edges. The pact as a face and the payment record as an edge-chain need not be identical objects. This distinction helps avoid treating an institutional promise as a realized value transfer. It also permits a researcher to compare legally required circulation, practically observed circulation, and actors' differing valuations of the same arrangement.

D.5 Relative Boundaries, Observation Frontiers, and Institutional Interfaces

A knowledge-production case is often open to wider networks of labour, energy, funds, credentials, recognition, and downstream use. An observed complex K may therefore be studied together with a designated subcomplex $L \subseteq K$ representing a declared analytic boundary, such as interface events and couplings connecting an archive to outside funders, users, or infrastructure providers. The relative cellular chain groups are the quotients $C_i(K, L; A) = C_i(K; A)/C_i(L; A)$, with induced boundary maps. The associated first relative homology is defined in Equation 26.

$$H_1(K, L; A) = \frac{\ker(\partial_1^{\text{rel}} : C_1(K, L; A) \rightarrow C_0(K, L; A))}{\text{im}(\partial_2^{\text{rel}} : C_2(K, L; A) \rightarrow C_1(K, L; A))}. \quad (26)$$

An edge-chain whose boundary lies in $C_0(L; A)$ is a relative cycle. This provides a mathematical way to keep track of paths whose endpoints are treated as interfaces rather than as internal sources or sinks. The choice of L is an empirical and analytical convention. If a governance boundary is contested, rival specifications of L may better express the disagreement than one apparently definitive quotient.

Relative homology is also appropriate when a researcher wants to study the incidence structure of a common infrastructure while admitting explicitly represented links to a commercial platform or public agency. Its algebraic output depends on what the boundary subcomplex contains. A formally nontrivial relative cycle can be important for comparing recorded cross-boundary pathways, yet it gives no independent measure of whether a payment is a fair return for maintenance, whether participation was consensual, or whether contributions are being appropriated. Those determinations require information about rights, bargaining conditions, alternatives, value conversion, and obligations.

Even where a circulation record is additive, cross-boundary accounting may be incomplete because the primary contributions are nonmarket or poorly observed. Volunteer labor, inherited software, tacit expertise, and epistemic recognition need domain-specific documentation. A relative cycle can be a useful bookkeeping structure, not a substitute for historically grounded accounting. The model should expose the analytical frontier and its losses of information to readers.

D.6 Historical Continuations and Cellular Reconfiguration

The paper treats historical continuity as a represented relation among configurations rather than presupposing a universal time axis. Let K_η and K_ξ denote complexes associated with two evidence-indexed historical configurations. When a justified cellular map $F_{\eta\xi} : K_\eta \rightarrow K_\xi$ is available, the induced chain maps commute with boundaries. Equation 27 records this compatibility.

$$\partial_i^\xi \circ F_{\eta\xi,i} = F_{\eta\xi,i-1} \circ \partial_i^\eta, \quad i = 1, 2. \quad (27)$$

The maps and their domains require interpretation. A software migration may preserve a recognizable validation workflow, a governance reform may replace one relational primitive with several, and a platform's closure may make a formerly valid event correspondence partial. In the latter cases a map between the full complexes may be unavailable or misleading. A span through a common recorded subcomplex, a partial correspondence, or a diagram of revisions can preserve the limited evidence more faithfully. The existence of a formal map does not demonstrate that an institution has remained substantively unchanged.

Changes in the represented complexes may alter homology. Attaching a two-cell along a previously unfilled cycle makes that cycle a boundary in the enlarged model. Deleting or deactivating a cell may have the converse effect. These changes can describe genuinely transformed coordination mechanisms, but they can equally result from newly recovered documents, revised coding rules, or a change in the observation frontier. Researchers should therefore record a provenance for each complex revision and separate model revision from claims about institutional history. A mathematical increase or decrease in a Betti number is not automatically an improvement or deterioration in public generativity.

Historical reconfiguration may also modify the generative-level dependency structure represented in Appendix C. A highly specialized application can develop into shared infrastructure, a validation standard may become practically replaceable, and a former commons can acquire new access controls. Representing each change requires both the relevant event-level alterations and the changed feasible production routes. The correspondence between complexes and hypergraphs should be revisited, since a continuation map preserving certain cellular incidences may coexist with radically changed legal rights or economically feasible alternatives.

Where the material calls for multiple noncomparable continuations, the analyst may preserve a branching family of admissible reconstructions. Its branches express evidential and model-relative alternatives rather than a catalogue of events assumed to exist in a privileged future. The distinction between feasibility, observation, and realization remains explicit. A selected continuation represents one argued configuration relation, not a pre-given direction of social development.

D.7 Worked Example: Archive Validation and an Unfilled Coordination Loop

Consider an explicitly hypothetical knowledge-production history with four recorded events. Event v_0 is a dataset deposit; v_1 is a methodological verification; v_2 is a validated-record release; and v_3 is an institutional decision concerning continued support. The event couplings are e_{01} , e_{12} , e_{23} , e_{30} , and e_{02} , with orientations indicated by their indices and the return coupling oriented from v_3 to v_0 . One two-cell f_{012} is attached along the triangular loop consisting of deposit, verification, and release. Its designation as a face means that the case model treats those three couplings as one specified validation arrangement. The other triangular loop, connecting release, support decision, and deposit, is left unfilled because the model contains no corresponding documented relational primitive.

Figure 2 displays this incidence structure. The grey face represents the recorded validation configuration, while the unfilled triangular region denotes an unassigned face, without a presumption about the existence of an arrangement in the represented institution.

With integral coefficients, the boundary of the included face and the second triangular cycle are given in Equation 28.

$$\partial_2 f_{012} = e_{01} + e_{12} - e_{02}, \quad c = e_{02} + e_{23} + e_{30}, \quad \partial_1 c = 0. \quad (28)$$

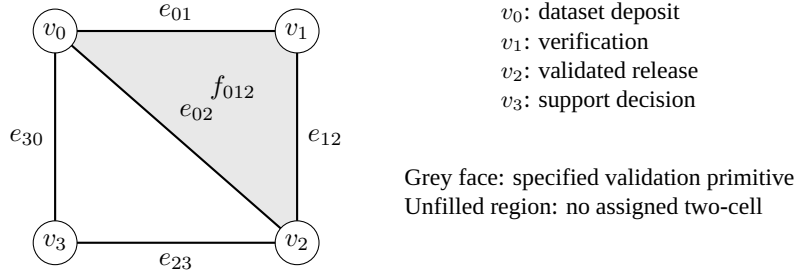


Figure 2: A hypothetical event-coupling two-complex with one attached validation face and one unfilled coordination loop. Cell incidence is stipulated for illustration; the drawing does not claim an observed causal or normative structure.

The graph is connected with four vertices and five edges. The rank of ∂_1 over $\mathbb{Q}$ is three, so its one-cycle space has dimension two. The single face boundary spans a one-dimensional subspace of that cycle space. Consequently $\dim_{\mathbb{Q}} H_1(K; \mathbb{Q}) = 1$, represented by $[c]$. The nonzero class means that the second cycle is not filled by a represented face. It is compatible both with a missing institutional agreement and with an intentional omission in the modeling vocabulary.

Suppose a later case specification supplies a second face f_{023} with attaching boundary $\partial_2 f_{023} = e_{02} + e_{23} + e_{30}$. A new complex K' then has $[c] = 0$, and in this finite example $H_1(K'; \mathbb{Q}) = 0$. The formal implication is stated in Proposition D.1; its interpretation requires evidence that the new face represents an actual documented change rather than revised observation.

Proposition D.1 (Homological effect of a single two-cell attachment). *Let K be a finite connected two-complex and $\mathbb{k}$ a field. Form K' by attaching one two-cell along a loop contained in the one-skeleton of K whose associated one-cycle c represents a nonzero element of $H_1(K; \mathbb{k})$. If the zero- and one-skeleta are unchanged, then $\dim_{\mathbb{k}} H_1(K'; \mathbb{k}) = \dim_{\mathbb{k}} H_1(K; \mathbb{k}) - 1$.*

Proof. The chain groups and the boundary ∂_1 are unchanged. The image of the enlarged ∂_2 is the subspace generated by the old image and c . The hypothesis that $[c]$ is nonzero states that c is linearly independent of the old image. Its dimension therefore grows by one while $\ker \partial_1$ stays fixed. Taking the quotient of the latter by the former reduces the first Betti number by one. $\square$

The proof establishes a property of attaching cellular data under the stated assumptions. It carries no conclusion about the quantity or fairness of value circulated around c . A face might record a reciprocity agreement without adequate compensation, a binding requirement with material costs, or a mutually beneficial public arrangement. Establishing such consequences would require records of contribution, control, access, negotiation, value transfer, and maintained productive capacities. The example shows how a two-complex can index those questions without answering them by topology alone.

D.8 Empirical Audit, Representation Limits, and Research Extensions

Application to a documented institution would require a reproducible protocol for choosing event granularity, identifying couplings, specifying face semantics, selecting a coefficient system, and reconstructing changes in the available records. An event timeline, a participant's account, a legal document, and a software transaction log may locate different parts of the same arrangement. Triangulation should preserve disagreements when the sources refer to different capacities or institutional meanings. Case-specific legal requirements and confidentiality limits may restrict which source records can be disclosed; the representation should not silently convert missing access into an assertion of missing events.

Table 23 separates the principal formal objects from the evidence and inferential cautions associated with them. The table complements Table 22 by emphasizing historical reconstruction and higher-dimensional relations rather than task-route feasibility.

A further issue concerns multi-party governance and the representation of social power. A decision over a common database may involve researchers, funders, legal custodians, maintenance workers, and

Table 23: Audit requirements for a relational two-complex model of knowledge production.

Represented object	Minimum evidential basis	Interpretive boundary
Event vertex	Identifiable act or trace; source and uncertainty	Event is not a primitive actor or institution
Coupling edge	Specified relational claim and supporting record	Orientation alone does not establish causality
Relational face	Explicit primitive semantics and justified attaching boundary	Face is not automatically value or consensus
One-cycle / class	Complete incidence description under declared coefficients	Hole is not proof of exclusion or extraction
Value chain / cochain	Operational units, attribution and observation boundary	Additivity and conservation are case-specific
Relative interface	Defensible subcomplex L and external connections	Quotient depends on the selected boundary
Historical map	Documented correspondence and changes of observation	Formal continuity does not imply institutional continuity

downstream users whose claims cannot be treated as interchangeable event endpoints. Representing a decision-making institution as a historically supported subcomplex helps locate relevant events but does not exhaust its practical authority. For example, the ability to veto a schema change may arise from a contract that is absent from the event record, and a formally shared vote may be ineffective when one participant controls all feasible technical alternatives. The two-complex should be interpreted jointly with explicit rights maps, practical access assessments, and counterfactual substitution analysis. A difference in topological centrality or homology across two cases is insufficient for a comparison of their political-economic freedom.

A related distinction concerns deep generative conditions. The standard of evidence for assigning a methodological or epistemic role to a cellular subcomplex is stronger than merely observing that many event couplings touch it. A case study should trace specific effects on admissible research methods, validation standards, and the capacity to revise or exit a dependence relation. Some highly connected structures may be easily substituted; a small, sparsely connected configuration may encode an indispensable authorization. Consequently, the account of effective generative dependency in Appendix C and the power analysis in the main text remain necessary even where a cellular representation is rich and visually informative.

Several research extensions are possible within a properly scoped programme. A cellular sheaf or cosheaf could assign local data or permissions to cells and use restriction or extension maps to investigate consistency across interfaces, provided the relevant algebra and data semantics are defined. A weighted or probabilistic complex could represent uncertainty about particular event connections or face assignments, subject to a defensible measurement model. A directed or filtered construction could distinguish admissible historical orderings without importing a universal time parameter, while a multiresolution family could track sensitivity to event aggregation and institutional reclassification. These approaches have different assumptions and should be assessed separately from the preliminary two-complex presented here.

The present model's central value is representational discipline. It records which relationships are being treated as events, couplings, or relational primitives; which one-dimensional patterns are supported or filled by documented structures; and which changes arise through stated historical correspondences. Its conclusions remain conditional on evidence, cell interpretation, and the selected case boundary. Whether a pattern produces distributive advantage, entrenches an epistemic standard, creates extractive dependency, or sustains public knowledge-capital reproduction requires the joint political-economic analysis developed in the main text and further formal investigation of value circulation in Appendix E.

E Heterogeneous Value Circulation and Cross-Level Transformations

Appendix E develops the value-circulation component of the multilevel account of knowledge-capital accumulation. Its role is to specify how observations of movement, conversion, retention, allocation, and reinvestment can be represented alongside the dependency hypergraphs of Appendix C.1 and the event complexes of Appendix D. The objective is to investigate the conditions under which value produced through heterogeneous contributions supports further productive activity, while keeping circulation accounts distinct from judgments about ownership, institutional power, and extraction. The inquiry proceeds through typed value domains, incidence-based records, conversion relations, reproduction constraints, cross-level reinforcement, counterexamples, and an evidence protocol. The formal constructions describe selected aspects of a historical configuration. They are proposed analytical devices, with their empirical validity dependent on the recorded transactions and generative activities that they are used to reconstruct.

The mathematical background of network flows provides well-defined concepts of edge assignments, incidence balances, and multicommodity constraints under specified measurement conventions [1]. Knowledge production, however, involves epistemic reliability, skill formation, recognition, institutional influence, use opportunities, monetary expenditures, and material maintenance, among other forms of value. The heterogeneous forms often admit distinct observational units, ordering relations, and conditions of generation. The present appendix therefore uses flow mathematics only within those domains for which its assumptions are warranted. The institutional interpretation draws on research concerning knowledge commons [40] and, as an explicit cross-domain methodological analogy, on Ostrom's framework for social-ecological systems [73]. The latter develops a framework for social-ecological resource governance; its application to knowledge infrastructures is a proposed extension requiring its own empirical validation. The account also considers the return of value to generative capacities as a question developed in generative-justice research [26]. These literatures motivate questions and do not supply one universal conversion law for the value forms considered here.

E.1 Plural Value Domains and Accounting Boundaries

Let $\mathcal{A}$ be a finite, case-selected index set of value dimensions. A dimension $\alpha \in \mathcal{A}$ might designate a monetary balance denominated in a specified currency, verified person-hours available for curation, a provenance quality measure, a kind of recognition, a participation entitlement, or an opportunity to execute a research procedure. Associate to each dimension a domain V_α with an explicitly stated interpretation. Where the relevant observations permit aggregation, V_α may carry a commutative monoid or an ordered abelian group. For qualitative judgments and multidimensional assessments, a preorder, a set of categories, a space of distributions, or a set of admissible states may be more appropriate. The notation V_α alone does not establish additivity, commensurability, or conservation.

The collection of value observations for a case may be treated as a typed family $\mathbf{V} = (V_\alpha)_{\alpha \in \mathcal{A}}$. The family is not assumed to possess a canonical map to real numbers. A decision maker may adopt a scoring or pricing convention for a documented purpose, but the resulting scalar is an institutional and epistemic construction whose domain, weights, exclusions, and sensitivity should be disclosed. A metric for scholarly citation counts, for example, is distinct from the epistemic status of a particular contribution. A payment associated with knowledge production records an exchange under identified terms; it does not determine the value of the resulting knowledge or the full reproduction costs incurred by its contributors.

The accounting boundary should name whose contributions, costs, and benefits are included and what is observed. Useful boundaries include a research team, a publishing platform, a software maintenance collective, a university programme, or a wider public knowledge network. Each boundary selects transactions and productive activities differently. Values arising from inherited infrastructure, volunteer labour, public funding, shared languages, or access to environmental resources may cross the chosen boundary without appearing in conventional financial accounts. An explicit boundary register is therefore part of the model rather than an administrative detail. Where values have contested attribution or meaning, the record can preserve multiple descriptions without forcing an arbitrary compromise.

Two axes of classification should remain separate. The index α identifies a form of value; a generative-level label ℓ locates a component or activity within the selected dependency representation. A payment can occur in an application-level activity or in the maintenance of a foundational standard. An epistemic improvement can be realized through a local experiment and become consequential for a method used elsewhere. The pair (α, ℓ) is an analytical annotation, not a presumption that a type of value intrinsically belongs to a specific generative level.

E.2 Typed Flow Records on Event Couplings

For an additive value dimension α , let K be the event-coupling two-complex described in Appendix D. A documented, signed record on its one-cells may be represented by a cellular one-chain $j_\alpha \in C_1(K; A_\alpha)$, with A_α a declared coefficient group such as $\mathbb{R}$. Positive coefficients follow the chosen edge orientation. At this level j_α is a bookkeeping representation of one measured kind of movement. The event-level net incidence record is $\partial_1 j_\alpha$, under the convention that an edge from event u to event v has boundary $v - u$. Equation 29 summarizes the relation.

$$b_\alpha = \partial_1 j_\alpha \in C_0(K; A_\alpha), \quad \partial_1 : C_1(K; A_\alpha) \longrightarrow C_0(K; A_\alpha). \quad (29)$$

The coefficients of b_α are net arrivals relative to net departures in the observed incidence record. They need not coincide with the observed change of an institution's value stock. Creation, expenditure, loss, copying, unpaid obligations, and boundary-crossing inputs can each change the stock independently of recorded edge transfers. A positive incoming balance also need not constitute a benefit where the incoming object creates a maintenance burden or a binding liability.

In a separately specified stock-accounting model, suppose α represents a reproducibly measurable and additive resource, all relevant quantities use the same unit, and a documented correspondence between two historical configurations $\eta \preceq \xi$ identifies the same accounting sites. Let s_α^η and s_α^ξ denote the stock vectors, g_α documented generation or external provision, and u_α documented use, depreciation, or disposal. Their stock-balance relation is stated in Equation 30.

$$s_\alpha^\xi - s_\alpha^\eta = g_\alpha + \partial_1 j_\alpha - u_\alpha. \quad (30)$$

Here g_α and u_α are zero-chains in the same coefficient group, and the equation is conditional on exhaustive, consistent accounting of that resource and on the specified historical correspondence. An absence of recorded generation or use would be a data claim, not a mathematical default. For a financial account, supporting evidence might include payment records, invoices, restricted grants, accrued obligations, and a valuation date. For skills or epistemic reliability, stock-balance arithmetic of this kind is generally too restrictive because learning, reproducibility, and interpretation call for other state-transition descriptions.

The closure condition $\partial_1 j_\alpha = 0$ discussed in Equation 24 is a property of the selected edge record. It neither guarantees reproduction of the measured resource nor demonstrates that the arrangement is institutionally closed. An internally balanced set of transfers could coexist with the depletion of a required infrastructure, while an open inflow of public funding could sustain a highly productive research commons. Relative-chain representations may be useful when endpoints lie on an explicitly designated external interface, but their interpretation depends on the chosen observational frontier.

E.3 Recognition, Valuation, and Relational Attribution

Knowledge-related value can arise through acts that are poorly represented as transfers. A methodological correction may improve the reliability of several subsequent studies without a measurable quantity leaving the corrector's possession. Public documentation can be copied without exhausting its source, although hosting and interpretation continue to require resources. Recognition may be shared, contested, delayed, or mediated by an institution that determines credit. Consequently, a circulation analysis should keep the creation event, the realization of usable opportunities, and the assignment of recognition as distinguishable records.

For an additive measurement dimension, a cellular one-cochain $\omega_\alpha \in C^1(K; A_\alpha)$ supplies an evaluation of one-chains. The duality in Equation 25 then permits evaluation of a face boundary through the coboundary of the cochain. Its interpretive content depends on the declared measurement. If ω_α assigns maintenance cost per event coupling, it may be meaningful to sum cost along a specified chain. If a qualitative research contribution changes the inferential reliability of an entire model class, an analogous additive cochain would need a separately justified operationalization. A nonzero cochain integral around a cycle is therefore neither a universal measure of generated value nor evidence of unfair transfer.

Attribution is also relational. A paper may depend on authors, data producers, software maintainers, reviewers, translators, laboratory personnel, public infrastructures, and predecessor research. Contributions can be complementary, partially substitutable, and difficult to isolate causally. A contribution record can therefore take the form of a hyperrelation connecting evidence-backed acts, produced artifacts, and affected productive capabilities. An authorship list, patent title, or financial beneficiary statement is one observed institutional representation within that broader relation. The difference between recognised and unrecognised contribution may have economic and epistemic effects, yet establishing those effects requires case-specific evidence about downstream activities and institutional decisions.

Where an institution applies a scalar valuation, a useful audit examines who selected its dimensions, which contributors were recorded, which dimensions were omitted, and whether those affected can contest the evaluation. This is especially salient at levels controlling epistemic standards, dataset interfaces, or research evaluation. A scoring rule can change what activities receive funding and recognition; a later change to the rule may alter the represented value without any corresponding alteration in the quality or utility of an existing contribution. The analysis should distinguish such a revision of evaluative convention from a demonstrated change in knowledge production.

E.4 Cross-Level Conversions and Transformation Relations

Cross-level value circulation commonly passes through transformations that change the form, recipient, or productive role of what is generated. Application revenue may support an open repository; maintenance labour may improve a shared method; better methods may enable new applications; public training may expand participation in a research collective. A numerical equality between the input and output of such a transformation is generally inappropriate. The transformation can depend on rights, available skills, complementary infrastructure, organisational consent, and historical circumstances.

Let $\mathcal{H}_\eta$ denote a declared knowledge-production configuration, a an institutionally constituted actor or coalition, and ℓ, m two relative generative-level descriptors. For a typed input $v_\alpha \in V_\alpha$, the feasible outputs in a different dimension V_β may be represented by a set-valued relation, as in Equation 31.

$$\mathcal{T}_{\alpha\ell \rightsquigarrow \beta m}(v_\alpha \mid \mathcal{H}_\eta, a) \subseteq V_\beta. \quad (31)$$

Membership means that a documented or explicitly hypothetical route, under the specified institutional configuration and participating actors, could produce the designated output given the input and any stated complementary resources. An empty set records the absence of a feasible route *within the modeled conditions*. Several outputs may remain admissible because different research efforts, costs, and institutional choices lead to different results. The symbol $\rightsquigarrow$ in Equation 31 is a formal relation marker defined here; it carries no implication that the transformation is intrinsically irreversible or temporally privileged.

The transformation family is generally conditional and incomplete. A funding stream does not automatically produce a reproducible dataset, and a reproducible dataset does not necessarily become a productive public capability. The possible paths involve distinct legal permissions, technical procedures, linguistic conventions, and maintenance arrangements. Likewise, a methodological improvement can produce more usable applications without any direct financial return to its contributors. The absence of a monetary return should be examined in connection with the conditions of reproduction and the relevant normative commitments; it is not, in isolation, proof of extraction.

Where several components are jointly necessary, a typed hyperrelation records their conjunction more accurately than separate one-input conversion factors. Let S be a set of available inputs and supplementary conditions. A proposed conversion route r may be described by a predicate $\text{Adm}_r(S, \mathcal{H}_\eta, a)$

for its admissibility, together with an output correspondence. This can be implemented using the task-support hypergraph of Appendix C.1. If an output at level m modifies one of the prerequisites at level ℓ , the generative structure itself may need to be reconstructed. Cross-level conversion then participates in changing the model of further feasible conversions.

The relation in Equation 31 also makes normative disagreement visible. A researcher may consider accurate attribution a necessary part of a legitimate conversion, while a publishing institution may consider compliance with a license sufficient. A public funder may attach open-release obligations; a private contractor may define rights more narrowly. Such differences can be represented as distinct institutional constraints on the same technically feasible transformation. The comparative question concerns which routes are open to whom, under which obligations, and with which effects on subsequent knowledge-producing capacities.

E.5 Reinvestment and the Reproduction of Generative Capacities

Value returns to productive conditions through combinations of resource allocation and capability formation. A repository may need payments for storage, time for metadata repair, trustworthy governance decisions, and access to specialist expertise. A training network may depend on facilities, mentoring labour, and recognition for participants. The maintenance requirements of different systems cannot necessarily be met by one substitute resource. Accordingly, the relevant analytical target is feasibility of continued productive routes under specified obligations, not aggregate financial surplus alone.

Let $\mathcal{R}(\mathcal{H}_\eta)$ be the family of candidate productive routes at a recorded configuration, and let $\mathcal{I}_r$ denote a family of sufficient alternative maintenance-input *bundles* for route r , expressed in a specified typed configuration space. Each bundle contains the jointly required inputs of a complete admissible maintenance plan, rather than identifying separate resources that could each suffice alone. Let $\mathcal{U}_r(\mathcal{H}_\eta, \mathbf{j}, \mathbf{g}, Q_a)$ denote the set of maintainable input configurations available through observed circulation records $\mathbf{j}$, generation records $\mathbf{g}$, and the effective access and governance rights Q_a of a named actor or coalition. A route is feasible for continued reproduction under the rule in Equation 32.

$$\text{Reprod}_a(r \mid \mathcal{H}_\eta, \mathbf{j}, \mathbf{g}) \iff \mathcal{I}_r \cap \mathcal{U}_r(\mathcal{H}_\eta, \mathbf{j}, \mathbf{g}, Q_a) \neq \emptyset. \quad (32)$$

Both sets in Equation 32 must be expressed in a compatible typed input-configuration space. The intersection says that at least one required input arrangement can be supplied under the declared constraints. It remains a modeling statement until the requirements, effective rights, and supplied capacities are identified in evidence. A feasible route may also create harms or inequitable burdens; feasibility and justification are different analytical questions.

This formulation accommodates combinations of monetary and nonmonetary support. Additional revenue can help maintain a repository when the necessary personnel and permissions are available. Money may be ineffective when a project lacks the right to preserve a dataset, when required expertise is unavailable, or when contributors reject the maintenance conditions. Conversely, shared learning, repaired documentation, reciprocal support, and institutional reform may create feasible routes without a proportional increase in revenue. The political-economic significance of reinvestment therefore depends on what productive conditions are changed and whose capabilities are supported.

The distinction among capital accumulation, its control, and institutional reproduction is important at foundational generative levels. An organization can accumulate a large number of training datasets or standards documents while losing the capacity to validate and maintain them. A public consortium may have relatively modest formal assets while preserving broad practical capacity through reciprocal access and shared knowledge. An enterprise may reinvest proprietary application revenue in shared infrastructure under enforceable public commitments; another may use the same kind of revenue to deepen technical and contractual dependency. Assessment should trace realized input configurations, accessible productive routes, and rights over maintenance and revision, alongside financial transfers.

Proposition E.1 (Qualified monotonicity of reproducible routes). *Consider a fixed knowledge-production configuration, actor or coalition a , and route family $\mathcal{R}$. Suppose that for two resource*

situations z and z' , the associated sets of accessible maintainable inputs satisfy $\mathcal{U}_r(z) \subseteq \mathcal{U}_r(z')$ for each $r \in \mathcal{R}$, while the maintenance requirements $\mathcal{I}_r$ and the rules governing feasible routes are unchanged. Then the family of routes reproducible under z is contained in the family reproducible under z' .

Proof. If a route r is reproducible under z , Equation 32 gives an element of $\mathcal{I}_r \cap \mathcal{U}_r(z)$. Set inclusion places that element in $\mathcal{I}_r \cap \mathcal{U}_r(z')$, so the route remains reproducible under z' . The argument applies independently to each route in the fixed family. $\square$

Proposition E.1 provides a limited formal baseline. It does not imply that observed additional revenue always improves collective generativity. A resource inflow can be accompanied by a restrictive license, additional mandatory expenditure, contractual exclusivity, displacement of workers, or changes in the set of recognized productive activities. These developments alter the feasible-input sets or the route requirements and therefore change the proposition's assumptions. The result helps identify why a comparison of gross value flows is insufficient: a meaningful institutional study must track how the conditions that determine feasibility are themselves transformed.

E.6 Institutional Power, Appropriation, and Circulation Asymmetries

The productive effects of circulation depend on which actors can initiate transfers, prevent others from using resources, determine conversion standards, and revise obligations. Legal ownership, de facto operational control, collective authority, and practical exit possibilities should be recorded separately. A nominally common resource may require private services to become usable, while a privately owned resource may support broad public production through enforceable access and maintenance commitments. These configurations call for examination of actual rights and their implementation rather than inference from institutional categories.

For a candidate circulation arrangement, a diagnostic record should identify contributors, beneficiaries, custodians, right holders, evaluators, and those bearing ongoing maintenance obligations. It should also record how representation and authority are distributed among them. A revenue stream can finance necessary maintenance and legitimately compensate labour under one arrangement, while a formally similar payment under another may rest on exclusion of contributors from essential productive conditions. The contrast depends on evidence about contribution, entitlement, alternatives, institutional rules, bargaining, and the persistence of burdens and benefits.

A structural concern arises when control over one generative condition gives an actor repeated opportunities to intercept value produced through several dependent activities. A validation standard, access credential, indexing service, or model-hosting interface may govern activities across multiple relative levels. The breadth of this effect should be assessed through substitution-sensitive feasible-route analysis, as developed in Appendix C.1, and the empirical intervention requirements discussed in Section 16. A deeply positioned component with accessible alternatives may have little practical leverage; a specialized application interface may become indispensable when contractual and technical arrangements constrain substitution. The direction and size of capital expansion depend on the resulting configuration, not on depth alone.

Extraction should therefore be evaluated as a historically and institutionally supported hypothesis. Indicators might include repeated capture of benefits arising from distributed contributions, constraints on contributors' access to productive conditions, unequal allocation of maintenance burdens, and enforceable barriers to contestation or transformation. Each indicator can also arise under circumstances with other explanations. Pricing, coordination, scarcity, compensation for investment, public obligations, and the stability of a shared infrastructure may account for particular asymmetries. An investigation must evaluate rival explanations and the relevant legal and ethical standards. The network model specifies where to look; it does not deliver a moral verdict from incidence or centrality statistics.

The direction of value circulation may also conceal its production history. Revenue attached to a downstream AI service may rely on publicly funded research, shared training materials, underrecognized evaluation labour, and reusable methods. A gross-output account can miss these contributions. Conversely, a public release may produce considerable social benefit while transferring storage, safety

review, and support burdens to an underfunded commons. A robust analysis should seek the pathways by which productive conditions are supplied, depleted, replaced, and governed; it should avoid assuming that any single observable price measures the entire process.

E.7 Illustrative Cross-Level Circulation Configurations

Consider a hypothetical scientific software and archive consortium. A team maintains an open validation library and a public data collection. Several firms use the library in commercial applications, while universities contribute documentation, bug reports, and methodological improvements. Assume that one firm offers financial support conditional on exclusive control of the library's future compatibility standard. A second arrangement provides fewer monetary resources but funds an independently governed maintenance group and permits alternative implementations. These are hypothetical institutional specifications, not findings about an existing organization.

The first arrangement could raise an immediately observable monetary inflow. Its continuing effect on public knowledge production depends on the extent of compatible alternative routes and whether the exclusivity condition changes who may repair, validate, or reinterpret the shared standard. If researchers cannot readily substitute another implementation, new revenue might coexist with diminished public productive autonomy. Under different conditions, a temporary exclusive arrangement could support reliable maintenance while preserving meaningful access and later institutional revision. The documentary record would need to distinguish actual payments, contractual authority, route alternatives, and realized changes of productive capability.

The second arrangement could support a different configuration. Shared maintenance, transparent standard revision, and accessible reference implementations may reduce some cross-level dependencies on a single operator. Yet the consortium could also suffer shortages of specialist labour, insufficient security maintenance, or uneven participation in governance. Public ownership or open licensing alone cannot establish reliable reproduction. The two arrangements require a comparative test of actual maintenance inputs, rights, responsibilities, and feasible production routes. In each case the same application-level use may contribute to a different structure of generative conditions.

A separate limiting example clarifies why circulation and creation cannot be assimilated to a conserved quantity. A publicly readable proof can be reused by many research groups without removing the proof from the original archive. The knowledge available to users may increase while the source remains accessible. The costs of verifying, translating, indexing, and teaching the proof may nevertheless be substantial and unevenly borne. Counting downloads captures one observed interaction but does not directly measure inferential achievement, productive freedom, or the sustainability of the archive. A useful circulation record would therefore combine the copying events with maintenance accounts, evidence of understanding and reuse, licensing conditions, and the capability changes that result.

Table 24 distinguishes a set of hypothesized circulation pathways and the information needed to interpret them. Its categories can coexist within a single institution; they do not rank arrangements by a universal notion of productivity or justice.

E.8 Evidence Protocol, Historical Revisions, and Open Questions

An empirical study should begin by declaring a case boundary and documenting the productive tasks, value domains, institutional rights, and evidence sources used. It should then distinguish at least four data layers: recorded transfers within a commensurable domain; events of value creation, loss, or reinterpretation; cross-domain and cross-level transformations; and the maintenance of productive capabilities. Claims about extraction require a further layer addressing contribution, effective authority, alternatives, burden allocation, contestation, and historical recurrence. Accounts should preserve conflicting records where legal documentation, platform data, participant testimony, and observed practices diverge.

A reconstruction protocol might first establish an evidence-indexed family of configurations $\mathcal{H}_\eta$ with justified partial continuations, then attach typed records to relevant events and couplings. Next, the analyst would infer feasible support routes under observed rights and maintenance conditions. Sensitivity

Table 24: Cross-level circulation pathways and the evidential distinctions required for interpreting knowledge-capital reproduction.

Pathway	Candidate observable record	Additional condition for interpretation
Application revenue to shared methods	Contracts, payments, maintenance budget	Usable alternatives, rights, continued verification
Collective labour to infrastructure	Work logs, releases, support records	Unpaid burdens, recognition, maintenance capacity
Knowledge reuse across domains	Citations, code links, documented uptake	Meaningful use, epistemic change, replication
Standards to downstream applications	Compatibility decisions, validation rules	Contestability, substitution and revision authority
Public financing to common facilities	Grants, access records, operating costs	Access distribution, long-term continuity
Private platform to public archive	Licensing, hosting and export interfaces	Exit capability, data portability, practical control

analysis would compare the results under alternative event granularities, model boundaries, attribution conventions, and substitution assumptions. A change in the accounting instrument should be recorded as a model revision; a documented change in institutional practice or available production routes should be stated as a historical claim. Neither type of revision should be made to stand in for the other.

The strongest remaining difficulty is causal identification of multilevel effects. A standard may become widely used because it offers technical reliability, because of network coordination benefits, because of institutional authority, or through some combination of these mechanisms. Its widespread use alone does not identify coercive control. Comparative institutional records, documented rule changes, credible counterfactuals, and participant-centred evidence may help distinguish these explanations. Measurement of heterogeneous outcomes adds a further issue: changing recognition standards can alter the observed data even where the underlying activity is stable, and some dimensions of public generativity are only partially measurable.

A second open question concerns historical transformation of value domains themselves. New practices may create forms of recognition and participation that an earlier vocabulary did not represent. Changes in legal rights or available methods may make formerly incomparable options jointly practicable, while an institutional enclosure can make previously feasible translations unavailable. Consequently, the family $\mathbf{V}$, the transformation relations $\mathcal{T}$, and the feasible input sets $\mathcal{U}_r$ may need to change together. Any attempt at long-range quantitative comparison should disclose the correspondences and information losses introduced by these revisions.

A third question concerns institutional design. Commons-oriented arrangements can seek to preserve maintenance resources, plural channels of recognition, portability, and the practical capacity to revise standards. Capitalist, public, cooperative, and other organizations can also construct such commitments under different legal and governance structures. Whether a particular arrangement succeeds depends on implementation, durable resources, and the effective capacity of those affected to participate or contest decisions. The preliminary formalism provides a common diagnostic vocabulary for these heterogeneous cases while leaving institutional evaluation open to historical evidence and normative argument.

Appendix E thus identifies a limited but useful connection between circulation and capital expansion. Typed movement records make certain transfers inspectable; transformation relations identify candidate conversions across generative levels; and reproduction constraints determine whether resulting combinations can sustain specific productive routes. Institutional power influences each of these stages through rights, coordination, recognition, and the capacity to revise generative conditions. Continued inquiry into ownership and extractive leverage in Appendix F can build on the resulting distinctions without equating monetary circulation with knowledge value or mathematical feasibility with justice.

F Ownership, Power, and Extractive Dependency Models

Appendix F develops the institutional-control component of the multilevel framework. Its role is to examine the relations through which actors obtain, exercise, contest, or lose effective command over knowledge-producing conditions. The objective is to distinguish property and authorization, practical control, dependence on productive routes, appropriation of heterogeneous value, and empirically supported findings of extraction. The appendix first specifies rights and capabilities, then examines intervention-based power, control of alternative support routes, appropriation and its evidential requirements, recursive reinforcement, institutional safeguards, a comparative hypothetical case, and the limits of causal interpretation. The formal constructions are conditional descriptions of institutional arrangements. Their use does not establish a universal ordering of property regimes or an automatic inference from structural centrality to exploitation.

Ownership is a historically and legally constituted relation involving differentiated claims, privileges, powers, duties, and remedies. The analytical value of decomposing a supposed unitary ownership position is established in Hohfeld’s account of juridical relations and in the study of rights bundles under common-pool resource governance [43, 82]. Knowledge-production systems require a further distinction between formal authorization and the practical ability to perform the authorized activity. Access to a dataset, repository, laboratory, journal, methodological standard, or interpretive forum depends on interfaces, resources, skills, governance and complementary relations. Its consequences for others depend in turn on substitutable production routes. An adequate account therefore relates institutional authority to productive capability and the heterogeneous circulation records developed in Appendices C.1 and E.

F.1 Differentiated Rights and Practical Command

For a bounded case, retain the historical configuration $\mathcal{H} = (V, E, A, Q, P, R, X, I)$ from Equation 1. Let A index analytically identified actors and organized collectivities, V the selected productive components, and O a declared set of operations. An operation may include inspecting a document, executing a validation procedure, changing a repository interface, licensing an output, excluding a class of uses, setting an evidentiary rule, deciding a maintenance budget, or initiating a review. The operation vocabulary should distinguish use from exclusion and rule revision. A right to read an item need not entail a right to prevent another institution from changing its permitted encoding; likewise, custodial responsibility need not confer unlimited power to monetize or restrict an archive.

For $a \in A$ and $v \in V$, define $\text{Auth}_a(v \mid \mathcal{H}) \subseteq O$ as the operations authorized under the modelled legal and governance rules. Define $\text{Prac}_a(v \mid \mathcal{H}) \subseteq O$ as those the actor could practicably undertake with the relevant equipment, expertise, coordination and resources, initially abstracting from authorization. The corresponding set of effectively executable authorized operations is specified in Equation 33.

$$\text{Exec}_a(v \mid \mathcal{H}) = \text{Auth}_a(v \mid \mathcal{H}) \cap \text{Prac}_a(v \mid \mathcal{H}). \quad (33)$$

Equation 33 represents an initial intersection of permissions and practicability, subject to a further assumption: both sets use an identical operation vocabulary and refer to the same bounded institutional situation. Where permissions or capabilities are conditional on an action by another actor, one may instead model executable *joint plans* and their contingencies. Effective command can also extend beyond formal authorization when actors are able to impose de facto restrictions through technological architecture or social position; those forms require separate records and must not be quietly included in the set of authorized operations.

Several distinctions follow. A public institution may own a server while an independent collective controls the knowledge required to operate its archive; neither relation entails complete control of the service. A contributor can possess copyright in a dataset component while another institution holds contractual powers to distribute the combined corpus. An open license may grant broad permissions while proprietary tooling, bandwidth limits, legal uncertainty, or inaccessible documentation obstruct practical reuse. Conversely, a platform may operate a system without holding the intellectual property

in the underlying public knowledge, yet acquire substantial influence through the services that mediate access. These relations are analytically separable even when contracts or practices combine them in a particular case.

The objects of the model require care. A researcher’s learned capacity, identity, or self-understanding is not treated as alienable equipment. Institutional permissions may govern participation in a laboratory or access to a restricted corpus, but this does not imply institutional ownership of the persons whose capacities are mobilized. Likewise, a community’s collective authority cannot automatically be reduced to the legal title of a spokesperson. A case study should identify internal deliberation and representation before assigning a collective operation to an apparently unitary organizational actor. The distinction matters when common resources, public administration, and cooperative ownership are compared [40, 70].

F.2 Institutional Intervention and Relational Power

An institution’s effective power is better examined through consequential operations than through legal labels alone. Let $P_a(\mathcal{H})$ be the identified family of interventions available to actor a in the configuration. An intervention may change an access rule, disable an interface, set a quality threshold, allocate maintenance resources, convene a governing body, or authorize a new implementation. The affected productive possibilities of actor b can then be compared using $\text{Cap}_b(\mathcal{H})$ and $\text{Cap}_b(\mathcal{H} \mid p)$, as defined in Equation 11. Both terms designate sets or structured profiles of feasible activities, with explicit activity, population, and institutional boundaries.

A complete intervention record should identify the authority used, its implementation channel, the affected tasks, other actors’ possible responses, and any power to contest or reverse the change. A legally documented right to withdraw a license may be exercised under contractual constraints or judicial review. A technical administrator may suspend access without holding a corresponding legal entitlement. A professional association may change an accepted evaluation standard through deliberation and collective consent. These are different mechanisms and may produce different feasible-set changes, even when a crude indicator registers a similar loss of access.

Power can also operate through recognition and interpretation. A dominant classification scheme can determine which contributions appear in a database, which results are deemed reproducible, and which forms of knowledge count toward a funding decision. Such influence need not involve physical exclusion or an observable monetary payment. Its identification requires a study of evaluative practices and their consequences, including the perspectives of affected participants. Theories of multidimensional power, epistemic injustice, and standardization illuminate distinct channels through which decision authority and recognition may shape productive opportunities [58, 33, 88]. These sources do not imply that each use of a uniform standard is coercive: comparability, interoperability and reliable evaluation can also provide shared benefits.

The comparison of interventions remains conditional. A decline in observed participation following a rule change is compatible with several causal explanations, including changed funding, altered demand, a rise in compliance costs, exclusionary decisions, and a shift to another service. Interventions may also improve safety, data protection, accessibility, or technical reliability for some participants while increasing costs for others. A power analysis should therefore retain multidimensional outcomes and allow countervailing decisions, negotiated settlements, and institutional revision. The purpose of the representation is to specify whose feasible options could change, through which mechanism, and under what documented constraints.

F.3 Control of Generative Routes and Substitution

Power over one component can affect many knowledge-producing activities when that component enters several feasible support plans. The relevant measure depends on the alternatives that other participants can actually mobilize. Let $\mathcal{R}_{bq}(\mathcal{H})$ be the nonempty family of feasible support routes by which actor or collectivity b can carry out task q , under declared standards, cost constraints, permissions, and available

skills. A route $r \in \mathcal{R}_{bq}$ is represented in this appendix as a subset of the disjoint, typed universe $V \sqcup G$, where G contains specified institutional gates, permissions, or enforceable operational conditions. This is an explicit extension of the component-only route family of Equation 19; projecting a route onto V discards the gate information and cannot establish complete institutional interception. Where conjunction and ordered operations matter, the underlying route is retained as a typed plan; the interception test below uses its explicitly identified institutional-gate projection, while productive feasibility is evaluated on the complete plan. The directed-hypergraph construction in Appendix C.1 supplies the appropriate support semantics.

For a specified intervention class, let $B_a(\mathcal{H})$ be the set of access gates over which actor a can exercise an effective restrictive decision. Each gate is explicitly mapped to a productive component, permission, or protocol dependency in the route representation. Define *complete route interception* for the activity (b, q) by Equation 34.

$$\text{Intercept}_a(b, q \mid \mathcal{H}) \iff (\forall r \in \mathcal{R}_{bq}(\mathcal{H})) (r \cap B_a(\mathcal{H}) \neq \emptyset). \quad (34)$$

In Equation 34, the statement is structural and relative to the declared route family. It describes a structural hitting-set condition under individually identified gate controls. It does not assert that the actor will exercise the restriction, that the decision would be lawful, or that all routes could be disabled concurrently. A stronger claim of simultaneous obstruction requires a jointly executable intervention plan, as specified in Equation 35. The gate set should contain only controls that the actor can actually exercise under the intervention class being assessed. Co-dependent coalitions may require a joint-control relation rather than attributing the entire gate family to one actor.

Let $\text{Plans}_a(\mathcal{H})$ be a declared family of gate subsets which actor a can restrict *jointly* under the same institutional and technical conditions. A subset of B_a need not be in this family: operations separately feasible may be mutually incompatible or require distinct coalitions. Equation 35 defines joint interception.

$$\text{JointIntercept}_a(b, q \mid \mathcal{H}) \iff \exists J \in \text{Plans}_a(\mathcal{H}) \forall r \in \mathcal{R}_{bq}(\mathcal{H}) : r \cap J \neq \emptyset, \quad (35)$$

Equation 35 implies the structural interception condition of Equation 34 when each admissible J is a subset of B_a . The converse can fail. For example, consider two feasible routes $\{g_1\}$ and $\{g_2\}$ and individually controllable gates $B_a = \{g_1, g_2\}$. If the only jointly executable nonempty plans are $\{g_1\}$ and $\{g_2\}$, the set B_a intersects both routes, but no feasible single plan interrupts both. Joint interception also remains a potential intervention property: observed exercise, financial consequences, and exploitative character require independent evidence.

Proposition F.1 (Route expansion and complete interception). *Fix an actor a , affected activity (b, q) , and control-gate set B_a . Let $\mathcal{R}$ and $\mathcal{R}'$ be nonempty feasible-route families with $\mathcal{R} \subseteq \mathcal{R}'$. If complete interception holds for $\mathcal{R}'$, it holds for $\mathcal{R}$. If $\mathcal{R}'$ contains a route r^* with $r^* \cap B_a = \emptyset$, complete interception fails for $\mathcal{R}'$. The result presumes that the control-gate set and the meaning of route feasibility are held fixed across the comparison.*

Proof. Every route in $\mathcal{R}$ is a member of $\mathcal{R}'$. If each route in $\mathcal{R}'$ intersects B_a , each route in $\mathcal{R}$ does as well. Conversely, the specified route r^* witnesses the failure of the universal intersection condition for $\mathcal{R}'$. The argument uses only set inclusion and the definition of complete interception. $\square$

Proposition F.1 is deliberately limited. A nominally alternative technical implementation may still depend on a common legal permission, supply chain, evaluation credential, or hosting provider. It then fails to produce a route disjoint from the effective control gates. An alternative can also be infeasible within a participant's budget, safety requirements, skills, or transition period, even if the abstract graph contains a path. The proposition addresses structural interception for a fixed gate set; the stronger joint-plan condition in Equation 35 must be investigated separately. Partial control, discriminatory pricing, differential reliability, switching costs, and network effects can sustain substantial leverage in the presence of alternatives. Rigorous empirical application must enumerate feasible rather than merely imagined support routes.

Generative depth enters this model through the route families that depend on a component or rule. An infrastructure-level authentication service or validation norm may appear in many routes, while an application-level distribution channel may likewise act as a widely shared gate. Relative depth alone specifies neither the number of affected activities nor the severity of an intervention. Moreover, successful downstream adaptation may revise foundational rules and create new support routes, altering the dependency structure itself. Institutional power and generative dependency thus require joint and historically situated analysis, consistent with the substitution-sensitive loss measures in Equations 12 and 13.

F.4 Appropriation, Reproduction Burdens, and Extraction Evidence

An account of extraction requires a richer record than control over support routes. The circulation analysis in Appendix E distinguishes movements within a value domain, creation or depletion, cross-domain conversion, and reproduction feasibility. The ownership analysis adds the institutional assignment of claims and the ability to alter the conditions under which value is produced or transferred. An institution may receive a subscription payment for a necessary research service, a royalty for intellectual property, public reimbursement for archiving, or grants to support freely available infrastructure. These receipts represent different arrangements. Whether a particular pattern constitutes extraction requires inquiry into contribution, justification, recurrence, imposed burdens, and the effective options of those affected.

For an actor a , let $\text{Rec}_a(\mathcal{H})$ denote the evidence-backed family of appropriated benefits or claims, typed by value domain and institutional channel. Let $\text{Bur}_b(\mathcal{H})$ denote recorded burdens on contributing actors or collectivities, including maintenance labour, verification costs, dependency-related risk, loss of productive access, and obligations arising from the use of their contributions. These symbols designate families of observations and contested attributions; they do not license subtraction of the two objects into a universal net surplus. Revenue and recognition may have incomparable units, and the significance of unpaid work may depend on consent, compensation, institutional commitments, and effects on future capabilities.

The proposed *extraction dossier* is a structured evidential object rather than a binary index. Equation 36 states its minimal analytical fields.

$$\text{Dossier}_{a|b}(\mathcal{H}) = (\text{Contrib}_b, \text{Rec}_a, \text{Bur}_b, \text{Rule}, \text{Depend}, \text{Reprod}, \text{Remedy}, \text{Alt})_{\mathcal{H}}. \quad (36)$$

In Equation 36, Contrib_b records contributions and their evidence; Rec_a records benefits and claims appropriated by a ; Bur_b records costs and imposed obligations; Rule names the applicable legal or institutional arrangements; Depend specifies relevant support-route dependencies; Reprod concerns continued productive capabilities; Remedy specifies meaningful avenues of challenge, revision or compensation; and Alt records rival mechanisms and counterfactual alternatives. The dossier may include disagreement over which actors contributed to a collectively produced value, and it should distinguish allegations from adjudicated findings or otherwise well-supported historical conclusions.

A sustained extractive arrangement is a candidate interpretation when recurrent appropriation is enabled by an identifiable control relation over distributed productive contributions, when affected contributors carry consequential burdens or lose productive autonomy, and when plausible alternative explanations have been assessed. The recurrence condition distinguishes a continuing institutional relation from a single exchange whose terms may be negotiated and contestable. The burden condition makes the reproduction of productive capability analytically visible. These considerations are informed by research on intellectual monopolies, rentier arrangements, and enclosure, but they do not imply that the same empirical or normative criteria apply unchanged in every sector [80, 16, 13].

Exploitation is a further theoretical and normative judgment. Different traditions specify exploitation through labour relations, unequal exchange, domination, unjustified benefit, or the constrained reproduction of productive capabilities. This paper does not presuppose that all criteria coincide. An empirical case requires an explicit evaluative account: a contractual payment may be consensual yet embedded in structural dependence; a subsidized public service may generate inequalities in access despite non-profit

governance; a cooperative may distribute cash surpluses fairly while leaving underrecognized maintenance work to a small group. A clear research record separates the descriptive facts of appropriation and dependence from the norms used to assess them and the remedies proposed.

F.5 Recursive Reinforcement Across Generative Levels

Control and value appropriation may change the conditions of further knowledge-capital accumulation. Consider a platform that uses application revenue to acquire computing resources, employ specialists, operate widely used validation services, and participate in setting methodological standards. The resulting configuration can offer genuine productive benefits while consolidating a position from which the platform influences downstream access and upstream knowledge conventions. A commons-based consortium can also reinvest revenue or voluntary labour into shared maintenance and governance capacity, allowing additional contributors to become independent producers. The relevant question is the trajectory of productive possibilities and authority, rather than the institutional label alone.

The historical representation adopted here specifies an evidence-indexed relation $\eta \preceq \xi$ between configurations $\mathcal{H}_\eta$ and $\mathcal{H}_\xi$ only when the researcher can justify the continuation relation. It does not assume an absolute temporal origin, a universal present, or a fixed time interval over which capital expands. A continuation may retain identifiable components, replace an institutional rule, introduce new methods, change the value domains that institutions recognize, or invalidate earlier representations. The account of recursive capital expansion in Equation 14 accommodates such changes at the level of specified transformations; the following representation tracks institutional consequences in a way that remains deliberately plural.

Let $\text{State}(\mathcal{H}_\eta)$ be the typed profile of support routes, enforceable claims, practical capabilities, institutional revision powers, and circulation records selected for a case. Define $\mathcal{C}_{\eta\xi}$ as a relation of admissible, evidence-compatible transformations between such profiles. Equation 37 records the admissibility requirement.

$$(\text{State}(\mathcal{H}_\eta), \text{State}(\mathcal{H}_\xi)) \in \mathcal{C}_{\eta\xi} \quad \text{for a documented continuation } \eta \preceq \xi. \quad (37)$$

The relation in Equation 37 encodes a proposed correspondence; it does not assert that authority or economic value grows monotonically along every continuation. Revenue concentration can fund improved public access or strengthen exclusionary dependence. A legal entitlement can expire; a new interoperable implementation can undermine a formerly unavoidable gate; contributors may coordinate to create a different standard. Conversely, a new public repository may reproduce older gatekeeping through evaluation rules or reliance on scarce technical maintainers. The analyst should trace alterations of the feasible route family, rights bundles, recognized value domains, and governance procedures independently before describing their coupling.

A special danger can arise where an institution controls procedures that classify and validate knowledge, while also obtaining advantages through those classifications. Its capital position may influence which contributions are recorded, which assets can be valued, and which alternatives receive institutional recognition. Such recursive influence affects the evidence by which its own significance is measured. This is one reason to examine epistemic authority alongside ownership and monetary circulation, with external audit, participant testimony, alternative representational schemes, and scrutiny of research evaluation practices [41, 24, 33]. The framework does not assert that all standard-setting authority is extractive; the risk depends on effective contestability, demonstrable outcomes, and the surrounding institutional arrangement.

F.6 Contestability, Portability, and Institutional Counterpowers

The existence of effective control relations directs attention to the conditions under which affected actors can contest or revise them. Exit, voice, and institutional loyalty are analytically distinguishable responses

Table 25: Institutional-control dimensions, relevant records, and principal interpretive limits.

Analytical dimension	Candidate evidence	Interpretive qualification
Legal and formal rights	Statutes, licenses, contracts, public mandates	Jurisdiction, enforceability, conditions and duties
Practical access and operation	Service records, skills, interfaces, maintenance logs	Capacity and cost under available alternatives
Route interception	Technical dependencies, certification rules, substitution studies	Feasible routes and independently controlled gates
Epistemic and evaluative authority	Standards decisions, classification protocols, appeals	Reliability goals, plural criteria and external scrutiny
Appropriation and benefits	Financial flows, use rights, citation and reward allocation	Contributions, conversion rules and justified claims
Reproduction burdens	Staff hours, risk allocation, repair and validation costs	Hidden labour, distributed maintenance and consent
Contestability and remedy	Appeals, portability tests, independent review, collective voice	Effective exercise, reversibility and retaliation risks

to organizational performance and dependence [42]. For knowledge production, exit can involve migrating a repository, adopting another validation route, retaining usable research records, or joining a different production collective. Voice can involve documented review rights, participatory standard revision, independent appeals, and collective bargaining over maintenance obligations. Loyalty may sustain long-term investment and cooperation, although reliance on continued cooperation without practical review rights can also obscure accumulating asymmetries. The relevance of these mechanisms varies with the characteristics of the knowledge resource and the distribution of expertise.

Portability is a technically and institutionally compound condition. A downloadable dataset may remain unusable without its metadata, code, data-use permissions, contextual knowledge, or validation records. An open standard may be formally available while certification rests with one actor. For that reason, the feasibility of an alternative route should include the realistic cost and competence of migration and the permissions necessary to use the alternative. The mere presence of an export button is not a sufficient measure of independence. Principles of reusable scientific data and collective governance are relevant to these questions, though the compliance and authority conditions must be examined in each setting [91, 14].

Table 25 summarizes the main dimensions through which an institutional comparison can be documented. It treats legal title, technical control, evaluative authority, value appropriation, reproductive burden and contestability as separate observations. A comparative inquiry may record divergent descriptions rather than force consensus where evidence remains disputed. The table is a diagnostic guide rather than a weighted governance score.

The audit can be applied across capitalist enterprises, public administrations, cooperatives, commons-governed infrastructures, and communist-oriented collective production arrangements. Its terms do not presume that a particular regime has stronger or weaker rights in every dimension. For example, a public institution may provide broad service guarantees while concentrating authority over classification; a proprietary research platform may accept enforceable interoperability and public access obligations; and a community-run archive may have formal participatory governance yet lack specialist capacity to maintain its preservation functions. Comparative claims require observable records of these concrete configurations. The distinction between legal rights and feasible exercise is important throughout.

F.7 Hypothetical Validation Infrastructure and Institutional Alternatives

Consider a hypothetical scientific community whose investigations depend upon a reference corpus d , a validation method m , a software implementation s , and a shared certification procedure c . Applications q_1 and q_2 use the validated outputs in separate research areas. Researchers, data curators, software contributors, and public funders have collectively supported the infrastructure. Suppose that certification

is recognized by several journals and agencies, while the method is sufficiently explicit to permit a technically distinct implementation s' . This construction is an illustrative institutional scenario; it is not an empirical description of a particular community.

In a first configuration, a company maintains s , contracts for operation of c , and offers reliable services for a fee. The organization publishes technical documentation, provides secure processing, and finances upkeep. The method m and source corpus d remain openly accessible. If certification can only be completed by the company's gate, it may intercept all currently feasible routes for a subgroup of dependent research tasks even though the corpus and method are openly available. Under such conditions, the decisive source of leverage would lie in the certification rules, complementary capacities and recognition of outputs, together with the actual costs of substitution. The company's revenue could nonetheless support valuable maintenance, and the presence of this bottleneck alone would establish neither unjust appropriation nor exploitation.

In a second configuration, a public consortium finances an independent implementation s' and creates a separately governed certification route c' , provided it satisfies a substantively equivalent quality standard. Affected researchers obtain enforceable rights to submit evidence through either route. Assume that the revised route family includes at least one feasible plan disjoint from the company's restrictive gates. Proposition F.1 then establishes that complete interception by that gate set is absent in the extended route representation. The result does not determine whether alternative certification costs, training needs, shared dependencies, or differences in epistemic reliability make one route dominant in practice. Such characteristics are required to assess partial leverage and equitable participation.

In a third configuration, the consortium owns the servers and nominally governs the certification procedure, yet contracts long-term operation to an organization with sole custody of essential documentation and specialist expertise. The legal owner may possess broad formal powers while lacking the ability to execute an independent transition. The route family may remain dependent on the contractor until expertise and complete records become available. A statutory public mandate does not by itself establish effective public generativity. An empirical assessment would investigate training investment, documentation obligations, source and data portability, and the capacity of the intended public beneficiaries to influence the standard. This configuration shows how a seemingly public ownership arrangement may reproduce concentrated practical command.

The comparison can be extended to value circulation. In one arrangement, application-service receipts pay curators and support open reference maintenance, with transparent audits and negotiated obligations. In another, substantial receipts accrue to one operator while preservation burdens and error correction remain with unpaid contributors, and changes to certification rules progressively restrict their ability to participate. The two arrangements could involve comparable gross revenue and similar technical performance while differing markedly in recognition, maintenance, autonomy and institutional voice. An extraction finding in the latter case would require evidence of the recurring appropriation mechanism, resulting burdens, actual alternatives, responsibility for investment, and the grounds on which the arrangement is judged problematic. The structural model indicates relevant observations; it does not make the final historical or normative assessment.

F.8 Identification, Robustness, and Open Institutional Questions

Empirical analysis should begin with a documented institutional and activity boundary. The researcher should list productive components, tasks, contributor groups, legally relevant actors, evidence sources, and meaningful alternatives. Each rights claim should be distinguished by jurisdiction, holder, scope, exception, and enforceability. Each practical-control claim should identify the operation that an actor can undertake and the resources required for its execution. Support-route models should declare technical validity conditions, maintenance standards, substitutive plans, and the decision horizon appropriate to the case. The choice of horizon is an observational and institutional convention; it is not an assertion of an ontologically privileged time parameter.

A second stage concerns the provenance of value and burden claims. Evidence may include con-

tribution histories, licensing records, royalty statements, contracts, financial accounts, software commits, issue trackers, platform logs, archival records, institutional minutes, and interviews. These sources have different observation biases. Financial records may omit unpaid maintenance; source repositories may obscure coordination or care work; citation databases may privilege particular languages or disciplines; institutional minutes may record formal decisions while overlooking de facto control. The researcher should preserve contested interpretations and test whether different contribution-attribution models change the conclusion. Claims concerning participant intentions require their own evidence, and causal explanations should be distinguished from hypotheses about motive.

Third, the analyst should compare credible counterfactual interventions. An alleged gate may become less consequential under a low-cost alternative, though a plan imagined by an analyst may remain infeasible under existing rights and staff capacity. A governance change can also alter the task set itself, the acceptable evidence standard, or the definition of productive success. Estimates based on fixed technical dependencies should therefore be accompanied by sensitivity analyses for feasible-route families, cross-level abstractions, legal enforceability, adaptation costs and valuation conventions. The distinction between an association and an identified causal effect is central to sound counterfactual inference [75, 44].

Finally, normative evaluation should remain transparent about its standards. A commons perspective may foreground value recirculation and contributor governance; public administrative standards may emphasize equal treatment, service continuity, legal accountability and rights protection; an enterprise evaluation may include investment incentives and enforceable obligations; labour-centred analysis may focus on productive dependence and contribution. These perspectives can overlap while preserving genuine disagreements. Researchers can examine the effects of a particular rule under several justified evaluative criteria without collapsing them into a universal scalar score. Political-economic diagnosis gains precision when descriptive records, causal interpretations, legal claims and normative conclusions are separately auditable.

The formal contribution of Appendix F is a structured account of differentiated authorization, practical capacity, complete route interception, heterogeneous appropriation, and institutional continuation. The qualified proposition identifies a precise condition under which independently feasible alternatives defeat complete interception by a fixed gate set. Its limits are as important as its conclusion: institutional control may survive through partial dependencies, common regulatory requirements, asymmetric costs or changing epistemic standards; formal openness can coexist with practical dependence; and concentrated authority can be used to maintain public services or to support extraction. Further inquiry must investigate how these relations evolve together with the productive and evaluative structures they govern. Appendix G develops the resulting questions of recursive expansion, structural transitions and formal counterexamples.

G Recursive Expansion, Structural Transitions, and Formal Counterexamples

Appendix G examines how an accumulation process can modify the conditions under which further knowledge-capital accumulation becomes feasible. Its role is to extend the static dependency, circulation, and institutional-control representations of Appendices C, E, and F to transformations of the represented production system itself. The objective is to make explicit the difference between expansion in an existing set of capabilities and a change in the generative relations through which capabilities are formed, controlled, and reproduced. The argument proceeds through admissible historical continuations, feedback across generative levels, structural transitions, a bounded dynamical illustration, counterexamples, a comparative hypothetical case, and an evidence protocol. Its propositions concern declared mathematical assumptions; interpretation as historical capital accumulation or extraction requires additional political-economic evidence.

A knowledge-producing system may develop instruments from methods that it subsequently uses to

revise those methods. The income from an application may finance a shared repository, and the repository may allow qualitatively different applications. Conversely, a service that grows through access to jointly produced knowledge may use some of its returns to control a validation interface or change the terms on which contributors can use their outputs. Such mechanisms have affinities with accounts of cumulative causation, increasing returns, technological learning, and organizational adaptation [4, 22, 67, 86]. Those literatures motivate the inquiry; they do not predetermine the institutional direction of a particular recursion. The central analytic object here is a historically situated *change in the space of admissible further changes*.

G.1 Historical Continuations and Comparable Capital Profiles

Let $\mathcal{H}$ be a bounded class of candidate configurations of knowledge production. A configuration $\mathcal{H} \in \mathcal{H}$ records typed productive components and dependencies, feasible tasks, the participating actors, differentiated rights, and the represented value-circulation relations, following Equation 1. The model's historical continuation relation is the admissible transformation family Adm used in Equation 14. Its elements require a documented or expressly hypothetical relation between the corresponding configurations. The mere presence of two different configurations does not establish that one was generated from the other.

For a specified actor or collective a , a capital profile should be multidimensional. A suitable profile can record accessible productive tasks Cap_a , maintainable support routes Rep_a , authorized and practically executable operations Exec_a , and an identified family of appropriately typed value claims Val_a . The first three objects are sets or structured collections, and the last can contain incomparable quantities and interpretations. A profile is therefore not intrinsically reducible to a single scalar. A further component may describe the routes through which a can participate in revising its own productive rules. The continuation repertoire $\text{Cont}_a(\mathcal{H})$ in Equation 15 provides a starting point for that component, conditional on the ability to compare the represented activities.

An inquiry into expansion must specify *whose* capabilities are expanding. A corporation can increase its command over productive interfaces while a consortium loses the practical capacity to maintain an open alternative. An expanding task repertoire for one group can coexist with increased costs, fewer contestable decisions, or the withdrawal of support from another group. It is also possible for a collectively adopted safety or privacy rule to remove previously available activities while supporting a more reliable research practice. Set inclusion records some changes in feasible activities; it does not itself rank their ethical desirability.

To compare configurations whose representations differ, introduce a partial correspondence $\phi_{\eta\xi}$ between tasks, components, and rights descriptions. It maps those elements for which continuity can reasonably be established, and leaves emerging or discontinued categories explicitly unmatched. For example, a repository may replace a machine-readable identifier scheme, merge two roles, and introduce a form of community consent that lacks a direct counterpart in its earlier governance arrangements. A total equivalence mapping would conceal these changes. Where only some operations are comparable, comparisons are restricted to that common domain. Recording the limits of $\phi_{\eta\xi}$ is a prerequisite for interpreting apparent growth as more than a relabelling or a change in observation.

G.2 Recursive Transformation of Productive Conditions

Knowledge capital participates in its own reproduction through admissible interventions on resources, methods, institutions, and relationships. The key phenomenon is not a multiplication of stored artifacts, but a transformation of what participants can productively do and subsequently revise. Let $\text{U}(\mathcal{H}, \iota)$ be a set of configurations that may result from an intervention ι admissible in $\mathcal{H}$. The intervention can represent research activity, maintenance expenditure, licensing reform, shared training, a contractual restriction, or a collectively negotiated change of standards. Its outcomes are set-valued because institutional and productive interventions often admit several results under the evidence available.

The recursive step is represented by Equation 38.

$$\mathcal{H}' \in \mathcal{U}(\mathcal{H}, \iota), \quad \iota \in \text{Act}(\mathcal{H}), \quad \text{Act}(\mathcal{H}') \text{ may differ from } \text{Act}(\mathcal{H}). \quad (38)$$

Equation 38 expresses a single admissible step and, crucially, allows the set of subsequent interventions to change. Here $\text{Act}(\mathcal{H})$ is the modeled repertoire of executable interventions in a configuration. An intervention on a foundational validation method might change research tasks, the standards by which those tasks are assessed, and the authorities entitled to revise the method. An application-level development might create a new public method or reveal a failure in an inherited evidentiary convention. The resulting structures therefore need not preserve a permanent upper-to-lower ordering of generative levels.

Recursive expansion may operate through at least four distinguishable channels. *Material recursion* uses productive outputs or proceeds to maintain or augment equipment and infrastructure. *Methodological recursion* employs results to modify practices of generation and verification. *Institutional recursion* reallocates permissions, responsibilities, coordination capacities, or authority to revise standards. *Epistemic recursion* changes the categories and criteria through which knowledge claims and contributors become recognizable. These channels can interact, yet evidence for one channel does not establish the others. A documented software update is evidence of technical modification, while a claim that the update altered disciplinary epistemology requires records of research practice, interpretation, and recognition.

Several distinct returns may also occur within a single continuation. Money may fund maintenance work; the maintenance work may make a validation method reproducible; reproducibility may attract contributions that extend the method. The value types and conversions in Appendix E can represent these relations without converting epistemic reliability into a monetary magnitude. In a different arrangement, revenue can finance a closed application interface while continued contributions to the underlying shared method remain uncompensated or insufficiently supported. The difference concerns the actually supported productive routes and the arrangements governing circulation, including contributors' rights and remedies. The mere presence of a profitable recurring service is insufficient to classify the arrangement as extractive.

G.3 Cross-Level Feedback and Compositional Limits

A relative generative-level descriptor identifies a position in a selected dependency representation. It is neither a permanent rank of social importance nor an absolute measure of conceptual abstraction. Consider a methodological component m , an application p that depends on m , and an observed research task in which use of p supplies evidence for revising m . A coarse representation can display two directional influences between m and p . This does not mean that the same item, unchanged, is simultaneously its own necessary prerequisite. One can model a method instance, its application, and the revised method as distinct typed components connected by explicit admissible continuation relations.

In this example, the application is consequential because it contributes to a change in conditions at a different relative generative level. If the revised method supports a new family of applications, a continuation may produce a wider repertoire than a model restricted to the original application-to-output link suggests. Conversely, evidence gathered through an application might lead a community to withdraw a methodological claim or narrow its permissible uses. Such a change can reduce the number of recognized feasible tasks while increasing reliability or protecting research participants. Recursive feedback therefore has no fixed sign with respect to either a task count or a normative assessment.

Feedback also complicates the meaning of an *upstream* site. In the typed hypergraph model, a support relation concerns a specified route under particular performance standards. Once new results alter those standards, the relevant hyperedge may change. Strongly connected components can be condensed to a partial order for a fixed representation, as developed in Appendix C.3. Structural changes may split, merge, or eliminate such components. Consequently, a component's graph-theoretic depth under one configuration need not transport to another configuration. This is an analytical issue, even when the underlying historical practice is documented with high confidence.

Formally, let $\mathcal{G}_\eta$ and $\mathcal{G}_\xi$ denote two typed support structures, and let $\phi_{\eta\xi}$ be a declared partial correspondence on their components and task types. A proposed feedback relation should identify (i) the productive intervention, (ii) the changed components or support assertions, (iii) the evidence for the change, and (iv) the ways that the revised structure changes feasible continuations for specified participants. A correspondence preserving component names may fail to preserve task feasibility; a mapping preserving reachability can still fail to preserve rights or practical maintenance costs. Structural comparison cannot be reduced to matching node labels.

This perspective sharpens the paper’s political-economic hypothesis. Control of a deep-level component *may* permit recurrent appropriation across numerous dependent practices when credible alternatives are costly, governance is difficult to contest, and the controller can retain benefits generated elsewhere. The same deep-level component may have broad, nonexclusive distribution, collectively governed revision, and independently maintained substitutes. A relatively specific application may likewise become an indispensable bridge for a small population with few alternatives. The consequences of accumulation are thus jointly mediated by level, actual dependency, substitute feasibility, institutional power, and the circulation and reproduction of heterogeneous value.

G.4 Bounded Feedback Dynamics and Stability

Some empirical questions concern recurrent adjustments measured using stable variables and a defensible observation schedule. In such cases, a finite-dimensional approximation can help state a conditional implication about feedback. For example, an analyst may track the resources dedicated to shared method maintenance and the capacity of an application service to deliver qualified tasks, using separately defined indices whose scales are held fixed. A matrix model may describe interactions within the scope of that measurement scheme. The numerical iteration index is a convention for the model’s observations or updates; it does not introduce a privileged physical present or establish a universal ordering of historically possible continuations.

Consider a constant vector $b \in \mathbb{R}_{\geq 0}^d$, an initial nonnegative vector z_0 , and a nonnegative matrix $A \in \mathbb{R}_{\geq 0}^{d \times d}$. The affine illustration is stated in Equation 39.

$$z_{n+1} = b + Az_n, \quad n \in \mathbb{N}. \quad (39)$$

An entry of A can represent a locally estimated contribution from one measured capacity dimension to another; the model does not identify the dimensions with homogeneous units. Rescaling or normalization conventions must be stated, and empirical use requires an account of why a linear constant-coefficient approximation is appropriate. An observed feedback loop in knowledge production is generally more complex because access rules, accounting practices, and the available productive activities can change.

Proposition G.1 (Convergence of a fixed nonnegative affine feedback model). *For Equation 39, suppose the matrix A is fixed and its spectral radius satisfies $\rho(A) < 1$. Then, for each finite initial vector z_0 , the iterates converge to the unique fixed point $z^* = (I - A)^{-1}b$. Under the nonnegativity assumptions, z^* is componentwise nonnegative.*

Proof. Repeated substitution yields $z_n = A^n z_0 + \sum_{j=0}^{n-1} A^j b$. The spectral-radius condition implies $A^n \rightarrow 0$ and convergence of the matrix series $\sum_{j=0}^{\infty} A^j = (I - A)^{-1}$. Therefore $z_n \rightarrow (I - A)^{-1}b$. The inverse is represented by a series of nonnegative matrices, giving a nonnegative fixed point. If two fixed points existed, their difference would be fixed by A ; invertibility of $I - A$ makes the difference zero. $\square$

Proposition G.1 establishes a property of a declared linear recurrence. It does not imply that a knowledge commons tends toward equilibrium, that capital accumulation is necessarily stable, or that a system’s historical transformations can be assigned constant numerical rates. The condition is intentionally strict. A model that increases output through positive feedback might generate ever-larger measured quantities when the spectral radius is at least one, while actual material constraints, governance changes, replacement technologies, or shifting research purposes can invalidate the approximation. An increase

in the numerical value of a capacity index can also coexist with decreasing public access or accumulating uncompensated maintenance burdens.

Importantly, even convergence of this illustrative model says nothing about ownership or justice unless those quantities are separately represented. Two organizations with identical measured production and maintenance profiles can have different licensing rights, decision rules, and conditions of productive autonomy. The matrix elements alone contain no information on whose contributions finance the recurrence or whose authority governs the results. The value of a simple feedback model is to isolate the implications of a limited set of assumptions, not to turn aggregate growth into a political-economic verdict.

G.5 Structural Transitions and Changes of Admissible Routes

A structural transition is a change in a modeled generative or institutional arrangement for which ordinary comparisons at a fixed task and component universe become incomplete. An example is the adoption of a new standard that alters which validation methods can certify a result. Another is the introduction of a new public implementation that creates an alternative route around an existing platform. Still another is a change in research practice that transforms an application into an infrastructure supporting tasks beyond its original domain. In each case the continuation may affect the universe of tasks, the conditions for recognition, and the ways capital is constituted.

The term *transition* should not obscure the distinction between a transformation in the investigated system and a revision in an analyst's model. A newly discovered archival record may reveal an alternative that existed throughout the observed period; a newly developed validation technique may create an alternative previously unavailable. Their implications for inferred historical dependence differ. Accordingly, a transition account should identify at least two dated or otherwise ordered bodies of evidence, the representational correspondence, and the type of change attributed to the system. A claim that an actor acquired control through the transition also requires a separate description of its enforceable powers and practicable interventions.

For a task q and actor a , let $\mathcal{R}_{a,q}(\mathcal{H})$ be the family of complete, feasible support routes in the sense of Appendix C.4. A transition can add a route, remove a route, revise a common gate, or change the performance standard that determines feasibility. If the activity and standard remain comparable, feasible-route families can be compared directly. If they change, the analyst should supply a partial correspondence of tasks and standards and refrain from an unqualified inclusion assertion. The route model can express a precise result under a fixed reference task.

Proposition G.2 (Loss of complete interception under an independent route). *Fix actor a , task q , a common universe of components and gates, and a set B of gates that a controller can actually restrict. Suppose the original nonempty feasible-route family $\mathcal{R}$ is completely intercepted by B , meaning that each $r \in \mathcal{R}$ intersects B . If a structural transition adds an admissible complete route r_* with $r_* \cap B = \emptyset$, while preserving the original task standard and the availability of r_* to a , then B does not completely intercept the enlarged route family $\mathcal{R} \cup \{r_*\}$.*

Proof. The added route r_* belongs to the enlarged family and has empty intersection with B . Hence the condition that every feasible route intersects B is false. $\square$

Proposition G.2 extends the structural route-interception idea of Appendix F.3 to a documented transition. Because a route disjoint from the entire gate set B is also disjoint from each feasible jointly executable plan $J \subseteq B$, it defeats joint interception as defined in Equation 35. Conversely, intersection of every route by B alone does not establish that any one feasible joint plan intersects every route. Its conclusion is deliberately narrow. It gives no guarantee that the new route has equal cost, quality, legitimacy, durability, or accessibility to other participants. Nor does the existence of an independent route imply that an earlier arrangement was exploitative. A new route may be legally available yet financially impossible for many users; a community-owned implementation may lack adequate maintenance. When such conditions affect the task criterion, they belong in the feasibility test. An intervention by the

original controller may also alter the rules governing all routes, including the purported substitute. The proposition's relevance depends on showing that the independence and feasibility assumptions actually hold.

G.6 Formal Counterexamples to Simplified Accumulation Claims

The formalism is most useful when it identifies the conditions under which an appealing generalization fails. Several finite examples test the relationships among generative depth, effective dependence, capital accumulation, and the existence of extractive arrangements. Each example is hypothetical. It specifies a possible configuration compatible with the model; it is not an allegation concerning a historical person, institution, or company.

Foundational position with weak exclusionary leverage. Consider a common validation vocabulary m used by several downstream research tasks. Let each task also have an independently usable alternative vocabulary m' that satisfies its evidence standard and can be maintained by an autonomous collective. The first vocabulary appears at a relatively deep level and has numerous outgoing dependency assertions, but the feasible-route family for each task contains a route that omits m . A controller of m thus lacks complete interception through m alone. This remains true even if m receives substantial scholarly recognition or has historically influenced many applications. Depth and intellectual influence do not establish exclusive practical command.

Application-level position with high practical dependence. Consider a specialized interpretation service s that is the sole validated interface capable of serving a small group of research users under their technical and institutional constraints. All their admissible task routes contain the gate s , despite its position near a terminal application in the chosen generative description. An operator able to suspend the service has complete route interception for that population and task. Its exercise, bargaining effect, or appropriative consequences require additional evidence. This construction shows that shallow placement can coexist with high effective dependency.

Increased production with diminished collective autonomy. Suppose two institutions support a shared task q , and an application investment makes two further tasks feasible within a new configuration. At the same time, a new exclusive license removes from the contributing collective its authority to inspect or modify the data interface supporting q . An aggregate count of feasible tasks increases, while the collective's executable governance operations decrease. The change is compatible with productive expansion and with an adverse change in participation or control. Neither property logically determines the other. A multidimensional capital profile is therefore necessary.

Recursive expansion without extractive appropriation. Suppose a commons-based consortium publicly documents its methods and funds maintenance through a transparent, collectively approved contribution rule. The resulting applications supply both new knowledge and material resources, and participating contributors retain workable opportunities to revise the shared standards. The process can recursively expand productive capabilities and support unevenly distributed expert responsibilities. Its asymmetries of skill or contribution do not, without further evidence, establish extraction. This example separates recurrence and specialization from a mechanism of recurrently appropriating benefits under constrained alternatives.

Public title with concentrated operational authority. Consider a publicly owned repository with open-license outputs and an outsourced validation gateway. The public institution holds legal title, yet the contractor alone possesses the expertise, credentials, and infrastructure required to keep the gateway operational. For users, all feasible validation routes may therefore pass through the contractor's effective gate. The institutional label *public* does not determine the practical location of operational power.

Table 26: Finite counterexamples and the inference each limits in a multilevel knowledge-capital model.

Configuration	Tempting inference	Missing condition or evidence
Deep method with independent substitute	Deep position establishes decisive leverage	Feasible-route necessity and effective exclusion power
Specialized terminal service	Application position implies limited influence	Population-specific alternatives and service substitutability
More tasks under an exclusive license	Productive expansion enlarges collective autonomy	Rights, participation, and practical access
Reciprocal commons reinvestment	Recursion entails extraction	Appropriation pathway, recurrent burdens, contested control
Public archive with outsourced gateway	Public title supplies operational autonomy	Technical custody, transfer of skills, enforceable remedies
Closed coupling path	Topological cycle establishes value circulation	Typed value events, conversion and receipt records
Expanded observation ledger	Larger recorded capital implies historical growth	Stable definitions and evidence of changed conditions

Procurement terms, transferability of expertise, accountability, and the development of usable substitute gateways determine whether this dependence is temporary, controlled, or entrenched.

Circular graph structure with absent economic circulation. Let the event-coupling diagram contain a closed cellular path. The path may record the return of a document for review, a recurrent citation exchange, or a methodological discussion. None of those relations by itself establishes a transfer of money, recognition, research capacity, or any other specified value. An empirically grounded value-circulation claim requires typed records of creation, transfer, transformation, and receipt, as developed in Appendix E. Conversely, value may circulate through an organizational process without creating a nontrivial homology class in the analyst's chosen two-complex.

Apparent growth under revised observation. Suppose a project begins counting previously undocumented volunteer maintenance hours, or changes its classification so that a subset of existing methods is relabelled as infrastructural capital. The recorded amount and apparent depth of accumulation may increase without corresponding new production conditions. A researcher should separate measurement expansion, representational reclassification, and demonstrated change in productive practices. An evidential audit with comparable definitions is required before attributing a capital transition to the observed system.

Table 26 collects the logical points illustrated by these constructions. The distinctions are relevant to the stronger historical claims assessed in Section 12 and the methodological boundaries developed in Section 16.

G.7 Illustrative Continuations of a Shared Validation System

Consider a hypothetical research collective that maintains a public corpus d and a validation rule m . Its members use a service interface s to perform a specified class of verification tasks q . At an initial represented configuration, the available complete routes all use s , even though the corpus and rule are openly documented. Contributors' capacities include organizing studies, reviewing validation results, and maintaining the corpus, while operation of s depends on specialist personnel and a limited technical environment. An investigator could reasonably identify an infrastructure bottleneck, yet any claim of extraction would still require tracing rights, benefits, maintenance obligations, and the participants' actual options.

A first hypothetical continuation allocates proceeds from applications, together with public or cooperative contributions, to independent documentation and an alternative service s' . The collective develops sufficient technical and institutional capacity to operate s' at an acceptable quality, and its governance

permits affected participants to review the validation rule. If s' supplies a route avoiding the original service gate while satisfying the fixed task criteria, Proposition G.2 applies. Productive capacity can expand because more people can perform qualified verification, and power can become more contestable because the incumbent service operator loses complete route interception. Whether the arrangement is sustainable additionally depends on available maintenance inputs and their distribution. The value-reproduction criterion in Equation 32 provides one limited test.

A second hypothetical continuation uses application revenues to enlarge the original service and develop a proprietary evaluation interface accepted as the default by several organizations. This can provide genuine gains in throughput, reliability and convenience. It can also create additional dependencies if the recognized task standards require the interface and credible independent routes become difficult to finance or certify. The relevant institutional questions include who may revise the rule m , who may audit the evaluation, who receives revenue or professional recognition, and whether contributor communities retain feasible and legitimate paths to use the public corpus without the interface. Increased use of s demonstrates demand or institutional adoption under the case assumptions; it does not independently demonstrate coercion, unjust enrichment, or extraction.

A third continuation combines nominal openness with fragile maintenance. The documentation for s' is released and legally reusable, yet the public project cannot sustain the personnel, computing environment, or governance arrangements necessary for reliable operation. The interface has a visible alternative on paper but remains the only feasible route under the practical task standard. A model using licensing alone would report reduced dependence, while a feasible-route model incorporating maintenance would not. This illustrates why apparently independent knowledge-production options can fail to provide meaningful contestability. Conversely, a maintenance agreement with transparent obligations and independent oversight may secure reliable public use without requiring every user to operate the underlying service.

These continuations can also transform the represented generative hierarchy. Once the alternative validation method is adopted in several research fields, an originally local service can become a shared infrastructure. If application experience leads to revisions in m , the apparent direction of upstream support changes. If an institutional recognition authority shifts the admissible evidence criteria, an otherwise technically equivalent route may lose standing. A longitudinal study should therefore reconstruct the relevant configurations rather than treat all observed changes as movements within one permanent dependency diagram. The hypothetical cases illustrate possible structural mechanisms and cannot by themselves rank actual governance regimes.

G.8 Evidence Protocol, Sensitivity, and Research Extensions

The empirical application of recursive models requires an evidence protocol that can discriminate productive growth from changed classification, and institutional transformation from altered legal labels. A minimum case record should identify the bounded research activities, the participating populations, the relevant production requirements, the typed route alternatives, and the actors' practically exercisable powers. Documentary material may include repository histories, governance decisions, licenses, service contracts, technical dependency records, financial accounts, maintenance schedules, contributor testimony, and records of disputed evaluations. The record should distinguish observed changes from counterfactuals, and should disclose missing observations that might materially affect an inference of dependency or appropriation.

For historical continuation claims, three further elements are needed. The first is a justified relation among configurations, whether documented through chronological records, partial-order causal evidence, or another specified ordering. The second is a translation or correspondence between the task and value descriptions used in the compared configurations. The third is a description of the intervention or coordinated activity said to have generated the change, alongside plausible competing explanations. Increased output following platform adoption, for example, could arise from collective methodological learning, funding changes, expanded public recruitment, or stronger institutional pressure to use a standard. At-

tribution to one mechanism requires additional evidence beyond a before-and-after comparison [75, 44, 15].

Sensitivity analysis should vary the represented task boundary, qualification standard, feasible substitutes, operational costs, and allocation of institutional rights. It should also vary which actors are considered capable of mobilizing a route. A validation technique that is economically feasible for a university consortium may be inaccessible to an independent scholar or a smaller community archive. A route whose data format is technically interoperable may remain blocked by permission or lack of training. Models should therefore report dependency for named populations under declared conditions, rather than infer a universal vulnerability from the topology of the component graph.

The stability illustration in Proposition G.1 suggests a separate empirical question about the local persistence of measured feedback, but identifying its coefficients would require stable measurements, defensible update intervals, and tests for changing rules. Evidence of structural transitions directly challenges the constant-coefficient assumption. The route-transition result in Proposition G.2 is more readily applied as a conditional audit of an independently operated alternative, provided the analyst verifies its admissibility and actual feasibility. Neither result supplies a normative criterion by itself. Historical analysis and the assessment of public generativity remain necessary to understand whose opportunities are supported and whose productive conditions are constrained.

Three open research problems follow. First, one needs empirical methods for tracking transformations across partially incomparable generative representations, particularly when new practices create previously unrecognized tasks. Second, research is needed on the collective cost of maintaining substitute production routes and on whether such costs can be distributed without recreating new, unaccountable choke points. Third, the feedback between epistemic recognition and institutional capital deserves investigation across successive continuations: changes in standards can affect which contributions are recorded as valuable, while concentrated resources may influence who participates in revising those standards. These questions call for formal, archival, ethnographic, and comparative methods with explicit attention to epistemic biases and revision rights.

Appendix G therefore treats recursion as a relation among changing productive conditions and admissible continuations, rather than as an automatic law of compound growth. The formal results exhibit what follows from specified update and route assumptions; the counterexamples prevent inference from depth, production scale, legal title, or topological cycles to claims about extractive capital relations. A substantive account of public knowledge accumulation must trace how value circulates, who bears the work of reproducing productive conditions, whose capabilities expand, and how the rules governing subsequent creation can be contested and changed.

H Comparative Institutional Configurations and Illustrative Models

Appendix H develops a comparative institutional application of the framework for knowledge-capital accumulation across generative levels. Its role is to make the conceptual distinction between capital formation and institutional appropriation operational in bounded cases. The objective is to compare arrangements that can sustain similar outputs while distributing the authority to use, maintain, alter, and benefit from productive conditions in different ways. The appendix specifies a common comparison unit, introduces an institutional configuration record, develops hypothetical proprietary, commons-based, public, cooperative, and collective-production cases, and examines hybrid arrangements and counterfactual changes. It concludes with an evidence protocol for comparative inquiry. The cases are constructed models. They illustrate possible relations among productive capabilities, heterogeneous value circulation, and governance; they do not report empirical outcomes or provide an institutional ranking.

The broader comparative problem has two parts. An investigator must establish how productive capacity becomes available, including the inherited labour, public resources, methods, infrastructure, and organizational effort on which a particular project depends. The investigator must then identify the institutional relations through which this capacity is mobilized and reproduced, including property claims, permissions, practical command, bargaining power, maintenance obligations, and the capacity to revise

shared rules. Institutions commonly combine these relations. The same public repository may have privately supplied computing services, community-created classifications, publicly funded maintenance, and intellectual-property rights held by different participants. The concepts of knowledge commons, polycentric governance, and differentiated property rights provide useful resources for analysing such arrangements [40, 70, 74, 82]. Their conceptual roles remain distinguishable from a political-economic inquiry into appropriation, class relations, and reproduction.

H.1 Comparative Units and Productive Boundaries

A defensible comparison begins with a bounded knowledge-producing activity rather than a governance label. Let q denote a specified class of tasks, such as the validation and public dissemination of research records under a declared evidentiary standard. Let a designate an identified participant population or collectivity with an explicit membership rule, and let I denote the institutional configuration governing the resources and operations relevant to q . The comparison must further specify the requirements for admissible output, the infrastructure and expertise on which the task depends, and the conditions of adequate maintenance. Otherwise, a system serving more users, a system validating more complex material, and a system applying a weaker standard could be described as equally productive merely because each reports a large number of processed records.

The units of analysis are relational. A university laboratory, a publishing corporation, a public agency, and a cooperative may each hold multiple positions in a single productive process. A researcher can contribute a classification method, employ a proprietary computing service, deposit results in a public archive, and participate in the governance of a commons. Assigning an exclusive institutional identity to the researcher would erase these relations. Accordingly, an institutional configuration is represented as a distribution of authority, productive obligations, and realized activities across interacting organizations and participant groups. The same productive component can be subject to distinct legal claims and practical dependencies, and the relevant actor population may vary between a local research group and a transnational scholarly community.

For comparative consistency, an investigator should freeze a declared *task reference* during the first diagnostic pass. A task reference includes the intended output properties, population, admissibility rules, minimum resource inputs, and the observation scope. Under this convention, a difference in feasible routes can be interpreted as a difference in productive opportunities for the defined task. A second pass may investigate how institutional change transforms the task reference itself. A revised standard can create new forms of research, invalidate previously accepted outputs, or alter the capacities needed for participation. Those transformations are substantive findings about the evolution of knowledge-production conditions. They should be represented as changes of the comparison frame, with a documented correspondence between the distinct frames, rather than silently folded into a single numerical productivity measure.

The proposed comparative investigation draws on at least three kinds of evidence. Legal and administrative materials identify formal rights and assigned responsibilities; operational materials identify effective technical and organizational capacities; and accounts from contributors and affected users illuminate recognition, practical obstacles, and disputed interpretations. These sources may disagree. A contract can promise portability while service logs demonstrate costly or incomplete export; an official open-access policy can coexist with inaccessible interfaces; a public report can describe community participation that some contributors experience as substantively constrained. Such disagreement motivates triangulation and an account of the authority of each source, not an automatic presumption that one evidentiary type exhausts the institutional situation. The distinction between recorded rules and the conditions of their enactment is also central to the diagnostic institutional approach [71, 72].

H.2 Institutional Configuration Records and Partial Comparability

A comparative record can organize the relevant relations without reducing them to a single index. For a configuration I , let $\mathcal{A}_I$ denote the participating actors and collectivities, $\mathcal{V}_I$ the identified productive

components, $\mathcal{Q}_I$ the bounded activities, and $\mathcal{K}$ the recorded types of value. An institutional profile should retain five analytically distinct coordinates: (i) authorized and practically executable operations; (ii) feasible support routes; (iii) heterogeneous benefits and burdens; (iv) maintenance and reproduction arrangements; and (v) recognized opportunities to review or contest decisions. Equation 40 abbreviates that record.

$$\mathcal{I}(I \mid a, q) = (\text{Exec}_a^I, \mathcal{R}_{a,q}^I, \text{Val}_a^I, \text{Rep}_{a,q}^I, \text{Rem}_a^I). \quad (40)$$

Here Exec_a^I collects the actor's executable, institutionally authorized operations on the relevant productive conditions, as elaborated in Equation 33. The route family $\mathcal{R}_{a,q}^I$ retains the alternative supported ways of performing q , including conjunctions of expertise, permissions, and infrastructure. The coordinate Val_a^I consists of separately typed records of benefits, recognitions, contributions, and burdens; $\text{Rep}_{a,q}^I$ describes the obligations and actual means for maintaining or replenishing required capabilities; and Rem_a^I collects available challenge, appeal, exit, and rule-revision procedures, including the conditions under which they are usable. The notation supplies a structured case description, not an ontological claim that institutional life is fully captured by five coordinates.

The profile in Equation 40 also clarifies the limited meaning of institutional comparison. An arrangement may permit a greater number of qualified tasks while placing more operational obligations on a small maintenance group. A second arrangement may provide more extensive participation rights while having fewer resources to sustain a particular service. A third may protect a restricted dataset for reasons of confidentiality while enabling broad research participation through governed access. Such configurations can be incomparable under a multidimensional public-interest description. A judgment that one is preferable requires a declared normative criterion, its scope, and consideration of trade-offs rather than an automatic scalar ranking.

A useful restricted comparison concerns the effect of changing institutional authorization while holding the task standard, technical capacities, and route requirements fixed. Let $\mathcal{R}_{a,q}^0$ denote a candidate family of technically supportable routes under those fixed assumptions, and let $\text{Gate}_I(a, r)$ assert that all permissions and governance conditions necessary for participant a to use route r under arrangement I are satisfied. The qualified feasible-route family is then defined in Equation 41.

$$\mathcal{R}_{a,q}^I = \{r \in \mathcal{R}_{a,q}^0 : \text{Gate}_I(a, r)\}. \quad (41)$$

Equation 41 isolates institutional gate conditions for one specified comparison. In an actual historical transformation, governance can also alter available expertise, investments, task standards, the membership of a collective, or the technical routes themselves. Those wider effects require reconstructing the candidate family and the institutional profile, as discussed in Appendix G. An apparently broad permission set may therefore coexist with a small feasible family when practical skills or resources are missing. Equally, stringent technical requirements may be compatible with wide public participation where shared expertise, accessible infrastructure, and reliable review procedures have been established.

H.3 Proprietary Research Gateway and Commercial Reinvestment

Consider a hypothetical research consortium that creates a public corpus of observational records through grant-funded research, volunteer review, and institutional data stewardship. A service firm develops a specialized gateway that validates new submissions against the corpus, converts them into a common representation, and provides a searchable interface. The firm owns its implementation and is compensated through subscriptions and institutional service contracts. The corpus remains available through a public license, and scholarly contributors may continue depositing or reusing material within the applicable rules. At the chosen starting configuration, the gateway is the most readily usable qualified route for numerous downstream research tasks.

The arrangement can support genuine productive-capacity accumulation. Concentrated engineering responsibility may improve reliability, interface design, data integrity, and the availability of continuous operational support. Fee revenue may finance computing capacity and specialist maintenance that a fragmented collection of grants would have difficulty sustaining. The firm can therefore accumulate

commercially organized productive knowledge capital while public researchers and contributing organizations also accumulate methods, usable records, and experience. The coexistence of public knowledge contributions and proprietary service provision presents a distribution of productive relations rather than a contradiction in the mere existence of accumulation. Literature on knowledge infrastructure and the political economy of scholarly communication identifies mechanisms through which service positions become consequential for the reproduction and governance of research [34, 56, 5].

The distributional and institutional questions emerge at the gateway's interfaces. Who can audit the validation rule, export the complete records, reproduce the derived classifications, and maintain an independently acceptable alternative? Does the service contract permit changing standards or disconnecting users, and under what review or appeal procedures? Which participants receive revenue, professional recognition, training, or additional capabilities from the continuing operation? Who performs unpaid correction work when automated classifications are inadequate? These questions cannot be answered from the proprietary character of the interface alone. They depend on documented rights, feasible alternatives, and the actual circulation of distinct values.

Suppose a scientific organization later recognizes only gateway-produced validation certificates. The proprietary implementation can then acquire a new position in the generative dependency structure, because certificates become a condition of admissibility for tasks that previously had other routes. Even if the underlying technical operation changes little, institutional recognition can increase the gateway's effective reach. Such a transition may improve uniformity and traceability, but it can also narrow contestability if certification is withheld or expensive and no independent qualification route exists. The change should be studied through modifications of recognized task standards and feasible-route families. A finding of recurrent extraction additionally requires evidence about the appropriation of benefits relative to distributed contributions and the associated reproductive burdens; leverage or commercial revenue on their own are insufficient.

A second hypothetical continuation is equally important. The firm may provide fully specified export functions, fund community implementations, publish auditable validation rules, and accept independent certification. In that situation, commercial profits and substantial infrastructural contribution could co-exist with accessible alternatives and stronger opportunities for external review. Any inference about structural capture must account for this configuration as seriously as one involving exclusive gateways. The comparative test concerns actual dependency and contested authority rather than the formal presence of a company.

H.4 Federated Knowledge Commons and Reproductive Commitments

A second hypothetical arrangement organizes the same corpus and validation task through a federation of contributor institutions, disciplinary groups, and public-interest maintainers. Participating organizations agree upon shared formats, distributed repositories, a qualification procedure, and a documented governance charter. Several teams maintain independently deployable validation implementations. Contributions include code, technical documentation, annotation labour, institutional hosting, translation, training, and review of contested classifications. The arrangement offers a plausible pathway for accumulating collective productive capacities, but its status as a commons depends on the specified resource-sharing and governing practices rather than on a label of openness [40, 8, 70].

This model draws attention to the allocation of reproductive commitments. Shared knowledge may be accessible at negligible marginal copying cost while the continued operation of the system requires recurring material expenditure and difficult skilled labour. Contributors may experience burdens unevenly: a few maintainers resolve technical failures, an archival institution pays long-term storage costs, and volunteers perform quality checks that become invisible to users who encounter only the final output. An apparently generous circulation arrangement can become fragile if downstream beneficiaries are institutionally detached from these requirements. For that reason, a commons case should document how resources are contributed, how maintenance is valued, how commitments are revised, and whether responsibility can be redistributed when participants leave. Work on the maintenance of shared digital

infrastructure and repair provides relevant distinctions between creation and sustained operation [25, 46].

Consider an internally negotiated rule under which downstream organizations contribute money, computing time, expert review, or equipment according to a schedule approved through the federation's governance procedure. This can support value recirculation from successful applications toward enabling infrastructures. The contributions are heterogeneous; their evaluation may involve separate in-kind accounting, deliberated obligations, and technical service thresholds. Monetary and nonmonetary benefits need not be translated into a single price. A high-demand participant may contribute substantial funding, while a less-resourced member supplies an indispensable local classification or community interpretation. The allocation becomes an institutional question about sustaining joint production rather than a single maximization problem.

Federation does not eliminate power. A small expert group might effectively determine accepted methods because others lack the capacity to evaluate them. A formally participatory committee could repeatedly defer to the institution hosting the reference implementation. A major funder might use withdrawal threats to change the federation's priorities. Each mechanism could coexist with nominally shared rights and numerous copies of the data. The inquiry should therefore examine decision processes, technical alternatives, participation resources, the practical ability to challenge expert claims, and the compatibility of independent routes with the relevant standards. A commons can accumulate capital while reproducing difficult asymmetries; those asymmetries call for investigation rather than an a priori conclusion of exploitation.

A further continuation permits differentiated access within the commons. Sensitive contributions may be governed by community restrictions, confidentiality rules, or specific consent arrangements. A common governance infrastructure can thereby support plural permissions rather than universal release. Such restrictions should be assessed through the stated purposes, represented communities, accountability arrangements, and effects on feasible activities. They may sustain trust and participation in one setting while producing exclusionary consequences in another. Commons governance and generalized open access are therefore related but analytically distinct institutions, a point also relevant to knowledge and data stewardship [14, 91].

H.5 Public Research Infrastructure and Procurement Dependence

A third hypothetical configuration places the corpus, validation specification, and public-facing service within a research agency funded through public appropriations. The agency holds responsibility for preservation, continuity, accessibility, and an articulated public research mission. Civil servants or contracted employees perform records management, domain evaluation, and service administration. A private contractor supplies a technically complex validation interface under a procurement agreement. This system can form and expand productive knowledge capital through stable public financing, cumulative expertise, and public dissemination. Its legally public character specifies important responsibilities, while leaving several questions about operational command and the circulation of benefits open.

A procurement agreement can improve public service capacity by obtaining specialized resources under enforceable performance conditions. The agency might require documented procedures, audit access, continuity planning, data portability, independent certification, and the transfer of necessary operational knowledge. Under such provisions, a contractor's technical specialization is compatible with publicly accountable service delivery and feasible transitions to alternative suppliers. Conversely, a contract that leaves critical interfaces opaque, documentation incomplete, or qualifications inaccessible can create a practical bottleneck despite public ownership of the underlying archive. The comparison should distinguish contractual control, the ability to exercise that control, and the cost of making another route operational.

The effects of budgetary reproduction are equally important. A public institution may provide open data but lack durable funding for preservation, review, equipment replacement, or methodological revision. Appropriations may finance new platforms while recurring maintenance is expected to be absorbed by under-resourced staff. Where long-term responsibilities are left unallocated, nominally public

resources can become inaccessible or obsolete. Funding stability, personnel continuity, collective knowledge of system operation, and legitimate rule-revision channels are part of productive capacity. They also influence how the costs of public service are distributed among workers, agencies, researchers, and users. The economics of public research spillovers and scientific infrastructure supplies background for studying these relations [66, 18].

The public arrangement has a further dimension involving epistemic authority. An agency might define validation criteria that researchers must satisfy to obtain recognition or funding. Such standards can improve comparability, protect public resources, and facilitate communication. They can also disadvantage forms of knowledge that do not fit prevailing classifications or are produced under different institutional conditions. The relevant evaluation concerns the standard's domain, justification, revision history, appeal process, and measurable effects on participation. The public interest cannot be inferred exclusively from the existence of legal public ownership, nor can a uniform evaluation rule be declared inappropriate solely because it shapes research priorities. A defensible inquiry brings governance, scientific justification, and affected contributors' perspectives into the same analytic frame [57, 41].

An important counterfactual concerns an agency's investment in internal capability. If additional public resources develop an independently operable gateway, staff training, and an accountable standards committee, the agency may gain credible options without ending its contractual relationship with the original service firm. Such a change can alter bargaining conditions and reduce the ability of one provider to intercept every feasible route. Its public value includes possible continuity and contestability benefits, while its opportunity costs require independent assessment. The analyst should record the financial and labour resources devoted to the alternative, the certification conditions it satisfies, and the populations actually able to use it.

H.6 Cooperative and Collective Production Arrangements

A fourth comparison concerns the organization of control by those engaged in producing and maintaining the infrastructure. In a hypothetical worker cooperative, the technical staff and participating knowledge workers hold voting and residual-claim rights according to an agreed constitution. Contracts may still provide services to public institutions or commercial clients, and collectively governed production may involve substantial investment, specialization, and expanded service revenues. The cooperative form describes particular ownership and governance principles; its practical outcomes depend on internal participation rules, financing, employment relations, treatment of outside contributors, and institutional context. The cooperative principles articulated by the International Cooperative Alliance provide a starting point for identifying these elements [45].

A cooperative validation service can redistribute authority that would otherwise reside with outside shareholders or a sole proprietor. Yet its members may depend on knowledge and effort supplied by nonmember researchers, contractors, volunteers, or community archivists. Cooperative membership is thus one boundary among several that matter for the distribution of generated value. An analytically adequate study would investigate which populations can join, who sets service prices and professional criteria, how outside contributors are credited, and who is responsible for preservation after a project ceases to generate sales. Internal democratic rules do not resolve all relations with those beyond the membership boundary. A cooperative can support relatively extensive productive autonomy for members while generating different dependencies for outside users.

A broader collective or communist conception of knowledge production may assign productive conditions to shared social use, associate decisions with collective deliberation, and orient reproduction toward socially determined needs. Such a conception can contain initial formation and expansion of knowledge-producing capacities, as well as investments in training, apparatus, libraries, and public dissemination. Its conceptual object differs from a specific cooperative legal entity and from the governance of an individual commons. Marx's discussion of a cooperative society in the *Critique of the Gotha Programme* is relevant to distinctions concerning social production and distribution; the present comparative model does not treat that text as an empirical account of any particular institution [62]. Historical inquiry would

require independent evidence about the institutions and productive relations under study.

For illustration, suppose a multi-institutional collective allocates trained staff, equipment, and archive services according to a common research programme. Generated outputs and methods can be returned to shared infrastructures, while downstream applications provide material and epistemic inputs supporting further research. There may be no transferable private claim to residual profits, yet decisions about scarce computing resources, the admissibility of outputs, and the priority of research fields continue to distribute effective authority. These decisions can influence participation and the reproduction of distinct capabilities. The absence of private shareholders is therefore insufficient to specify the distribution of institutional power, just as the existence of collective decision procedures does not establish their effective accessibility to affected populations.

Collective production can also sustain asymmetries through administrative delegation, specialized expertise, unequal voice, and control over recognition procedures. Such features are compatible with highly productive coordination and also generate questions about contestation, transparent allocation, appeal, and institutional revision. Their assessment should address the historical rules and practical avenues through which participants can alter productive conditions. Where a claim of extraction is made, evidence must specify the appropriation mechanism, who receives the benefit, how the burdens are distributed, and what meaningful alternatives contributors possess. The same evidential discipline applies across capitalist, cooperative, public, commons-based, and communist arrangements. Institutional variation changes the configuration of possible relations; it does not exempt a configuration from analysis.

H.7 Hybrid Interfaces and Cross-Level Institutional Transitions

Actual systems frequently combine arrangements represented separately in the preceding hypothetical constructions. Consider a research project with publicly funded data collection, a commons-governed terminology, cooperative software maintenance, proprietary cloud services, and an agency-controlled recognition standard. Intellectual property in outputs may reside with contributing authors, while repository licenses permit reuse and a funding body sets minimum preservation requirements. The accumulation of productive capabilities occurs across all these interfaces. Its effects depend on how authority travels through them, which components are indispensable for named tasks, and how the benefits and costs of reproduction are allocated.

The generative level at which an institutional gate acts may change through continued activity. A commercial interface first built for a specialized application can become a widely accepted infrastructure, and its certification format can subsequently shape what counts as a validated research output. In another continuation, a community-developed method is adopted into a public standard, with an independent validation route funded through the associated public programme. Either transition can expand aggregate productive capacity, and either may redistribute control. The direction and magnitude of the changes remain conditional on technical substitution, practical adoption, organizational capabilities, and governance. Generative level is therefore a relational position in the reconstructed production system, rather than a permanent property of an artifact.

A constrained counterfactual comparison helps locate institutional leverage. Assume that the technical candidate routes and accepted quality requirements remain unchanged between two arrangements I and J . Suppose also that every route available to participant a under I satisfies the governance and authorization conditions under J . Equation 41 then entails the inclusion $\mathcal{R}_{a,q}^I \subseteq \mathcal{R}_{a,q}^J$. This result supports the narrow claim that the institutionally qualified options for the fixed task have weakly expanded. It does not establish higher scientific reliability, greater well-being, lower maintenance burden, or the absence of extraction. Those outcomes depend on further coordinates in Equation 40, including which routes are realistically operated and who determines the standards used to assess them.

The converse issue is also significant. A larger feasible-route family can be accompanied by concentrated decision authority. For example, a consortium may finance several interchangeable interfaces while maintaining an exclusive power to approve the data schema on which all interfaces depend. The expansion of technical alternatives weakens control at one service level without necessarily making the

Table 27: Comparative institutional diagnostics for a shared knowledge-production infrastructure.

Illustrative arrangement	Productive and governance coordinates	Circulation or dependency mechanism	Evidence needed for assessment
Proprietary service gateway	Implementation control; contractually defined external access	Service fees and reinvestment; possible certification bottleneck	Export, contract, route alternatives, maintenance and benefit records
Federated knowledge commons	Shared rules; distributed operations and negotiated responsibilities	Knowledge recirculation; uneven burdens of maintenance	Governance records, contributor accounts, funding and operational logs
Public research infrastructure	Public mandate; agency standards; possible contractor operations	Public appropriations and services; procurement dependence	Procurement, budget, portability, staff capacity and appeal records
Worker cooperative	Member governance and residual claims; possible nonmember contributions	Member reinvestment; differentiated internal and external benefits	Membership, labour, client, outside-contributor and surplus records
Collectively organized or social production	Socially coordinated investments and decision rules	Shared capacity formation; allocation through collective institutions	Actual allocation, participation, review and reproduction arrangements

epistemic rule contestable. A study confined to service duplication would miss this deeper gate. In a different arrangement, a common standard might be genuinely revisable while one small application remains difficult to replace. The comparative profile should retain these distinct positions and avoid inferring an overall distribution of power from one graph measure.

Table 27 summarizes potential mechanisms to investigate in the five illustrative institutional families. The table is a diagnostic guide to rights, operational conditions, and evidentiary requirements. The descriptions indicate possibilities within each configuration and should not be read as typical empirical outcomes or a fixed hierarchy of publicness.

H.8 Comparative Evidence Protocol and Model Limits

A comparative case study should report the construction of the institutional categories before drawing conclusions. The core case record includes the participating populations, tasks, chosen observation boundary, relevant productive components, source of initial capital inputs, legally differentiated rights, actual operating capabilities, typed flows and benefits, maintenance requirements, governance procedures, and documented changes of the system. Where possible, a route inventory should specify substitute methods and platforms, including the resources needed for each route to meet the same task qualification criteria. Missing data should be disclosed and analysed for its likely directional consequences. A commercial operator may provide reliable service-performance logs but incomplete information about internal finance; a public agency may disclose budgets without accurately recording unpaid labour; a federation may preserve deliberative minutes while leaving maintenance costs poorly measured. Such differences can affect comparative conclusions.

The first empirical question concerns formation and expansion of productive capabilities. Evidence may show that an arrangement created durable validation skills, increased the reliability of records, or improved the ability of researchers to carry out specified tasks. An institutional comparison should separate these demonstrated improvements from changes in access, recognition, ownership, or governance. The second question concerns appropriation and heterogeneous circulation: what different values were created, by whom and through which cooperative relations, and what pathways returned resources or opportunities to those maintaining productive conditions? The third question concerns effective control: what interventions could relevant actors undertake, what feasible options would those interventions alter, and which institutions could review or reverse them? The fourth concerns historical separation or dispossession, if alleged: what relations of production changed, who lost command over previously accessible conditions, and what documentary evidence supports that claim? These are complementary questions rather than successive stages through which every case must pass.

A stronger causal account requires attention to selection and rival mechanisms. Large repositories may choose specific governance forms because of the technical complexity of their work, inherited funding, legal obligations, or existing participant organization. Observed success or failure may therefore reflect selection into arrangements as well as institutional effects. An agency's adoption of an open format may coincide with a broader policy reform; a cooperative's survival may depend on continuing procurement revenue; and a proprietary service may be preferred by users because of reliability rather than exclusion. Counterfactual comparisons should consequently clarify their identifying assumptions, document alternative explanations, and report sensitivity to task and population definitions. The causal-evidence distinctions elaborated in Section 16 and Appendix G remain applicable [75, 15, 72].

The interpretation of institutional extraction requires an additional evidentiary step. An actor's command over an indispensable gateway, a substantial revenue stream, or an unequal allocation of expertise can support a hypothesis about the capacity to appropriate value. An extractive finding requires documentation of recurrent value capture, the relevant distribution of contributions and burdens, constraints on meaningful alternatives, and the legal and normative circumstances of the arrangement. An exploitation claim may additionally depend on contested theoretical and ethical criteria that should be identified explicitly. The institutional dossier in Appendix F supports such inquiry without collapsing the categories of dependence, appropriation, extraction, and exploitation.

The comparative models also have representational limitations. They simplify internal organizational diversity and assume that actors, task criteria, and institutional operations can be bounded sufficiently for analysis. They cannot fully encode tacit professional judgement, culturally situated meanings, or emergent forms of collective self-understanding. Some knowledge practices cross legal jurisdictions and epistemic traditions in ways that challenge stable categories of property and institution. Historical continuations may alter the comparative vocabulary itself. These issues support an iterative research design in which formal descriptions are tested against documentary, qualitative, and operational evidence, revised when they fail, and reported with explicit translation limits.

Appendix H thus supplies a structured institutional comparison rather than a preference ranking. Accumulation and expansion can appear under multiple productive arrangements; the distinguishing questions concern the formation of the productive base, the practical authority to govern it, the circulation of heterogeneous values, and the continuing possibility of maintaining and revising generative conditions. Appendix I develops the empirical research designs, identification difficulties, and measurement protocols through which these proposed comparative relationships could be investigated.

I Methodological Limitations and Empirical Research Design

Appendix I specifies an empirical programme for investigating knowledge-capital formation, expansion, and possible extractive dependencies across generative levels. Its role is to connect the manuscript's historical, relational, and formal proposals to evidence that may sustain, qualify, or challenge them. The objective is to distinguish observations of productive-capability formation, inferences concerning effective dependencies, accounts of differentiated institutional authority, and evaluative claims about appropriation, extraction, and justice. The appendix develops research units and historical reconstruction procedures, operational definitions, qualitative and quantitative identification strategies, comparative sampling, robustness protocols, and research-ethics safeguards. A final study blueprint integrates these elements for a bounded shared research infrastructure. The proposed designs are methodological specifications, not reports of completed investigations; the cases described here remain hypothetical.

The analysis starts from a limitation of the manuscript's formalism. A typed hypergraph, event two-complex, or institutional configuration record is an investigator's representation of selected observations and assumptions. Its edges, cells, feasible routes, and actor classifications may require substantial interpretation. Formal coherence establishes consequences under stated premises, whereas empirical adequacy depends on how those premises were elicited, tested, challenged, and revised. A documentary record can establish that an organization claims ownership of a validation system, while an operational test may establish whether a competing route performs the same qualified task. Contributor testimony

can reveal experienced barriers whose institutional causes require further investigation. Accordingly, the present research programme combines documentary history, interviews, operational audits, comparative institutional analysis, and counterfactual inquiry. The choice among them follows the local evidentiary question, consistent with methodological pluralism and the treatment of research design as a problem of explicit inference [50, 72, 15].

I.1 Research Objects, Boundaries, and Units of Observation

The first research decision is the specification of a *productive activity*, such as the creation, validation, maintenance, or public communication of a class of scientific records. This is preferable to treating a named platform, university, corporation, or intellectual tradition as an indivisible unit of production. An activity may rely on several organizations and heterogeneous forms of labour, while an organization may perform several activities at different generative levels. Its boundary should therefore identify an output qualification rule, relevant contributor populations, productive components, support routes, and circumstances under which maintenance is judged adequate. The same activity may have multiple observational views. A legal unit identifies rights holders; a computational unit identifies data-processing dependencies; an ethnographic unit identifies communities of practice; and a political-economic unit identifies contribution, allocation, reproduction, and control relations. Comparisons between these views need explicit correspondence rules.

The research record should distinguish the *unit of observation* from the *unit of analysis*. Individual procurement records, policy revisions, interviews, licensing events, software releases, budget entries, datasets, or rejected validation requests may be observations. The unit of analysis could be a historically bounded activity, an institutional interface, a particular support-route family, or an actor–task relation. Distinct observations can refer to the same underlying event, and apparently independent documents may reproduce a shared public statement. Data collection should preserve provenance, version identifiers, recording methods, authorship where releasable, and the degree of source independence. This prevents a large document corpus from being mistaken for a large number of independent institutional observations.

The initial boundary should remain explicit, yet revisable. A study of a research archive might begin with document ingestion, metadata validation, and dissemination. Evidence may reveal that external grant eligibility, proprietary indexing, educational training, or scholarly recognition constrains who can perform those tasks. The researcher can then add a second boundary encompassing those conditions while preserving the original bounded task for comparison. Similarly, an apparent foundational standard may be optional for a local community but indispensable in an international certification setting. The empirical meaning of its generative position changes with the population, the qualifying task, and the available alternatives. A generative level is consequently recorded as a model-relative hypothesis about productive relations, not assigned by an investigator’s intuition about conceptual abstractness.

Each case should include a description of what the chosen boundary excludes. Relevant exclusions may include unpaid household and care work that supports professional participation, public education that establishes research competencies, environmental and material costs of computing, and the social histories of culturally situated categories. These omissions may alter the interpretation of net reproduction and value circulation. Recording them does not require that a single study measure every background condition; it requires that a finding about the bounded system be presented with its boundary conditions and possible dependencies beyond the observation frame.

I.2 Historical Reconstruction of Capital Formation and Separation

Historical investigation should reconstruct the formation of the productive base before interpreting the ownership and income arrangements associated with its operation. An *input genealogy* traces public appropriations, inherited datasets, professional education, research grants, volunteer contributions, community-maintained code, purchased services, legal permissions, and institutional coordination. An *authority genealogy* traces the introduction or revision of ownership claims, access rules, credential requirements, organizational mandates, contracting practices, and the power to revise standards. The two

genealogies can diverge: knowledge may be produced collectively while exclusive authority over a crucial interface arises through a subsequent contract, platform migration, regulatory decision, or technical standard.

The documentary protocol should assemble dated and versioned materials that directly bear on these genealogies. Potential sources include project charters, employment and licence agreements, repository histories, procurement specifications, grant disclosures, meeting minutes, technical standards, correspondence made available with consent, public archives, service-level records, and documented user complaints. Historical narration requires careful treatment of missing records and retrospective rationalization. An interview conducted following a disputed governance change may illuminate participants' interpretations but may offer an incomplete account of the earlier decision process. Contemporary documents can also contain strategic representations of responsibility. Within-case process tracing, supported by triangulation between differently situated sources, can help reconstruct a proposed sequence of mechanisms while maintaining uncertainty about motive and causality [7].

The term *primitive accumulation* requires a narrower historical test than the initial appearance of a durable knowledge asset. Where the manuscript's Marxian usage is invoked, a case should document a change in producers' effective relations to productive conditions and establish how a specific separation, enclosure, or dispossession contributed to the formation of the capital relation under investigation. The presence of a valuable privately operated service is insufficient evidence by itself. A public repository established through voluntary contributions and governed by shared rules may exhibit substantial initial capital formation without demonstrating that history of separation. Conversely, a change from a community-accessible database to an exclusive operational gateway may merit investigation even where the accumulated knowledge records remain nominally public. The inquiry should specify the previously feasible activities, the resulting restrictions, affected populations, and the relation between the change and subsequent productive dependence.

Historical reconstruction also requires care with temporal language. Record dates and transaction order are evidentiary resources, whereas a singular, universally privileged temporal ordering is unnecessary for the conceptual theory. Event correspondences, documentation of institutional succession, and partial causal order should be distinguished. A later-found archive may change the investigator's reconstruction of an earlier configuration without proving that the investigated production system underwent a corresponding transformation. For historical comparisons, a researcher should record separately changes in the productive system, changes in institutional rules, revisions of epistemic categories, and improvements in observation.

I.3 Operationalizing Generative Dependencies and Substitutability

Generative dependencies can be investigated by constructing a task-specific inventory of complementary prerequisites, alternative productive routes, and qualification criteria. For a defined actor population a , activity q , and institutional configuration I , let $\mathcal{R}_{a,q}^I$ denote the latent family of feasible routes used in Appendix H. An audit observes only some routes. It may confirm that a route works, fail to observe an existing route, or record a claimed alternative whose qualifications have never been tested. Equation 42 states a conservative relation under a fixed activity definition and sufficiently faithful audit procedures.

$$\hat{\mathcal{R}}_{a,q}^{\text{confirmed}}(I) \subseteq \mathcal{R}_{a,q}^I \subseteq \hat{\mathcal{R}}_{a,q}^{\text{candidate}}(I), \quad (42)$$

where the confirmed family includes routes demonstrated under the declared qualification test and the candidate family includes all routes judged plausible within the chosen inventory. The second inclusion is an *assumption of coverage*, which may fail when unknown routes exist; it is therefore disclosed and sensitivity-tested, rather than inferred from the audit. The first inclusion assumes the tests adequately replicate the relevant practical and institutional conditions. Both families should retain conjunctions of inputs, permissions, competence, maintenance, and reliability rather than recording a software interface as an autonomous productive route.

A route audit can use executable test cases, documentation review, participant observation, and independent replication of tasks. For example, a nominal alternative to a commercial validator should be

tested for data import, error handling, output qualification, ongoing staffing, governance permission, and recurrent operating costs. Technical compatibility without adequate expertise or access to a necessary data source may leave the alternative practically infeasible for the affected population. A study should record the *actor-specific* and *task-specific* status of each condition. A public institution with paid technical staff may have an executable alternative that a community volunteer group cannot maintain. Multiple redundant routes may also share an upstream credential provider, computational supplier, or authoritative standard, creating a joint dependency that is invisible at the level of platform names.

The interpretation of generative depth follows from these tested relations. Dependency diagrams may have cycles, overlapping mechanisms, and different resolutions of representation. A researcher may obtain a partial order by contracting strongly connected components, as formalized in Appendix C, but the resulting order is a property of the reconstructed network. A long path from a methodological construct to many applications does not, on its own, establish that the construct is necessary for their continuation. The relevant counterfactual concerns what qualified activities remain feasible under specified restrictions and substitutes. Auditors should therefore report changes in productive route coverage, common-mode failures, and the ability of participants to revise or replace constraining components. Results should be stable under plausible changes in graph resolution before being used to support broader claims about multilevel dependencies.

An additional limit concerns the distinction between *formal availability* and *practical mobilization*. The existence of open-source code, a permissive licence, or an alternative classification standard does not ensure that affected actors possess the resources, skills, coordination, or institutional recognition to use it. Where the investigation claims that a productive option is feasible, it should record evidence of executable capacity and recurrent support at the scale relevant to the task. Lack of observed use may have competing interpretations, including low demand, superior existing service, social exclusion, prohibitive transition cost, or absence of institutional permission. Interpretation requires attention to those rival mechanisms.

I.4 Measuring Heterogeneous Values and Productive Reproduction

A study of heterogeneous value should adopt an explicitly typed measurement protocol. Economic value may be observed through payments, revenues, appropriated rents, wages, procurement expenditures, or opportunity costs, subject to suitable accounting boundaries. Epistemic value may concern reliability, reproducibility, justified inferential reach, or usefulness for specified inquiry tasks. Social and institutional value may include access to collaboration, recognition, autonomy, trust, public accountability, or the capability to participate in governance. These dimensions need different measurement procedures and may conflict. A bibliometric score or aggregate monetary valuation cannot be assumed to encode their relations or to establish an overall worth of knowledge production [2, 57, 41].

The measurement record should distinguish a realized outcome from the *capacity* to generate outcomes under specified conditions. A laboratory might produce a large number of papers in one funding period while losing experienced maintainers or access to a necessary measurement infrastructure. Another collective might produce fewer papers but develop training materials, shared validation procedures, or independent support routes that enlarge productive opportunities for other participants. Evaluating such cases requires activity-qualified capability measures, not gross output comparisons alone. Candidate indicators include the range of tasks executable by the affected group, the reliability and reproducibility of those tasks, qualified participant access, the number and independence of sustainable support routes, and the resources required for ongoing maintenance. Each indicator should declare its population, task qualifications, and method of observation.

The feasibility audit should also keep *unobserved* arrangements separate from tested failures. A missing software implementation, absent contract, or unanswered interview request can leave route status unknown; it does not by itself prove that the corresponding activity is infeasible. Conversely, a technically reproducible route is not sufficient evidence of practical availability if a licensing gate, skill bottleneck, or maintenance obligation remains untested. An empirical dossier should therefore record the

tested component inputs, qualified outcome criterion, actor-specific institutional constraints, and missing observations for each candidate route. These requirements implement the typed feasibility convention in Equation 5.

The empirical register should include contributions, benefits, burdens, and reinvestment as separate fields. Contributions might include original research, data cleaning, translation, peer review, volunteer maintenance, community consultation, and institutional coordination. Benefits may include revenue, scientific reuse, professional credit, educational opportunities, and the capacity to influence future standards. Burdens may include unpaid maintenance, legal exposure, compelled migration, inaccessible interfaces, or the costs of reproducing expertise. Reinvestment requires evidence that resources, rights, labour time, or institutional commitments actually support continued productive capabilities. A grant announcement or open-access pledge may establish intent but cannot alone demonstrate realized reproductive support. The circulation framework in Appendix E supplies typed records, while empirical attribution should account for joint production and the limited separability of individual contributions.

Quantitative comparisons are most defensible within well-defined measurement domains. Monetary costs recorded in a common currency can be adjusted with declared conventions; reproducibility rates may be compared across similarly qualified validation tasks; participation may be reported as the proportion of a specified population with effective access. By contrast, translating increased public trust directly into money or adding academic recognition to hours of volunteer labour requires additional, contestable valuation decisions. One possible reporting architecture is a vector of separately measured changes, supplemented by explanatory qualitative accounts. Equation 43 records the vector's domain-specific character.

$$\mathbf{Y}_{a,q}(I) = (Y_{a,q}^{\text{cap}}, Y_{a,q}^{\text{econ}}, Y_{a,q}^{\text{epist}}, Y_{a,q}^{\text{recogn}}, Y_{a,q}^{\text{burden}})_I. \quad (43)$$

The coordinates in Equation 43 are placeholders for operational measures, not commensurable scalars. In an empirical application, each coordinate must carry its unit, observation window or event boundary, provenance, and uncertainty statement. Some coordinates may consist of ordinal judgements or qualitative categories rather than numbers. For comparisons involving different knowledge traditions, investigators should consult participants about whether a proposed measure retains the relevant meaning, and report where a common measurement instrument fails.

I.5 Documenting Rights, Power, and Extractive Relations

Claims about ownership and institutional power require distinct evidentiary records. Legal documents may identify authorship, title, licence terms, contractual rights, fiduciary duties, or public mandates. Technical and operational evidence may identify which actors can exclude others, change an interface, revoke access, certify outputs, impose costs, or redirect value flows. Governance evidence may identify who has standing to propose revisions, deliberate, appeal adverse decisions, or exit a system without disproportionate loss of productive capability. Testimony from users and contributors supplies information about how these powers are experienced in practice. The empirical question is which interventions are actually available to which participants, under what constraints, and with what consequences for qualified productive activities.

A *control-intervention dossier* can combine four classes of evidence. The first records the relevant decision authority and its limits. The second specifies a feasible intervention, such as changing a licence, withholding certification, increasing a charge, revising an evaluation rule, or restricting an input. The third records how support routes and participant capabilities change under the intervention, including substitutes and contestation mechanisms. The fourth records resulting distributions of heterogeneous benefits and burdens. Where an intervention has not occurred, its effects may be examined through explicit scenarios or bounded simulations; such exercises remain counterfactual proposals until their assumptions are tested. The route-interception construction in Appendix F can help organize the technical portion of this dossier without proving the existence of an extractive arrangement.

Extraction should be investigated through a separate and more demanding evidentiary inquiry. Researchers must specify the candidate mechanism of recurring value capture, the contribution and main-

tenance relations supplying that value, the institutional means of appropriation, and the consequences for affected actors' reproductive opportunities. Evidence of revenue concentration, unequal bargaining power, or a dominant epistemic standard can motivate this inquiry; each has plausible alternative interpretations. Market payment may finance a costly service, a standard may reduce coordination losses, and centralized operation may provide reliability that distributed providers cannot currently replicate. A finding of extraction requires a transparent account of how the observed appropriation is related to the relevant labour and productive conditions, the nature of dependence, the reproduction of asymmetry, and applicable competing explanations. Stronger claims of exploitation additionally depend on explicitly defended political-economic and normative criteria.

Power over *recognition* demands special attention. Standards for valid evidence, disciplinary prestige, classifications, rankings, and discoverability algorithms can influence which contributions are seen as valuable. Such effects may be difficult to infer from aggregate publication or citation metrics because those measures are shaped by the same classificatory infrastructure under study. Documentary analysis of rule-making, counterfactual reclassification, audits of discoverability, and interviews with excluded or differently recognized contributors can provide complementary evidence. The construction of categories is an empirical and ethical part of the inquiry: classification systems can shape institutional practice and the social visibility of knowledge [12, 27, 33]. Investigators should disclose their own category choices and their likely effects on attribution.

I.6 Causal Identification and Competing Explanations

The manuscript proposes that accumulated capital can affect downstream knowledge production through generative dependencies, and that institutional control can transform the value circulation and further development of these dependencies. Assessing the causal elements of this proposal requires an explicit distinction between descriptive association, within-case mechanism evidence, and identification of effects under interventions. An observed association between platform concentration and participant dependence may reflect economies of scale, initial investments, selection of difficult tasks into particular platforms, legal obligations, market conditions, or prior institutional inequalities. Causal claims should state the alternatives addressed, the information still missing, and the extent to which the research design permits an intervention interpretation [44, 75, 15, 60].

Several designs may be appropriate for different questions. Process tracing can investigate documented transitions in authority, support routes, maintenance obligations, and value capture. A comparative design can match otherwise similar activities that differ in licensing, governance rights, or independently feasible alternatives, although comparability may remain partial. Interrupted operational histories can examine specific rule changes, provided concurrent funding, staffing, demand, and standard changes are recorded. Controlled technical audits can assess whether an alternative route performs a task under fixed qualification criteria. Interviews and participatory observation can investigate informal permissions and tacit capabilities that system logs overlook. Each design supplies different evidence; strong empirical conclusions often require their combination [7, 50].

A prospective inquiry might identify a policy change that modifies data-export rights while leaving an archive's validation standard provisionally fixed. Researchers could document whether an independent team can establish and maintain a qualified validation route, compare the cost and reliability of candidate routes, and assess changes in access and governance. The causal estimand, if one can be defended, would concern a clearly specified intervention for a defined actor population and activity, rather than a generic effect of openness or ownership. Where no credible untreated comparison exists, a carefully reconstructed within-case mechanism may support a narrower conclusion about the consequences of the particular event. A methodologically limited finding should retain that limited scope.

Causal feedback presents a distinct problem. Productive capabilities may influence governance arrangements that subsequently affect capabilities, so ordinary associations between governance and productive success may suffer from reciprocal causation. Participants may enter or leave systems according to their skills and preferences, and successful communities may attract disproportionate external

resources. The observation of institutional outcomes can itself alter recognition, funding, and strategic conduct. Analysts should therefore preserve the order and dependence of documented interventions and events, disclose potential anticipatory effects, and avoid mechanically treating historical observations as exchangeable samples. When a comparison relies on stable categories or task criteria, a change in those categories requires a new identification argument.

The strongest empirical contribution may sometimes be a negative result: a prominent methodological gate proves substitutable; a purportedly open alternative cannot sustain qualified production; observed revenue concentration does not correspond to reduced reproductive capability; or an important epistemic dependency remains powerful without demonstrable value extraction. Such outcomes help delimit the proposed theory. They should be recorded alongside supportive findings, with attention to publication selection and hindsight bias. Formal counterexamples in Appendix G are useful for planning discriminating tests, but their mathematical possibility is not an estimate of empirical prevalence.

I.7 Comparative Sampling, Robustness, and Representation Revision

A comparative programme can use a purposive initial sample spanning scholarly publishing, open-source research software, shared validation services, scientific standards, and public or cultural archives. The sample should include variation in effective control, resource endowment, participant autonomy, and tested alternative routes within and across institutional families. The investigator should document why cases entered the sample, including access limitations and whether selection favoured successful, visible, or conflict-ridden examples. Subsequent case recruitment may seek cases that challenge an emerging mechanism: public ownership with contractor dependence, a proprietary service with strong portability and appeal, a commons with concentrated unpaid maintenance burdens, or an application-level technical component that becomes a critical bottleneck. Such selection expands the range of possible explanations while making the limits of population inference clear.

Robustness should be examined at several levels. *Boundary robustness* tests whether a finding persists when the task, participant group, or material infrastructure boundary changes. *Route robustness* tests the reliability of candidate alternatives and the degree to which seemingly independent routes share an upstream dependency. *Measurement robustness* tests alternative operational definitions of capability, maintenance, value recognition, or concentration. *Classification robustness* tests how different coders or participant groups interpret institutional roles and generative levels. *Historical robustness* tests alternative event correspondences and different interpretations of uncertain documents. *Causal robustness* evaluates plausible rival mechanisms and missing-data assumptions. The purpose of these checks is to reveal the domain in which a conclusion is supported, not to force apparently heterogeneous cases into a single normalized index.

Missing observations deserve a formal status in the evidence register. A failed search for a contract, an unobserved route, an unavailable revenue record, and an inaccessible interview are different missing-data conditions. Non-disclosure may itself be related to institutional power. A study should preserve the provenance of missingness and, where possible, report bounds under alternative assumptions. Equation 42 provides one example: conclusions about route interception should be reported separately for confirmed routes and for candidate routes whose feasibility remains unresolved. A finding sensitive to an untested candidate should be marked as conditional. A similar discipline applies when benefits are known but the burdens of volunteer maintenance remain uncertain.

The model may need revision when empirical materials challenge its categories. Productive activities can be organized through tacit craft knowledge, nonformal expertise, and historically constituted standards whose meanings shift with community practice. An interview may identify a dependency that a technical diagram misses; a new regulatory arrangement may dissolve an assumed boundary between producer and evaluator; a publicly shared standard may be enacted differently across cultural or disciplinary contexts. Revision should preserve a versioned mapping between earlier and later representations, a statement of which observations changed, and a distinction between modification of the empirical system and correction of the researcher's model. The two-complex and hypergraph formalisms remain

Table 28: Empirical design matrix for multilevel knowledge-capital research.

Claim or construct	Candidate observable evidence	Primary comparison or test	Interpretive failure risk
Initial capital formation	Funding and labour histories; code and data provenance; maintenance records	Input and capability genealogy across bounded activities	Inherited or unpaid contributions omitted
Generative dependency	Executable route tests; complementary inputs; standards and skill requirements	Qualification-preserving substitutes and joint-failure audits	Nominal alternative confused with feasible route
Value circulation	Typed revenue, recognition, service, contribution and burden records	Contribution–benefit–reinvestment tracing	Different value domains collapsed into a price index
Effective institutional power	Rights instruments; operational interventions; appeal and exit evidence	Authority and counterfactual control-dossier audit	Legal title mistaken for executable command
Possible extraction	Recurrent appropriations; maintenance burdens; restricted alternatives	Mechanism tracing with rival explanations	Concentration treated as sufficient proof
Collective reproduction	Maintainer continuity; durable skills; accessible qualified routes	Repeated activity-qualified capability assessment	Gross outputs substituted for reproductive capacity

options among several representations, selected for fit to the research question rather than ontological priority.

Table 28 summarizes the principal empirical claims, their potential observables, and failure modes. It is intended as a reusable design instrument. The evidence suggestions are illustrative; the actual protocol should be negotiated with relevant research participants and adapted to the legal and disciplinary setting.

I.8 Research Ethics, Participation, and Responsible Disclosure

An inquiry into knowledge capital may involve unequal professional relationships and commercially or institutionally sensitive information. Contributors, maintainers, junior researchers, contractors, and users may face reputational, employment, legal, or community harms from disclosure. Ethical procedures should specify the purpose of data collection, meaningful consent where required, foreseeable risks, secure access controls, appropriate retention periods, and opportunities to correct factual misrepresentation. Data-minimization and aggregation may be necessary even when records are technically accessible to researchers. The use of public documents does not remove the obligation to avoid unsupported insinuations about identifiable persons or organizations. Digital records also require attention to consent, reidentification, and secondary use [81].

Participants may also disagree about the meaning of value, legitimate ownership, appropriate governance, or the boundary of a productive community. The research design should make room for these disagreements rather than treating a dominant institutional vocabulary as neutral. Participatory validation of case descriptions, translation checks where knowledge practices cross languages or disciplines, and documented opportunities for response can improve interpretive accountability. Yet participation cannot guarantee consensus or settle contested normative claims. The investigator remains responsible for distinguishing participant testimony from independently corroborated facts and for disclosing the framing choices that shape analysis. CARE principles, research on epistemic exclusion, and the analysis of classification practices supply relevant ethical and epistemic considerations [14, 24, 12].

Responsible publication should distinguish a finding of concentrated authority from an allegation of wrongdoing. A manuscript can report a contractually exclusive interface or a lack of verified substitutes without attributing improper intent. Claims of extraction should include the operational definition used, evidence of recurring capture and related burdens, response to competing explanations, and material uncertainty. If disclosure of an extractive-dependency model could expose an exploitable technical weakness, personally identifiable data, or confidential contractual details, a safer account may report the mechanism at a level that protects affected people while retaining enough information for scholarly scrutiny. Public accountability and research reproducibility require careful balancing with confidentiality

and participant autonomy.

I.9 Illustrative Study Blueprint and Reproducibility Protocol

An initial pilot study could investigate the creation, certification, and public distribution of validated research records through a shared infrastructure. The unit of analysis would be a bounded class of validation tasks and the relations among contributors, maintainers, a service operator, governing authorities, and downstream users. The study would begin by fixing the task qualification rule and participant populations. Investigators would reconstruct public and private inputs to the infrastructure, inventory formal rights, and interview differently situated participants about actual productive capabilities and constraints. Independent task audits would test candidate validation routes, including data portability and continuing operating costs. Typed records would document financial transfers, credit allocation, maintenance effort, governance participation, and changes in reproducible capability. A historical process-tracing component would investigate selected revisions in standards, contracts, funding arrangements, and appeal procedures.

The pilot would predefine several discriminating observations. If a governance change grants an operator exclusive certification authority while independent qualified routes cease to be usable, evidence would support a claim about increased effective dependency under the declared task reference. If a feasible, sustainably maintained independent route continues to operate, the strongest route-interception hypothesis would be weakened. If a substantial portion of service revenue is demonstrably reinvested in shared maintenance, a claim about value leaving the productive system without reproductive support would need qualification. If contributor labour and maintenance obligations increase while access, influence over rules, and durable capacity decline, an extraction hypothesis may become more plausible, subject to documentation of capture and competing explanations. These observations identify tests rather than predict outcomes.

A reproducibility package should include the case-selection rationale, research questions, coding protocol, data dictionary, versioned task qualifications, admissible route conditions, decision rules for institutional coding, source-provenance log, de-identification rules, and analysis scripts where permitted. It should distinguish public replication materials from confidential evidence held under restricted access. Codebooks should record ambiguous and disputed classifications, and independent coders should be able to reproduce the transition from raw observation to typed claims. For the formal models, researchers should publish machine-readable component and route descriptions, modelling assumptions, coverage claims, and sensitivity scenarios. For interviews and ethnography, reproducibility concerns transparent methods, reflexive interpretation, and auditable analytical decisions rather than unrestricted release of participants' private accounts.

The final reporting stage should organize findings by epistemic status. A *documented fact* is supported by identified primary materials within their evidentiary scope. A *model reconstruction* is an explicit representation of selected facts and assumptions. A *causal inference* depends on an identification strategy with stated alternatives and residual uncertainty. A *political-economic interpretation* connects the evidence to a defended account of capital formation, ownership, reproduction, and possible appropriation. A *normative assessment* specifies criteria of justice, autonomy, responsibility, or public generativity. The distinctions permit disagreements to be located precisely: two investigators may accept the same operational observations yet differ about the legitimacy of a property relation or the normative significance of a distribution.

The pilot permits model failure: generative levels may resist ordering, historical correspondences may be contested, and value domains may be incomparable. Such results delimit formal representation. The programme seeks inspectable accounts of knowledge-capital formation, circulation, control, and reproduction that distinguish productive accumulation, institutional authority, recurrent appropriation, and collective generative capability.

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