

Governance and Survival near Criticality: Functional Resource Distribution and Distributed Optionality

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Abstract

Governance near a plausible critical transition faces a resource problem in addition to problems of diagnosis, intervention, and evidence. Elevated susceptibility can increase the value of observation, bounded experimentation, and revisability, while waiting can simultaneously consume the fiscal, material, organizational, temporal, and relational capacities required for survival and later action. This paper develops a discussion framework for that tension. Its central object is functional resource distribution: the allocation of heterogeneous capacities across observation, probing, short-horizon survival, selective commitment, reserve or option preservation, and recovery or repair. The categories are analytical functions rather than a scalar budget partition and can overlap in practice. The paper introduces distributed optionality as a relational property of a response architecture in which materially different future actions remain supported by functionally diverse and sufficiently non-coincident pathways. It distinguishes exact reversal from recoverability, spatial dispersion from independence of failure modes, and delay as information gathering from delay as resource dissipation. The framework inherits, rather than restates, earlier arguments about response-oriented governance and evidence-to-action instability near criticality. Its distinctive question is how governance capacity may be composed when the future regime is uncertain, resources are partly non-substitutable, and both premature commitment and indefinite waiting can narrow the feasible future. The proposal is conditional and non-prescriptive: criticality requires domain-specific empirical support, and the appropriate resource portfolio depends on transition mechanism, horizon, institutional structure, and explicit normative commitments.

Keywords: near criticality; functional resource distribution; distributed optionality; resilience; recoverability

Discussion Paper Note

This paper examines governance under a conditional near-criticality hypothesis from the standpoint of finite and heterogeneous response capacity. It does not propose that political or social systems are generally near a mathematical critical point, and it does not infer near criticality from crisis rhetoric, volatility, conflict, or rapid change alone. Applications require domain-specific evidence concerning response structure, transition sensitivity, recovery, coupling, or related diagnostics.

The paper is designed as a companion to two earlier manuscripts. *Governance Near Criticality: Rethinking Intervention under Critical Transition Uncertainty* develops the broader problems of susceptibility, perturbation, response, reversibility, restraint, and trajectory closure. *Evidence-to-Action near Criticality: A Qualification for EBPM* isolates the instability that can arise between locally supported evidence and forward action when intervention can alter the response regime. The present paper does not restate those arguments as new contributions. It asks a different question: how finite governance capacity may be distributed across observation, probing, short-horizon survival, selective commitment, reserve, and recovery when waiting itself consumes resources and exact reversal may be unavailable.

The central proposal is therefore functional rather than sectoral. Resources are distinguished by the future governance functions they can support, not only by where they are physically located or which

organization controls them. The categories introduced in the paper are heuristic and may overlap in practice. They are not assumed to be commensurable, exhaustive, or universally optimal.

Responsible Use and Rights Reservation

The author encourages good-faith discussion, criticism, independent inquiry, and responsible use of the material in this work. The framework concerns uncertain and potentially high-consequence governance settings; its categories should therefore be treated as objects for critical analysis rather than instructions for manipulating real systems. This ethical request leaves the licence’s permissions and legally authorized uses unchanged.

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Notices

Status. This manuscript is an early-stage discussion paper on functional resource distribution and optionality under a conditional near-criticality hypothesis. Its categories and hypotheses remain open to empirical and conceptual revision. It does not infer criticality from political crisis, volatility, conflict, or rapid change alone.

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Statement on the use of language models. The exploratory discussions and preparation of this paper involved OpenAI’s ChatGPT. ChatGPT supported exploratory dialogue, source discovery followed by verification, conceptual reconstruction, argumentative criticism, and LaTeX drafting. The author selected the research problem, directed and approved the theoretical commitments, and bears sole responsibility for the manuscript, including its definitions, claims, interpretations, and errors. Authorship credit remains with the human author.

1 Introduction

This section establishes the paper’s distinct problem within the broader study of governance near critical transitions. Its objective is to move from the question of how strongly a sensitive system should be steered toward the question of how finite governance capacity should be distributed while the system remains difficult to diagnose, delay consumes resources, and later correction may be incomplete. The argument begins from a conditional near-criticality hypothesis, distinguishes survival from state preservation, introduces functional resource distribution and distributed optionality, and states the paper’s scope relative to earlier work on response and evidence-to-action relations.

Research on ecological and other complex dynamical systems has shown that some systems can undergo abrupt regime shifts after gradual changes in underlying conditions, and that loss of resilience can precede such transitions [2]. Work on early-warning signals has further examined patterns such as critical slowing down, rising autocorrelation, and rising variance in classes of systems approaching certain transitions [4]. These literatures do not establish that political or institutional systems generally satisfy the same dynamical models. They nevertheless provide a disciplined vocabulary for asking what changes

when recovery slows, susceptibility increases, alternative regimes become relevant, or local perturbations acquire unusually persistent consequences. The present paper uses that vocabulary conditionally and requires independent justification before any empirical application.

The paper also inherits a resilience distinction that predates the current critical-transition literature. Holling’s classic formulation separated persistence in the face of disturbance from rapid return to a single equilibrium [1]. Later social–ecological work extended resilience thinking toward adaptive capacity, transformability, learning, and governance under nonlinear change and uncertainty [3]. These traditions motivate attention to what a system can continue to do and what capacities remain available after disturbance. They do not by themselves answer how scarce governance resources should be distributed when observation, experimentation, immediate provisioning, commitment, reserve, and recovery compete for the same limited capacity.

That allocation problem is the center of the present paper. A near-critical configuration can create two opposing pressures. High susceptibility can increase the value of information, staged intervention, and preservation of revisability because a poorly understood action can participate in a persistent transition. At the same time, waiting is rarely costless. Financial reserves decline, infrastructure degrades, inventories are consumed, political attention shifts, organizational capacity fatigues, biological needs continue, and opportunities for intervention can disappear. A governance strategy that preserves every option by refusing commitment can therefore destroy the material conditions required to exercise those options later.

The relevant problem is consequently neither maximal intervention nor maximal delay. It is the distribution of finite capacity across functions that operate on different horizons. Some capacity supports observation of the evolving system. Some supports bounded probes that improve knowledge about response. Some sustains actors and essential processes through the period of uncertainty. Some enables commitments that cannot be postponed without unacceptable loss. Some remains deliberately uncommitted so that later information can still change action. Some is preserved for recovery, repair, or transition into a newly revealed regime. The balance among these functions can change as evidence, depletion, and system response evolve.

Definition 1.1 (Functional resource distribution). Functional resource distribution is an assignment of available capacities to distinct governance functions over a declared horizon. The functions considered in this paper include observation, probing, survival provisioning, selective commitment, reserve or option preservation, and recovery or repair. The categories are analytical roles rather than mutually exclusive physical stocks; one resource can support several functions, and resources serving different functions need not be commensurable.

Definition 1.1 avoids treating the paper’s central categories as a scalar budget identity. A hospital bed, a trained mediator, a fiscal reserve, a data stream, legal authority, electrical storage, and public trust cannot generally be added without an explicit accounting convention. The paper therefore represents the functional portfolio by the ordered family in Equation 1.

$$\mathcal{B}_t = (B_t^{\text{obs}}, B_t^{\text{probe}}, B_t^{\text{surv}}, B_t^{\text{commit}}, B_t^{\text{reserve}}, B_t^{\text{recover}}). \quad (1)$$

Each component in Equation 1 denotes a bundle of capacities currently available for the corresponding function. The representation does not imply additivity, independence, or fixed conversion rates among bundles. Those properties are empirical and institutional questions. The formal purpose is narrower: it makes visible that a system can possess substantial aggregate resources while remaining fragile because too little capacity is available for a function that becomes decisive under a particular trajectory.

This functional view also clarifies the meaning of distribution. Spatial dispersion can reduce some correlated risks, but geographically dispersed assets can remain dependent on one communication network, payment rail, supplier, legal authorization, energy source, technical standard, or decision center. Conversely, a geographically concentrated resource can sometimes provide several independent response pathways if its use is institutionally and technically flexible. Resilience therefore depends partly on the relation among functions, dependencies, and failure modes rather than on dispersion alone.

The paper uses *distributed optionality* for this broader property. Optionality here does not mean the indefinite retention of every possible future. Such retention is usually impossible and can itself consume resources. It refers to the preservation of a sufficiently diverse set of feasible future responses, including capacity to revise a current course when new information or a new regime becomes visible.

Definition 1.2 (Distributed optionality). Distributed optionality is a configuration in which future response capacity is supported by multiple pathways that are materially distinct under declared functional, architectural, and dependency criteria. The pathways are sufficiently non-coincident for the stated application when the loss or commitment of one represented pathway does not, by the declared dependency structure alone, eliminate every materially relevant route for continued action, adaptation, or recovery.

The qualification “sufficiently non-coincident” in Definition 1.2 is important. Redundancy measured by asset count can be illusory when nominally separate resources share the same hidden bottleneck. Later sections therefore distinguish functional diversity, path redundancy, institutional diversity, and dependence among failure modes. Distributed optionality is a relational property of the response architecture rather than a count of reserves.

A second distinction concerns survival. In the present paper, survival does not mean preservation of the current regime at any cost. A system can remain viable by changing form, abandoning a failing structure, or crossing into a different regime while retaining enough capacity for subsequent adaptation. Conversely, strong defense of the current state can consume the reserves needed to survive the transition itself. The paper therefore uses survival in a functional sense tied to the persistence of selected essential capabilities rather than to identity of state.

Definition 1.3 (Functional survival). Functional survival is the continued availability, over a declared horizon, of a specified set of capabilities judged necessary for ongoing response, adaptation, or recovery. The definition does not require preservation of every component, institution, or state variable present at the initial configuration.

Definition 1.3 deliberately leaves the selected capabilities open. In a biological emergency they may include food, shelter, care, and communication. In a financial system they may include liquidity and settlement capacity. In an organization they may include staffing, authority, information, and minimum operating capability. In a political setting the relevant set can also contain procedural and normative requirements. Selection of the survival set is therefore partly empirical and partly normative; the dynamical framework does not determine it by itself.

The distinction between reversibility and recoverability follows naturally. Exact reversal asks whether a previous configuration can be restored. Recoverability asks whether a viable response set can be reconstructed after the system has changed. Near a regime transition the second question can be more practical. Historical path dependence, depleted resources, newly formed expectations, institutional learning, and irreversible physical changes can make exact return unavailable even when a new viable trajectory remains attainable. The governance problem then shifts from preserving a particular state toward preserving the capacities from which another viable path can be generated.

This perspective also changes the interpretation of waiting. Delay can increase information and preserve freedom from premature commitment. It can also deplete survival resources and narrow the feasible action set. The value of waiting is therefore conditional on what is consumed while waiting and on whether information arrives quickly enough to justify the depletion. In a dissipative setting, non-decision is itself a trajectory.

The paper uses *dissipative delay* for this structural possibility.

Definition 1.4 (Dissipative delay). Dissipative delay is a period in which postponing commitment changes the future action set because capacities required for survival, intervention, reserve, or recovery are consumed, degraded, expire, or otherwise become unavailable during the delay.

Definition 1.4 does not imply that faster action is preferable. Some forms of delay can increase optionality by generating information, reducing uncertainty, allowing coordination, or avoiding premature

lock-in. The point is that delay must be evaluated as an active temporal allocation of resources rather than represented as a costless baseline.

These distinctions locate the paper relative to two companion manuscripts. *Governance Near Criticality: Rethinking Intervention under Critical Transition Uncertainty* develops the broader problem of susceptibility, perturbation, response, restraint, reversibility, and trajectory closure. *Evidence-to-Action near Criticality: A Qualification for EBPM* isolates a narrower epistemic problem in which evidence can remain locally informative while intervention changes the response regime to which the evidence would otherwise be transported. The present paper takes both results as background. Its contribution is not another argument for cautious intervention or another account of evidence transport. It asks how governance capacity can be functionally distributed when caution, information gathering, urgent provisioning, commitment, and future recovery all compete for limited and partly non-substitutable resources.

The central working hypothesis can therefore be stated without prescribing a universal allocation rule.

Hypothesis 1.5 (Functional portfolio hypothesis). Under conditions in which a near-criticality hypothesis is empirically plausible, delay is materially dissipative, and future response requirements remain uncertain, the family of supportable future responses and recovery possibilities can depend on the functional composition and dependency structure of available capacity in addition to whatever aggregate resource description is justified for the application. Under a declared common accounting or coarse resource comparison, portfolios that preserve observation, bounded probing, short-horizon survival, selective commitment, reserve, and recovery functions can retain feasible future responses that a more functionally concentrated portfolio would not retain under some trajectories.

Hypothesis 1.5 is intentionally conditional. It does not establish that every function must receive resources in every case, that equal distribution is desirable, or that diversification always dominates concentration. Concentration can be necessary when scale economies, indivisibilities, coordination demands, or imminent threats make distributed capacity ineffective. The empirical question concerns which functions and dependencies matter under the relevant transition mechanism and horizon.

The normative question also remains open. Preserving optionality can conflict with urgent protection, rights, distributive justice, democratic authorization, or duties to commit resources to present needs. A reserve held for future flexibility can be ethically costly when current deprivation is severe. A recovery fund can privilege restoration of one institution over transformation toward another. The paper therefore treats functional resource distribution as a governance problem whose evaluation requires explicit normative commitments; dynamical resilience alone does not determine the just allocation.

The remainder of the paper develops this argument in stages. Section 2 defines the near-critical governance regime and separates transition uncertainty, susceptibility, and recovery. Section 3 examines observability, perturbations as probes, and the limits of local linearization. Section 4 states the inherited response-oriented background without reproducing the earlier governance paper. Section 5 develops the resource costs of delay and the conditions under which survival provisioning competes with continued observation. Section 6 develops the functional portfolio in detail. Section 7 analyzes redundancy, diversity, and hidden common dependencies. Section 8 imports the relevant evidence-to-action qualification only where it constrains resource commitment. Section 9 reviews the empirical identification problem for near-critical conditions. Section 10 examines distributed capacity with selective central coordination. Section 11 develops stylized applications, and the final sections state limitations and conclusions.

2 Near-Critical Governance Conditions

This section specifies the dynamical conditions under which functional resource distribution becomes a distinct governance problem. Its objective is diagnostic: the analysis identifies a compact set of response properties that can justify treating a situation as provisionally near critical for the purposes of this paper. The section separates transition uncertainty, perturbation sensitivity, and recovery structure, then combines them into a non-scalar diagnostic profile. The construction remains model-relative and

evidence-dependent. A near-critical attribution therefore requires transition-relevant evidence beyond political volatility, institutional conflict, rapid change, or crisis language.

The present paper inherits the broader motivation from work on abrupt regime shifts, resilience loss, and early-warning behavior in nonlinear systems [2, 4]. That literature establishes neither a universal criticality model nor a direct mapping from ecological dynamics to governance. It does, however, motivate a response-centered question: under what conditions should an analyst expect the current state to provide an incomplete description of the system’s practical vulnerability? For the resource problem developed here, three properties are especially relevant. Several materially different regimes may remain accessible over the decision horizon; responses to small perturbations may vary sharply by direction or context; and recovery from disturbance may become slower, more path-dependent, or more dependent on scarce intervention capacity. These properties can coexist in different combinations and degrees.

2.1 Transition Uncertainty

Transition uncertainty concerns uncertainty over which materially different response regime will become realized over a declared horizon. The term is narrower than general uncertainty. An institution may face substantial uncertainty about prices, preferences, implementation, or political support while remaining within one broadly stable response regime. The present concept becomes relevant when plausible disturbances, endogenous evolution, or interventions can lead to configurations whose subsequent response properties differ materially.

Let Ω denote a working configuration space and let $\omega_t \in \Omega$ denote the configuration represented at decision time t . A regime map $\gamma : \Omega \rightarrow \Gamma$ assigns configurations to a declared family of response regimes Γ . The map is an analytical device whose resolution depends on the empirical task; it carries no ontological claim about uniquely real regime boundaries. A regime distinction may concern, for example, contrasting recovery behavior, feedback structure, institutional operating mode, or another response property relevant to the decision.

For a declared horizon H and a family of plausible perturbation and intervention paths $\mathcal{P}_t$, let $\text{Reach}_H(\omega_t; \mathcal{P}_t)$ denote the configurations treated as reachable within that horizon under the model and evidence currently in use. The corresponding accessible-regime family is defined in Equation 2.

$$\mathcal{G}_t(H; \mathcal{P}_t) = \{\gamma(\omega') : \omega' \in \text{Reach}_H(\omega_t; \mathcal{P}_t)\}. \quad (2)$$

Equation 2 keeps mathematical reachability and empirical plausibility distinct. Both the reachability relation and the path family $\mathcal{P}_t$ are constrained by the analyst’s model, observations, institutional knowledge, and uncertainty representation. Their contents can therefore change as evidence accumulates. Changes in model structure or evidence can enlarge or narrow the represented regime family by revealing omitted pathways, excluding formerly plausible pathways, or changing how regimes are distinguished.

Definition 2.1 (Transition uncertainty). For a declared horizon and modeling frame, transition uncertainty is present when more than one materially distinct response regime remains empirically plausible and the available evidence does not justify collapsing the decision problem to a single regime trajectory.

Definition 2.1 uses material distinction as its operative criterion; simple regime count is insufficient. Two labels in Γ may represent differences too small to matter for the allocation problem, while one coarse label can conceal changes in recovery, coupling, or resource requirements that are decision-relevant. The operational task is therefore to specify which regime differences would alter the response architecture. The same empirical system can support different regime partitions for different questions without contradiction.

Transition uncertainty also has a temporal structure. At a short horizon, several local actions may appear equivalent because their immediate outputs are similar. At a longer horizon, the same actions can differ in the regimes they keep accessible, the recovery capacities they consume, or the dependencies they create. The declared horizon should consequently accompany any near-critical diagnosis. An attribution

that is meaningful over days may become uninformative over years, and a long-run regime distinction may be irrelevant to an emergency decision whose binding horizon is measured in hours.

The practical implication for Paper IV is limited but important. Where materially different regimes remain plausible, resources committed exclusively to one forecast can lose value if another regime becomes realized. This observation leaves the merits of diversification open. Some transitions require concentrated action, and some resources deteriorate when held in reserve. Transition uncertainty merely creates a reason to examine how strongly the current portfolio depends on one future regime being correct.

2.2 Susceptibility and Recovery

Susceptibility concerns how strongly trajectories respond to perturbations, while recovery concerns what forms of return, stabilization, adaptation, or functional reconstruction remain feasible after disturbance. The two concepts are related but distinct. A configuration can be highly responsive to a particular perturbation and still recover rapidly, while another can show modest immediate displacement followed by persistent degradation. Resource planning therefore requires both response amplitude and recovery structure.

A scalar susceptibility parameter would be too restrictive for the purposes of this paper. Governance systems are heterogeneous, perturbations differ in direction and timing, and response can depend on the observational scale. The paper therefore uses a finite-horizon sensitivity profile. Let $\Pi : \Omega \rightarrow \mathcal{Y}$ denote a declared readout into a comparison space $\mathcal{Y}$ equipped with a task-appropriate distance $d_{\mathcal{Y}}$. Let $\Phi_h(\omega_t; \eta)$ denote the configuration reached after horizon h when perturbation path η is admitted, with $\eta = 0$ denoting the comparison path under the same modeling frame. The finite-horizon response contrast is stated in Equation 3.

$$\Delta_h(\omega_t; \eta, \Pi) = d_{\mathcal{Y}}(\Pi(\Phi_h(\omega_t; \eta)), \Pi(\Phi_h(\omega_t; 0))). \quad (3)$$

Equation 3 measures a modeled contrast whose political significance depends on the declared readout, metric, horizon, and application. The readout Π , the comparison metric, the perturbation path, and the horizon all require justification. A large contrast in one readout can coexist with a small contrast in another. A perturbation can also matter through distributional or institutional effects that a coarse aggregate readout fails to represent.

The associated sensitivity profile is defined in Equation 4.

$$\mathcal{S}_t(H; \Pi, \mathcal{E}_t) = \{(\eta, h, \Delta_h(\omega_t; \eta, \Pi)) : \eta \in \mathcal{E}_t, 0 < h \leq H\}, \quad (4)$$

where $\mathcal{E}_t$ is the family of perturbations considered credible or decision-relevant at time t . Equation 4 preserves direction and horizon and avoids compressing heterogeneous sensitivity into one number. The profile can be estimated only partially in empirical applications. Its main role in the present framework is to make explicit which perturbations are believed capable of producing materially different responses.

Early-warning research provides several empirical motivations for examining changes in response and recovery. In some classes of systems approaching particular transitions, recovery from small perturbations can slow and observable variance or autocorrelation can rise [4]. These indicators are conditional on mechanism, measurement, and data-generating structure. Their presence supplies mechanism-dependent evidence whose interpretation belongs within an explicit model. Their absence likewise need not exclude every transition mechanism.

The resource problem also requires a recovery concept broad enough to accommodate functional continuity and reconstruction. Holling's distinction between persistence and rapid return already cautions against identifying resilience with return to one equilibrium [1]. Social-ecological resilience research similarly emphasizes adaptation and transformability alongside persistence [3]. Paper IV therefore represents recovery relative to a declared target set, with exact state reversal treated as only one possible recovery criterion.

Let $V \subseteq \Omega$ denote configurations satisfying a declared recovery criterion. The criterion can represent restoration of essential services, legal operability, minimum provisioning, network connectivity, or another function relevant to the application. Let $\mathcal{A}_t$ denote the recovery actions considered available from time t , and let ω_t^η denote the configuration from which recovery is evaluated after perturbation η . The finite-horizon recovery profile is defined in Equation 5.

$$\mathcal{R}_t(H; V, \mathcal{A}_t, \mathcal{E}_t) = \{(\eta, \text{Reach}_H(\omega_t^\eta; \mathcal{A}_t) \cap V) : \eta \in \mathcal{E}_t\}. \quad (5)$$

For a given perturbation, a nonempty recovery component in Equation 5 indicates modeled recoverability within the declared horizon and action repertoire. The set establishes only modeled recoverability; likelihood, cost, justice, and institutional authorization remain separate questions. A recovery path may require resources that are scarce, impose burdens on particular groups, or depend on capacities that a preceding intervention has already consumed. Later sections therefore treat recoverability as a property jointly shaped by system dynamics and resource architecture.

Remark 2.2 (Recovery as a relational property). Recovery in the present framework is relative to a target set, horizon, action repertoire, and resource configuration. A system can be recoverable with respect to one function and unrecoverable with respect to another. The relevant question for governance is therefore which functions remain reconstructible, for whom, over what horizon, and through which resource pathways.

Remark 2.2 is the bridge to the resource analysis developed later: recoverability can deteriorate because the dynamics change, because the required capacity is unavailable, or because both processes occur together.

The distinction between susceptibility and recovery matters for intervention design. High sensitivity can make small probes informative or dangerous. Weak recovery can make errors persistent even when the initial perturbation is modest. Strong recovery can sometimes support experimentation because adverse responses remain containable. These relationships remain conditional; they do not yield a universal ranking between probing, commitment, and restraint.

2.3 Near-Critical Diagnostic Profile

The paper treats near criticality as a composite diagnostic hypothesis assembled from response evidence and represented through several linked response dimensions. The purpose is to prevent a governance recommendation from resting on an undefined assertion that a system is simply “close to critical.” A useful attribution should identify the transition structure believed to be relevant, the directions in which susceptibility appears elevated, the recovery properties that appear to be changing, and the evidence supporting each part of the diagnosis.

For the current paper, the three principal components can be collected into the diagnostic profile stated in Equation 6.

$$\mathfrak{C}_t(H) = (\mathcal{G}_t(H; \mathcal{P}_t), \mathcal{S}_t(H; \Pi, \mathcal{E}_t), \mathcal{R}_t(H; V, \mathcal{A}_t, \mathcal{E}_t)). \quad (6)$$

Equation 6 serves as a bookkeeping device and carries no scalar-index interpretation. The first component concerns accessible regimes, the second concerns perturbation-response structure, and the third concerns recoverability. The components need not move together. A system can display rising sensitivity while one recovery route remains robust, or recovery capacity can erode because of resource depletion even when the underlying dynamical susceptibility changes little. The profile therefore preserves heterogeneity across the three components.

Definition 2.3 (Near-critical governance profile). A near-critical governance profile is a model-relative and empirically defeasible representation in which evidence supports concern about a transition-relevant combination of regime accessibility, perturbation sensitivity, and recovery structure over a declared decision horizon.

Definition 2.3 allows the components to display different patterns and leaves numerical thresholds to mechanism-specific empirical work. Different mechanisms can generate different observable signatures. The empirical burden is to show why the identified response properties matter for the specific intervention and resource problem under consideration.

Table 1 summarizes how the diagnostic components connect to the later resource analysis. The table states analytical implications whose normative significance remains open. Each implication remains dependent on empirical evidence and normative judgment.

The fourth row in Table 1 concerns the evidential status of the profile and therefore remains outside the three formal components in Equation 6. Diagnostic uncertainty concerns the evidential status of the profile itself. An analyst can be uncertain whether the represented accessible regimes, sensitivity directions, or recovery paths have been specified correctly. Governance must therefore distinguish uncertainty within the modeled system from uncertainty about the model used to characterize the system.

Caution 2.4 (Indicator aggregation). No single early-warning indicator, volatility measure, network statistic, or crisis descriptor is treated in this paper as sufficient evidence of near criticality. Empirical applications should specify the candidate transition mechanism, the measurement process, plausible alternatives, and the relation between the diagnostic evidence and the intervention horizon.

Caution 2.4 is especially important for social and political applications. Rising variance can reflect measurement change, heterogeneous shocks, strategic adaptation, or ordinary nonstationarity. Slower institutional response can result from legal procedure or organizational overload rather than dynamical critical slowing down. Apparent regime flickering can reflect classification artifacts. A near-critical interpretation should be compared against these alternative explanations within the empirical design.

The diagnostic profile also clarifies where Paper IV begins to differ from the earlier governance manuscript. The earlier work asks how response should be conceived when susceptibility and trajectory closure make aggressive steering risky. The present paper accepts that problem as background and asks what happens once response capacity itself is scarce, heterogeneous, and exhaustible. Under that condition, observation, probing, provisioning, commitment, reserve, and recovery draw on partially overlapping capacities. A strategy that preserves diagnostic openness can consume the resources needed for later survival; a strategy that maximizes immediate provisioning can leave too little capacity for recovery; and a strategy that commits heavily to one regime can make alternative response pathways unavailable.

The transition to the resource problem can therefore be stated as a conditional hypothesis.

Hypothesis 2.5 (Portfolio relevance under transition-sensitive conditions). When materially different regimes remain plausible, perturbation responses are sufficiently heterogeneous to affect intervention consequences, recovery depends on scarce capacities, and resource use changes what remains available later, the composition and dependency structure of governance resources can become decision-relevant in addition to their aggregate quantity.

Hypothesis 2.5 leaves the optimal degree of diversification open. Concentrated commitment can be warranted when a threat is sufficiently urgent, one trajectory is strongly supported, or fragmented resources cannot meet a binding threshold. The hypothesis identifies the conditions under which portfolio composition deserves explicit analysis. Sections 3–6 will progressively specify how information, delay, survival requirements, and resource function interact within that problem.

Table 1: Diagnostic components of the near-critical governance profile and their resource implications.

Diagnostic component	Structural meaning	Resource question opened by the diagnosis
Transition uncertainty	Several materially different response regimes remain plausible over the declared horizon.	How strongly should current capacity depend on one regime forecast, and which capacities preserve usefulness across alternatives?
Perturbation sensitivity	Response magnitude and direction vary materially across perturbations, horizons, or readouts.	Which observation and probe resources can improve discrimination without consuming disproportionate survival or recovery capacity?
Recovery structure	Return, stabilization, adaptation, or reconstruction depends on available paths, horizons, and functions.	Which reserve and recovery capacities must remain accessible after commitment, and which functions require protection before disturbance?
Diagnostic uncertainty	Evidence about regimes, sensitivity, and recovery remains incomplete or model-dependent.	Which resource commitments remain revisable while additional information is generated, and what costs are created by continued delay?

3 Observability near Criticality

This section specifies the epistemic problem that connects the near-critical diagnostic profile in Section 2 to the resource portfolio developed later in the paper. Its objective is to distinguish observation of a current configuration from discrimination among plausible response regimes. The section proceeds through four steps. It first defines regime-level visibility relative to a declared family of readouts. It then treats natural or designed perturbations as possible system probes, while preserving the fact that a probe can alter the system it is used to learn about. The third subsection identifies the limited role of local linearization in regime discrimination. The final subsection makes the resource footprint of observation explicit. Throughout, observability remains model-relative and task-relative: greater measured detail does not automatically imply greater ability to distinguish the future response structures relevant to a governance decision.

3.1 Regime-Level Visibility

A governance actor can observe many features of a system while remaining unable to distinguish the response regimes that matter for action. Aggregate output, institutional status, market prices, network statistics, or public indicators can be measured with considerable precision while several materially different transition structures remain compatible with those observations. The relevant object for this paper is therefore regime-level visibility rather than observation volume alone.

Let $\mathcal{G}_t(H; \mathcal{P}_t)$ denote the candidate regime family defined in Section 2.1, let Π_t denote a declared family of observation maps, and let H be the decision horizon. For each candidate regime g , the model generates an observation signature $\text{Sig}_t(g; \Pi_t, H)$, which may be a trajectory, a set of trajectories, a distributional description, or another model-appropriate representation of the readouts expected under that regime. The exact construction is left to the empirical model. Two candidate regimes are observationally equivalent relative to the declared observation architecture when Equation 7 holds.

$$g \sim_t^{\Pi_t, H} g' \iff \text{Sig}_t(g; \Pi_t, H) = \text{Sig}_t(g'; \Pi_t, H). \quad (7)$$

Equation 7 induces a partition of the candidate regime family into observational equivalence classes.

The partition is stated in Equation 8.

$$\mathcal{P}_t(\Pi_t, H) = \mathcal{G}_t(H; \mathcal{P}_t) / \sim_t^{\Pi_t, H}. \quad (8)$$

A finer partition in Equation 8 means that the declared observation architecture distinguishes more of the candidate regimes represented by the model. It does not imply that the observations are more accurate in every statistical sense, nor that the distinctions are decision-relevant. The value of finer discrimination depends on whether the separated regimes imply materially different survival, commitment, recovery, or resource requirements.

Definition 3.1 (Regime-level visibility). Regime-level visibility is the discriminatory resolution of a declared observation architecture over a model-relative family of candidate response regimes and a declared decision horizon.

Definition 3.1 separates visibility from a claim that near-critical systems become inherently easier to understand. Some transition mechanisms can produce observable changes in recovery patterns, autocorrelation, or variance before a transition, while the reliability and interpretation of such indicators remain mechanism-dependent [4]. Other settings can become harder to diagnose because rapid adaptation, measurement noise, strategic behavior, or changing institutional definitions obscure the relevant response structure. The present framework therefore permits both increased and decreased regime-level visibility.

The distinction also clarifies the limited role of the ridge metaphor inherited from the earlier conceptual work. Near a transition, several future directions can become practically salient, but salience is not equivalent to epistemic access. Multiple trajectories can become consequential at the same time that the evidence needed to discriminate among them remains weak. The resource problem begins precisely because governance may have to preserve response capacity before the relevant regime has become fully identifiable.

3.2 Perturbations as System Probes

Passive observation can leave candidate regimes observationally equivalent when their differences appear only in response to disturbance. Naturally occurring shocks can then reveal latent susceptibility, and deliberately bounded perturbations can sometimes be used to learn about response structure. The analytical role of a probe is therefore to modify the conditions under which candidate regimes generate observable signatures. This role does not imply that probing is always desirable or safe.

For a perturbation η from the declared probe set $\mathcal{E}_t^{\text{probe}}$, let $\text{Sig}_t^\eta(g; \Pi_t, H)$ denote the modeled observation signature following that perturbation under candidate regime g . Because the probe supplements rather than erases information already available before intervention, the relevant diagnostic object is the augmented signature in Equation 9.

$$\begin{aligned} \text{Sig}_t^{+\eta}(g; \Pi_t, H) &= (\text{Sig}_t(g; \Pi_t, H), \text{Sig}_t^\eta(g; \Pi_t, H)), \\ g \sim_{t, +\eta}^{ \Pi_t, H } g' &\iff \text{Sig}_t^{+\eta}(g; \Pi_t, H) = \text{Sig}_t^{+\eta}(g'; \Pi_t, H). \end{aligned} \quad (9)$$

Let $\mathcal{P}_t(\Pi_t, H; +\eta)$ denote the partition induced by Equation 9. The augmented construction can only preserve or refine distinctions already present in the baseline signature. A probe is diagnostically discriminating when the augmented partition strictly refines the baseline partition in Equation 8. The condition is stated in Equation 10.

$$\mathcal{P}_t(\Pi_t, H; +\eta) \prec \mathcal{P}_t(\Pi_t, H), \quad (10)$$

where $\prec$ denotes strict refinement of partitions. Equation 10 means that at least one pair of regimes that is observationally equivalent under the baseline architecture becomes distinguishable once the probe response is considered together with the baseline observations. This construction avoids the stronger and unnecessary assumption that the post-probe signature, considered by itself, preserves every distinction already available before probing.

Definition 3.2 (Diagnostically discriminating probe). A diagnostically discriminating probe is a modeled perturbation whose induced observation partition strictly refines the baseline regime partition relative to the declared observation family and horizon.

The same perturbation can simultaneously provide information and change the state from which future action proceeds. Let $\mathcal{B}_t$ be the functional resource portfolio introduced in Section 1. A probe is represented here by the joint update stated in Equation 11.

$$\mathcal{U}_\eta^{\text{probe}} : (\omega_t, \mathcal{B}_t) \mapsto (\omega_t^\eta, \mathcal{B}_t^\eta). \quad (11)$$

Equation 11 makes two effects explicit. The configuration can change because the system has been perturbed, and the resource portfolio can change because measurement, deployment, protection, interpretation, or recovery consumes capacity. A perturbation that is small in one physical or administrative dimension can still have a substantial portfolio footprint if it requires scarce personnel, political capital, protected infrastructure, or recovery reserves.

The recovery construction in Equation 5 allows a further structural distinction. A probe can be diagnostically discriminating while leaving the protected functional target V recoverable, or it can improve discrimination while moving one or more candidate regimes outside the modeled recovery set. Because the true regime is uncertain, a stronger robustness condition can be useful. A probe is uniformly recovery-compatible over the current candidate family when Equation 12 holds.

$$\forall g \in \mathcal{G}_t(H; \mathcal{P}_t), \quad \text{Reach}_H(\omega_t^{\eta,g}; \mathcal{A}_t) \cap V \neq \emptyset. \quad (12)$$

Equation 12 is a structural condition rather than a universal decision rule. It can be too demanding where urgent action is required, where some candidate regimes are weakly supported, or where every informative probe carries material risk. Its role is to expose a central tension: diagnostic discrimination and preservation of recovery capacity can vary independently.

Remark 3.3 (Dual role of perturbation). A perturbation can be simultaneously an epistemic event and a dynamical event. Its value as a probe depends on what it helps discriminate; its governance significance also depends on the state and resource changes generated by performing it.

Remark 3.3 provides the direct bridge to later sections on response and resource distribution. Observation near criticality can require action, and action undertaken for epistemic reasons can consume the capacities required for survival or recovery.

3.3 Local Linearization and Regime Discrimination

Local response models can be useful for identifying directions of susceptibility, estimating short-horizon effects, or designing bounded probes. Their interpretive range narrows when the governance question concerns finite-horizon regime selection, recovery, or trajectory closure. This subsection states that limitation without treating local linearization as intrinsically defective.

Suppose a candidate regime g admits a differentiable local state representation with one-step update map F_g . For a sufficiently small perturbation δ , the local expansion is stated in Equation 13.

$$F_g(\omega_t + \delta) = F_g(\omega_t) + J_g(\omega_t) \delta + r_g(\delta), \quad \frac{\|r_g(\delta)\|}{\|\delta\|} \rightarrow 0 \text{ as } \|\delta\| \rightarrow 0. \quad (13)$$

Equation 13 is conditional on a representation for which differentiability and the indicated norm are meaningful. It supplies a first-order description of one-step local response. It does not, by itself, identify the finite-horizon regime that will be realized, the recovery set after repeated updates, or the resource requirements of maintaining a viable trajectory.

A simple regime-discrimination limitation occurs when two candidate regimes share the same local Jacobian at the observed configuration while generating different finite-horizon signatures. The condition is stated in Equation 14.

$$J_g(\omega_t) = J_{g'}(\omega_t) \quad \text{and} \quad \text{Sig}_t(g; \Pi_t, H) \neq \text{Sig}_t(g'; \Pi_t, H). \quad (14)$$

When Equation 14 holds, first-order local response cannot distinguish the two regimes even though the declared horizon reveals a difference relevant to observation. Higher-order structure, longer observation, alternative readouts, or perturbation-based discrimination may then be required. The converse is also possible: locally different Jacobians can lead to differences that are irrelevant to the protected functions or decision horizon. Local distinguishability therefore remains task-relative.

The same caution applies to repeated use of a locally adequate approximation. A probe can remain inside the domain where Equation 13 is informative for the immediate response while subsequent evolution approaches a boundary, changes the active feedback structure, or alters the intervention repertoire. The paper therefore treats local linearization as one observational instrument within a broader regime-sensitive architecture. This use is intentionally narrower than the general tangent-space critique developed in the companion governance work.

3.4 Resource Footprint of Observation

Observation is often modeled as though information arrives without changing the resource state of the decision maker. That simplification can be useful in low-cost settings, but it becomes restrictive when the same personnel, infrastructure, time, fiscal capacity, legitimacy, or recovery reserves support both learning and action. The present paper therefore makes the resource footprint of observation explicit.

Let m denote an observation activity, including passive monitoring, data integration, protected sensing, active probing, or interpretive coordination. Its effect on the functional resource portfolio is represented by the partial update in Equation 15.

$$\mathcal{U}_m^{\mathcal{B}} : \mathcal{B}_t \rightarrow \mathcal{B}_{t+1}^{(m)}. \quad (15)$$

Equation 15 allows different observation activities to draw on different components of the heterogeneous portfolio. It does not require those components to be commensurable. An activity is resource-neutral relative to the modeled portfolio only when it leaves that portfolio unchanged. In many applications the more relevant issue is whether the activity depletes or encumbers capacities needed for another function, such as immediate provisioning or recovery.

Table 2 distinguishes four observation-related modes. The categories are analytical and can overlap in practice.

Table 2 also shows why maximization of diagnostic resolution is not an adequate standalone objective. A highly discriminating probe can consume resources whose opportunity cost becomes severe under dissipative delay. A low-cost observation strategy can preserve resources while leaving important regime ambiguity unresolved. A committed intervention can generate abundant information after the fact while simultaneously removing options that the information would otherwise have helped compare.

This interaction motivates the following conditional hypothesis.

Hypothesis 3.4 (Observability–capacity tradeoff). When diagnostic activities require scarce capacities that are also needed for survival, commitment, reserve, or recovery, improvements in regime-level visibility can reduce the future action capacity available to respond to the information obtained. The magnitude and direction of this tradeoff depend on the observation architecture, resource dependencies, and decision horizon.

Hypothesis 3.4 does not imply that less information is preferable. It identifies a portfolio effect that becomes relevant when information production and response draw on shared or coupled resources. The implication for Paper IV is that observation and probing belong inside the resource-allocation problem rather than preceding it as costless preparatory stages.

Section 3 therefore establishes four conditions for the subsequent governance discussion. Regime-level visibility is distinct from measurement density; perturbations can refine diagnosis while altering the

Table 2: Observation-related modes and their structural relation to governance capacity.

Mode	Primary epistemic role	Possible system effect	Portfolio implication
Passive monitoring	Update readouts under the existing trajectory.	Can be approximately non-perturbative in the modeled system, while measurement institutions can still affect behavior in reflexive settings.	Draws mainly on observation, interpretation, communication, and maintenance capacity.
Natural perturbation observation	Learn from disturbances that occur independently of the diagnostic design.	The disturbance can alter state, recovery demand, or accessible regimes.	Observation can compete with emergency response and survival provisioning.
Bounded active probe	Intentionally generate response contrast among candidate regimes.	Changes the state by design and can alter recovery requirements or later action space.	Uses probe capacity and can encumber survival, reserve, or recovery resources.
Committed intervention with monitoring	Learn while pursuing a substantive response objective.	Can reconfigure the regime being studied and narrow future alternatives.	Couples information production to commitment resources and potentially to recovery obligations.

system; local response models can be informative without resolving finite-horizon regime differences; and observation itself can consume or encumber scarce capacity. Section 4 turns from this epistemic architecture to response-oriented governance, asking how action can remain adaptive when observation is incomplete and the resources supporting continued response are themselves part of the evolving system.

4 Response-Oriented Governance

This section specifies the response architecture that connects the diagnostic profile developed in Section 2 to the resource-allocation problem developed later in the paper. Its objective is to represent governance response as a joint transformation of system state, functional capacity, and future action repertoire. The discussion proceeds in three steps. First, disturbance response is represented as a portfolio-sensitive update rather than as movement toward a preselected target state. Second, the section distinguishes intervention magnitude from commitment depth and introduces a comparative language for future-repertoire closure. Third, it develops staged adaptive steering in which later actions can be conditioned on updated observations while the costs of delay and continued option preservation remain explicit.

The section does not rank observation, buffering, probing, staged commitment, decisive commitment, or recovery in advance. Their appropriateness depends on the diagnostic profile, the protected functions, the available resource portfolio, the horizon, and the normative constraints governing action. The analytical contribution is narrower: responses can differ simultaneously in their immediate system effects, resource footprints, and effects on what remains feasible later.

4.1 Disturbance Response

Response-oriented governance begins from the relation between a disturbance and the evolving capacities available to answer it. A disturbance can be external, internally generated, institutionally mediated,

informational, or intentionally introduced as a probe. The relevant governance object is therefore a response process rather than the disturbance in isolation.

Let $\mathfrak{A}_t$ denote the coarse response repertoire represented as institutionally or conceptually available at time t . This repertoire is broader than the recovery-specific action set $\mathcal{A}_t$ used in Equation 5; recovery actions can be represented as a context-dependent subset of $\mathfrak{A}_t$. Explicit joint resource supportability is introduced in Section 6, so membership in $\mathfrak{A}_t$ should not yet be read as proof that all execution requirements can be assembled simultaneously. Let d_t denote the realized resource-allocation state, whose admissibility set is formalized in Section 6. The working governance configuration is collected in Equation 16.

$$\Xi_t = (\omega_t, \mathcal{B}_t, d_t, \mathfrak{A}_t). \quad (16)$$

In Equation 16, ω_t records the represented system configuration, $\mathcal{B}_t$ is the functional resource portfolio introduced in Section 1, d_t records its realized allocation, and $\mathfrak{A}_t$ records the coarse response repertoire admitted by the current modeling and institutional frame. The repertoire is model-relative. An action absent from $\mathfrak{A}_t$ can be physically possible yet institutionally excluded; an action present in $\mathfrak{A}_t$ can still fail the explicit joint supportability test developed later.

For a response $u \in \mathfrak{A}_t$, the joint update is represented in Equation 17.

$$\mathcal{U}_u^{\text{resp}} : \Xi_t \rightarrow \Xi_{t+1}^{(u)} = \left(\omega_{t+1}^{(u)}, \mathcal{B}_{t+1}^{(u)}, d_{t+1}^{(u)}, \mathfrak{A}_{t+1}^{(u)} \right). \quad (17)$$

Equation 17 makes four response effects visible at once. A response can change the represented system state, consume or reconfigure functional resources, change their realized allocation, and alter the set of responses that remain available later. A protective action can reduce immediate harm while depleting reserve capacity. A probe can increase diagnostic resolution while increasing future recovery demand. A decisive commitment can stabilize one pathway while making other interventions institutionally or materially unavailable. The framework therefore avoids identifying response quality with immediate state improvement alone.

The same action label can also produce different updates under different configurations. A temporary liquidity facility, a network isolation measure, or a bounded evacuation can have contrasting consequences depending on coupling structure, resource reserves, institutional authority, and timing. The paper consequently treats $\mathcal{U}_u^{\text{resp}}$ as configuration-dependent in application even when the action category u is described by a common name.

Definition 4.1 (Response footprint). For a declared recovery target V and horizon H , the response footprint of u at time t is the modeled tuple consisting of its resulting configuration, resulting functional resource portfolio, resulting allocation state, resulting response repertoire, and resulting recovery profile relative to V and H .

A schematic representation of Definition 4.1 is stated in Equation 18.

$$\text{Foot}_{t,H}(u; V) = \left(\omega_{t+1}^{(u)}, \mathcal{B}_{t+1}^{(u)}, d_{t+1}^{(u)}, \mathfrak{A}_{t+1}^{(u)}, \mathcal{R}_{t+1}^{(u)}(H; V) \right). \quad (18)$$

The recovery component $\mathcal{R}_{t+1}^{(u)}(H; V)$ in Equation 18 denotes the recovery profile recomputed from the post-response configuration and the recovery repertoire represented as available after u . The notation is intentionally schematic because the perturbation family and recovery action set can change after the response. The footprint is therefore a bookkeeping object, not a scalar cost function.

Definition 4.1 also clarifies the limited meaning of a “small” intervention. Small expenditure, short duration, low physical magnitude, or narrow administrative scope does not guarantee a small response footprint. A symbolically salient announcement can change expectations with little fiscal expenditure. A short-lived emergency measure can create durable legal or organizational dependencies. Conversely, a materially large intervention can be designed to expire automatically and leave substantial future response capacity intact. Response magnitude and commitment depth should therefore be analyzed separately.

Table 3 summarizes several response modes used throughout the paper. The table describes structural roles rather than policy recommendations.

Table 3 shows why response-oriented governance cannot be reduced to a continuum running from passivity to stronger intervention. Observation, buffering, probing, commitment, and recovery perform different functions. A governance architecture can combine them, shift among them, or assign them to different institutions and scales.

4.2 Bounded Intervention Footprints

A recurrent intuition in near-critical governance is that interventions should remain limited when the response regime is uncertain. The intuition becomes more precise when limitation is defined through the response footprint rather than through intervention magnitude alone. The relevant question is which future capacities an intervention consumes, encumbers, or leaves available.

For two responses $u, v \in \mathfrak{A}_t$, suppose their post-response repertoires are expressed in a common response vocabulary, or have first been mapped into an explicit common taxonomy. Define a comparative future-repertoire relation by Equation 19.

$$u \preceq_{\text{close},t} v \iff \mathfrak{A}_{t+1}^{(u)} \supseteq \mathfrak{A}_{t+1}^{(v)}. \quad (19)$$

Under Equation 19, $u \preceq_{\text{close},t} v$ means that, within the declared common response vocabulary, response u leaves at least the future response repertoire left by v . The relation is intentionally partial in practical use. Two responses can preserve different, non-nested sets of future actions and therefore remain incomparable. The relation also carries no normative verdict: preserving more options can be undesirable when rapid elimination of a harmful pathway is itself the justified objective.

Future repertoire is only one component of the footprint. Two responses can leave the same named actions technically available while differing sharply in whether those actions remain supportable by the remaining portfolio. A nominal recovery option is of limited practical significance when the personnel, liquidity, infrastructure, legitimacy, or time needed to execute it have already been depleted. The paper therefore treats repertoire preservation together with functional resource support rather than as a purely formal option count.

Let $\mathfrak{K}_{t,H}$ denote a declared set of footprint constraints relevant to the decision. The constraints can concern protected functions, maximum encumbrance of particular resource components, preservation of specified response branches, recovery compatibility, legal authorization, distributional limits, or other application-specific requirements. The bounded response set is defined in Equation 20.

$$\mathfrak{A}_t^{\text{bd}}(H; \mathfrak{K}_{t,H}) = \{u \in \mathfrak{A}_t : \text{Foot}_{t,H}(u; V) \in \mathfrak{K}_{t,H}\}. \quad (20)$$

Equation 20 gives “bounded intervention” a multidimensional meaning. The constraint set $\mathfrak{K}_{t,H}$ must be declared rather than hidden inside the adjective bounded. In one application the binding condition can be preservation of emergency provisioning. In another it can be legal revisability, containment of spillover, preservation of a recovery corridor, or a ceiling on reserve depletion. Different normative theories and institutional settings can specify different constraint sets.

Remark 4.2 (Magnitude and commitment depth). Intervention magnitude and commitment depth are analytically distinct. A low-magnitude action can produce deep closure when it changes expectations, legal status, network structure, or institutional dependence. A high-magnitude action can remain comparatively shallow in commitment when it is temporary, compartmentalized, and supported by credible exit and recovery paths.

Remark 4.2 replaces a vague preference for “low-force” intervention with a more discriminating question about the structure of the footprint. It also prevents a simple inference from restraint to justice. Some threats require rapid and concentrated response because delay imposes severe or irreversible harm. The framework therefore asks which dimensions of the footprint should be bounded under the actual decision conditions.

Table 3: Response modes and their possible effects on state, resources, and future response capacity.

Response mode	Immediate role	Typical portfolio demand	Possible future-repertoire effect
Observation and monitoring	Update diagnosis while limiting direct state change.	Observation, interpretation, communication, maintenance.	Can preserve broad response choice, while delay and monitoring costs can still reduce later capacity.
Buffering and protection	Reduce exposure or absorb disturbance without selecting a long-run regime.	Survival, reserve, logistics, temporary coordination.	Can preserve time for learning; prolonged buffering can consume reserves needed for commitment or recovery.
Bounded probe	Generate discriminating response information.	Probe capacity, monitoring, recovery reserve.	Can refine the diagnostic profile while creating new recovery obligations or closing fragile paths.
Staged commitment	Commit part of the response capacity and retain later checkpoints.	Commitment, monitoring, reserve, coordination.	Can keep contingent branches available if intermediate commitments remain revisable.
Decisive commitment	Concentrate capacity on a selected response pathway.	Commitment, coordination, possibly substantial survival resources.	Can meet binding thresholds rapidly while narrowing alternative pathways and increasing switching costs.
Recovery and repair	Restore or reconstruct protected functions after disturbance or failed response.	Recovery, reserve, institutional and relational capacity.	Can reopen future options, although some prior trajectories or resources may remain unavailable.

A second distinction concerns buffering. Buffering can reduce the system's exposure to a disturbance without selecting a long-run trajectory. It can therefore create time for learning while preserving later commitment capacity. The same buffering strategy can also become unsustainable when the protected state consumes reserves faster than diagnosis improves. Section 5 will develop this temporal constraint. At the present stage, the structural point is that buffering occupies a response category of its own: it modifies the disturbance–system relation while deferring some forms of trajectory selection.

Hypothesis 4.3 (Footprint-sensitive response selection). When candidate responses differ materially in their effects on future response repertoire, functional resource support, and recoverability, comparison of immediate state effects alone can omit decision-relevant consequences of intervention. Under such conditions, explicit response-footprint comparison may improve the transparency of governance reasoning.

Hypothesis 4.3 is deliberately procedural. It does not state that the response with the broadest future repertoire should be selected. It states that future-capacity effects can be relevant enough to warrant explicit representation when those effects differ materially across responses.

4.3 Staged Adaptive Steering

Staged adaptive steering uses intermediate commitments and observation checkpoints to condition later responses on information generated during the process. The architecture is relevant when one-shot commitment is difficult to justify under the current diagnostic profile, yet indefinite waiting would consume resources or permit avoidable harm. Staging therefore links observability, commitment, and dissipation rather than treating them as separate problems.

Let $t_0 < t_1 < \dots < t_n$ denote declared response checkpoints. At checkpoint t_k , let H_k denote the realized response and observation history up to that point. A staged response rule is represented in Equation 21.

$$u_k = \pi_k(H_k, \mathfrak{C}_{t_k}(H_k), \mathcal{B}_{t_k}, d_{t_k}, \mathfrak{A}_{t_k}), \quad u_k \in \mathfrak{A}_{t_k}. \quad (21)$$

Equation 21 makes later commitment conditional on realized history, the updated near-critical diagnostic profile, the remaining resource portfolio and its realized allocation, and the coarse response repertoire still represented at the checkpoint. The rule can be formalized probabilistically or algorithmically in a specific application, but the present paper uses it only as a structural representation.

The joint update from one checkpoint to the next is stated in Equation 22.

$$\Xi_{t_{k+1}} = \mathcal{U}_{u_k}^{\text{resp}}(\Xi_{t_k}), \quad k = 0, \dots, n-1. \quad (22)$$

Equation 22 shows why adaptive steering is not equivalent to repeatedly solving the same decision problem. Each response changes the state, the portfolio, and potentially the future repertoire. Later stages can therefore have more information and fewer resources, or more information and a more favorable response position, depending on what the earlier stages produced.

A useful checkpoint requires more than the passage of time. It should create a possibility of meaningful revision. If the response selected at t_k has already made all later alternatives unavailable, the nominal checkpoint supplies monitoring without adaptive choice. Conversely, maintaining a broad continuation set can be costly when survival resources are being depleted. The architecture therefore requires an explicit relation between learning value and the cost of keeping branches open.

For a staged plan, define the continuation repertoire after stage k as $\mathfrak{A}_{t_{k+1}}^{(u_k)}$. The plan exhibits checkpoint-contingent optionality at stage k when at least two materially distinct later responses remain represented as feasible and their relevance can depend on information available at t_{k+1} . This definition is qualitative because material distinction and feasibility depend on the application. A numerical branching count would be misleading when several nominal actions share one hidden bottleneck or perform the same practical function.

Staging also interacts with recovery. An intermediate action can be valuable because it protects a function, buys observation time, or keeps multiple recovery paths available. Another intermediate action can improve short-run conditions while consuming the reserve needed to correct an error at the next checkpoint. The response footprint in Equation 18 should therefore be recomputed after each stage rather than treated as fixed at the initial decision point.

Hypothesis 4.4 (Conditional value of staged response). When intermediate observations can materially update the diagnostic profile, intermediate actions preserve enough survival and recovery capacity for later revision, and checkpoint delay does not impose dominant losses, staged response can preserve contingent action capacity that a one-shot commitment would close earlier. These conditions need not hold when thresholds are immediate, learning is weak, or delay rapidly exhausts the relevant portfolio.

Hypothesis 4.4 identifies the conditions under which staging deserves consideration; it does not establish a universal preference for gradualism. Decisive commitment can be the more supportable architecture when a minimum response threshold must be crossed quickly, when the candidate regime family is already sufficiently discriminated, when fragmented commitment would fail, or when the cost of delay dominates the value of future learning.

Response-oriented governance therefore has a resource architecture even before Section 6 introduces explicit functional allocation. Responses alter the state being governed, draw on heterogeneous capacities, and reshape which actions remain supportable. Boundedness is consequently represented through declared footprint constraints rather than intervention magnitude alone, while adaptive steering is represented as a sequence of state- and portfolio-changing commitments with meaningful checkpoints. Section 5 turns to the temporal pressure on this architecture: the resources required to preserve observation, buffering, and future choice can themselves decay while governance waits.

5 Dissipative Constraints on Waiting

This section identifies the temporal constraint that turns optionality preservation into a resource problem. Its objective is to distinguish informationally useful delay from delay that erodes the capacities required for survival, commitment, or recovery. The discussion first represents waiting as an active continuation policy with a portfolio footprint, then develops functional survival provisioning over a sequence of checkpoints, and finally introduces commitment windows whose availability can change while diagnosis continues. The resulting framework treats delay neither as a neutral baseline nor as an intrinsic error: waiting can generate information, enable replenishment, and improve coordination, while also consuming resources and closing future responses.

5.1 Resource Depletion

Waiting in governance rarely means that nothing happens. Observation continues, personnel remain deployed, infrastructure requires maintenance, inventories are consumed, contracts expire, biological needs persist, and buffers must be financed. Some capacities can also regenerate: information accumulates, damaged infrastructure can be repaired, external assistance can arrive, and organizational learning can improve later response. A useful representation should therefore avoid assuming that every component of the portfolio declines monotonically with clock time.

Let $\chi_{t,\Delta}$ denote a continuation policy applied over the interval $[t, t + \Delta]$. The policy can include monitoring, buffering, maintenance, survival provisioning, replenishment, negotiation, and other activities that stop short of the focal commitment being deferred. Its joint effect is represented in Equation 23.

$$\mathcal{W}_{t,\Delta}^x : \Xi_t \rightarrow \Xi_{t+\Delta}^x = (\omega_{t+\Delta}^x, \mathcal{B}_{t+\Delta}^x, d_{t+\Delta}^x, \mathfrak{A}_{t+\Delta}^x). \quad (23)$$

Equation 23 treats delay as a state-, portfolio-, and repertoire-changing process. The map is partial because a proposed continuation policy can itself become infeasible before the interval ends. For example, a buffering policy can fail when the reserve supporting it is exhausted, or a monitoring architecture can lose access to the infrastructure on which its observations depend.

The heterogeneous portfolio in Equation 1 requires function-specific measures of availability. For each governance function f in a declared function family $\mathcal{F}$, let κ_f be an application-specific capability readout with codomain K_f . The family of readouts is collected in Equation 24.

$$\mathcal{K}_{\mathcal{F}}(\mathcal{B}_t, d_t) = (\kappa_f(\mathcal{B}_t; d_t))_{f \in \mathcal{F}}. \quad (24)$$

The codomains K_f in Equation 24 need not share a common scale. A capability readout can be quantitative, categorical, set-valued, or partially ordered. Its role is to state what counts as more or less support for a particular function without forcing observation capacity, food supply, legal authority, liquidity, trust, and repair capability into one additive unit.

Where a function-specific preorder $\succeq_f$ is justified, continuation over $[t, t + \Delta]$ is *functionally dissipative* for f when the later capability is strictly weaker under that preorder, as stated in Equation 25.

$$\kappa_f(\mathcal{B}_t; d_t) \succ_f \kappa_f(\mathcal{B}_{t+\Delta}^x; d_{t+\Delta}^x). \quad (25)$$

Equation 25 is deliberately local to one function. A continuation policy can be dissipative for survival reserves while improving observational capability, or dissipative for fiscal flexibility while increasing organizational knowledge. The term *dissipative delay* in this paper therefore refers to delay whose continuation policy degrades one or more declared functionally relevant capabilities over the decision horizon. It does not imply that every effect of waiting is negative.

Definition 5.1 (Functional dissipation during delay). A continuation interval exhibits functional dissipation relative to a declared function family when the associated continuation policy produces a strict deterioration in at least one functionally relevant capability under its stated comparison relation. This condition operationalizes one channel of dissipative delay from Definition 1.4; it is model- and function-relative and permits simultaneous gains in other capabilities.

Definition 5.1 clarifies why optionality cannot be identified with postponement. A government can defer commitment while consuming the reserve that made later commitment possible. It can also improve diagnosis while losing a time-sensitive legal, logistical, or physical intervention window. Conversely, delay can be constructive when replenishment, learning, coalition formation, or repair expands later capability faster than holding costs consume it.

The effect on future action can be described without assigning a scalar value to the repertoire. Suppose that the same response labels can be meaningfully compared across the two checkpoints. The responses lost and gained under continuation policy χ are defined in Equation 26.

$$\begin{aligned}\mathfrak{L}_{t,\Delta}^\chi &= \mathfrak{A}_t \setminus \mathfrak{A}_{t+\Delta}^\chi, \\ \mathfrak{G}_{t,\Delta}^\chi &= \mathfrak{A}_{t+\Delta}^\chi \setminus \mathfrak{A}_t.\end{aligned}\tag{26}$$

Equation 26 preserves both directions of change. Waiting can close actions through depletion, missed timing, or institutional drift and can open actions through new information, replenishment, coordination, or technological adaptation. The representation is inappropriate when response identities change so substantially that cross-time comparison is meaningless; in that case the repertoire should first be mapped into a stable functional classification.

Figure 1 illustrates the central tension schematically. The figure is not a monotonic law. It depicts one possible case in which diagnostic resolution improves while survival or recovery capacity declines and the set of supportable response branches narrows.

The important analytical object is therefore the joint trajectory rather than the direction of any single component. A continuation policy that produces excellent information after exhausting the capacity needed to act on it can fail differently from a policy that preserves resources while generating no useful discrimination among candidate regimes. Section 6 will use this point to motivate explicit functional distribution rather than a generic instruction to “hold reserves.”

5.2 Survival Provisioning

Dissipative delay becomes consequential when essential capabilities must be maintained while diagnosis remains incomplete. Functional survival, as defined in Section 1, requires persistence of a selected capability set rather than preservation of the initial state. This subsection represents the provisioning burden required to keep those capabilities available across a sequence of decision checkpoints.

Let $\mathcal{F}^* \subseteq \mathcal{F}$ denote the functions designated as essential for a declared horizon. For each $f \in \mathcal{F}^*$, let $K_f^* \subseteq K_f$ denote the set of capability states regarded as sufficient for that function. The selection of $\mathcal{F}^*$ and K_f^* is not supplied by dynamics alone; it can depend on legal duties, biological needs, institutional mandates, distributive judgments, and the identity of the population whose survival is being evaluated.

A joint configuration is survival-supporting relative to the declared function set when Equation 27 holds.

$$\text{Supp}_{\mathcal{F}^*}(\Xi_t) = 1 \iff \kappa_f(\mathcal{B}_t; d_t) \in K_f^* \text{ for every } f \in \mathcal{F}^*.\tag{27}$$

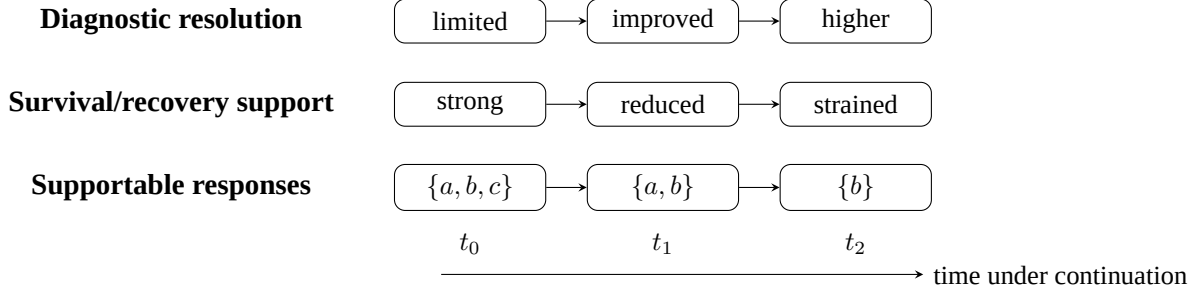


Figure 1: Stylized coexistence of informational gain, capability dissipation, and repertoire narrowing during continued delay. The pattern is illustrative rather than universal: replenishment or learning can also expand later capacity and response options.

Equation 27 is a sufficiency test, not a welfare function. It does not rank two survival-supporting configurations and does not imply that every threshold is equally important. In empirical work the sufficiency sets can also be time-, group-, or state-dependent.

Consider checkpoints $t_0 < t_1 < \dots < t_n$ and a continuation history $H_{0:n}^x$ generated by provisioning, observation, buffering, and other continuation actions. The history belongs to the functional survival corridor when the sufficiency condition is maintained at every declared checkpoint, as defined in Equation 28.

$$\mathfrak{H}_{\mathcal{F}^*}^{\text{surv}} = \{H_{0:n}^x : \text{Supp}_{\mathcal{F}^*}(\Xi_{t_k}^x) = 1 \text{ for } k = 0, \dots, n\}. \quad (28)$$

The corridor in Equation 28 makes explicit that survival is temporally demanding. It is insufficient for essential capabilities to be available at the beginning and end of the horizon if they collapse at an intermediate point whose consequences cannot be repaired. The checkpoint resolution should therefore match the persistence and failure timescales of the functions being protected.

Survival provisioning can draw on several portfolio components. Dedicated survival capacity can be consumed directly; reserve capacity can be converted into provisioning; commitment resources can be used to secure external supply; and recovery resources can be sacrificed to stabilize the present. These substitutions can be justified under urgent conditions, but they create intertemporal consequences. Maintaining the survival corridor today can narrow the recovery corridor tomorrow.

Table 4 summarizes representative dissipation channels. The entries are analytical examples rather than an exhaustive taxonomy.

The final row of Table 4 is intentionally constructive. A delay interval can improve later capability rather than merely deplete it. The relevant question is whether the continuation policy maintains the survival corridor while producing informational, organizational, or material gains that remain usable at the later decision point.

A further complication is distribution. Aggregate survival capacity can remain adequate while a subgroup, location, institution, or essential service falls below its sufficiency set. Functional survival should therefore be indexed to the relevant bearer when the application contains heterogeneous exposure. The present paper leaves that indexing abstract because the appropriate units differ across domains, but later case analysis should state explicitly whose survival capability is being maintained and whose resources finance the continuation policy.

Hypothesis 5.2 (Survival–optionality coupling). When the capacities used to maintain essential functions overlap materially with the capacities required for later commitment or recovery, prolonged survival provisioning can reduce future optionality even while it successfully prevents immediate functional failure. The strength and direction of this coupling depend on substitution, replenishment, and the independence of resource pathways.

Hypothesis 5.2 prevents a false separation between “keeping the system alive” and “preserving future choice.” In some settings the same reserve performs both tasks. In others, institutional design can

Table 4: Illustrative channels through which continued delay can change functional governance capacity.

Channel	Mechanism during continuation	Function potentially weakened	Possible countervailing process
Consumable stocks	Inventories, liquidity, energy, or emergency supplies are used to maintain current operations.	Survival, reserve, later recovery	Replenishment, substitution, external supply
Maintenance burden	Infrastructure, monitoring systems, and organizational routines require continuing upkeep.	Observation, survival, commitment	Repair, automation, load reduction
Human and organizational fatigue	Attention, staffing, coordination, and decision capacity degrade under prolonged strain.	Observation, commitment, recovery	Rotation, reinforcement, simplification
Time-sensitive windows	Legal, logistical, seasonal, technological, or physical opportunities expire.	Commitment, recovery	Early option reservation, alternative pathways
Relational and institutional erosion	Trust, authorization, coalition support, or compliance capacity can weaken while action is deferred.	Commitment, reserve, recovery	Communication, participation, negotiated renewal
Learning and coordination	Observation and interaction can improve discrimination, shared models, or cooperative capacity.	Can strengthen observation and later commitment	Active monitoring, bounded probes, coalition building

partially separate them. Section 7 will later examine why independent pathways and hidden common dependencies matter for that separation.

5.3 Commitment under Delay Costs

The final temporal problem concerns the availability of commitment itself. A response that is feasible now can become infeasible after a period of continued observation or buffering because the required resources have been consumed, a physical or legal window has closed, or the system has moved into another regime. Another response can become feasible only later because new information, replenishment, or coordination has arrived. The timing problem is therefore better represented by response-specific commitment windows than by a universal rule favoring either immediate action or delay.

Let $\mathbb{T} = \{t_0, t_1, \dots, t_n\}$ be the declared decision checkpoints generated under continuation policy χ . For a response u whose identity remains meaningful across these checkpoints, define its constraint-compatible commitment set in Equation 29.

$$\mathcal{T}_u^\chi(H) = \left\{ t_k \in \mathbb{T} : u \in \mathfrak{A}_{t_k}^{\text{bd}}(H; \mathfrak{R}_{t_k, H}) \right\}. \quad (29)$$

Equation 29 records the checkpoints at which response u remains feasible under the declared footprint constraints. The set need not be a contiguous time interval. A response can become temporarily infeasible and later reopen after replenishment or institutional change. The phrase *commitment window* therefore refers to the set of supportable checkpoints rather than to an assumed single deadline.

When the commitment set is ordered and has a last element, that element can be interpreted as a latest represented checkpoint for the response under the current continuation policy. Such a checkpoint is model-relative. It can shift when the diagnostic model, replenishment assumptions, legal conditions, or footprint constraints change. The framework consequently avoids presenting a modeled deadline as an objective property of the world.

Delay can also alter the intensity of the later response required to protect the same essential function. A small early repair can sometimes prevent a larger later reconstruction; in other cases premature intervention can lock the system into an inferior trajectory that later becomes expensive to reverse. The current framework does not assume either pattern. It requires the response footprint to be recomputed at later checkpoints because the state, portfolio, and future repertoire have changed.

A continuation policy becomes especially consequential when the information gained by waiting and the action capacity lost through waiting move in opposite directions. To state this without collapsing them into one utility measure, let $\mathcal{P}_t$ denote the relevant observational partition from Section 3, and let $\mathfrak{A}_t^{\text{bd}}$ denote the current footprint-compatible response set. A continuation can simultaneously refine $\mathcal{P}_t$ and shrink $\mathfrak{A}_t^{\text{bd}}$. The decision problem then concerns whether the remaining distinctions can still be acted upon by the time they are learned.

Hypothesis 5.3 (Diagnostic gain and commitment erosion). When continued observation materially improves discrimination among candidate regimes while the same continuation policy depletes capacities or closes timing windows required by regime-contingent responses, diagnostic confidence and practical responsiveness can diverge. Under such conditions, waiting can produce better knowledge of a decision whose feasible action set has become narrower.

Hypothesis 5.3 is one of the reasons Paper IV treats observation resources and reserve or recovery resources jointly. Increasing information has limited governance value when no materially relevant response remains supportable after the information arrives. The converse is also important: preserving resources without generating the information needed to discriminate their use can leave capacity idle until a forced commitment occurs.

The temporal architecture can now be summarized without selecting a universal optimum. Continued delay is supportable when its continuation policy preserves the required survival corridor, leaves adequate later commitment and recovery pathways, and generates informational, material, or coordination gains that justify the resources consumed under the applicable decision criteria. Earlier commitment becomes more pressing when waiting causes essential functions to approach their sufficiency boundary, commitment windows close, or the reserve needed for later recovery is being consumed faster than useful uncertainty is resolved. These conditions can coexist and change over time.

The section therefore replaces the intuition that “more optionality means more waiting” with a stricter proposition about supported options. Optionality exists only when future responses remain materially executable. Preserving that executability can require current provisioning, maintenance, reservation of capacity, or timely commitment. Section 6 develops the direct consequence: governance resources should be analyzed according to the future functions they support and the conversions or conflicts among those functions, rather than treated as an undifferentiated stock available to a later decision maker.

6 Functional Distribution of Resources

This section develops the resource architecture at the center of the paper. Its objective is to represent how heterogeneous capacities can support several governance functions at once, while remaining subject to rivalry, institutional constraints, conversion delay, and function-specific sufficiency requirements.

The discussion first refines the functional portfolio into feasible allocation states and action-specific support requirements, then examines interaction between survival provisioning and commitment, and finally distinguishes held reserve from the broader resource-architecture response coverage that can also arise through conversion, replenishment, maintenance, or institutional change. The formalism remains deliberately non-scalar: it identifies joint supportability, reassignment, and conversion without presuming a common unit of value across money, personnel, authority, information, infrastructure, time, or relational capacity.

6.1 Observation and Probe Resources

The functional portfolio introduced in Equation 1 records which broad roles governance capacity can serve. That representation suppresses a further question that becomes important once functions compete: which concrete resource carriers can serve which functions under the current technical and institutional configuration. A data-access agreement can support observation while remaining useless for emergency provisioning; trained personnel can support observation, coordination, or recovery but may be unable to perform those functions simultaneously; fiscal capacity can sometimes be reassigned across several purposes but only after authorization, procurement, or logistical delay.

For allocation analysis, let $\mathcal{R}_t$ denote a declared family of identifiable resource carriers at time t . A carrier can be divisible or composite as long as its deployment constraints are represented consistently at the chosen level of analysis. Its potential functional roles are summarized by the support correspondence in Equation 30.

$$\Sigma_t : \mathcal{R}_t \longrightarrow 2^{\mathcal{F}}, \quad \Sigma_t(r) = \{f \in \mathcal{F} : r \text{ can support } f \text{ under the current configuration}\}. \quad (30)$$

Equation 30 represents functional eligibility rather than actual deployment. Eligibility can depend on law, skill, technical compatibility, timing, location, contractual restrictions, or other institutional conditions. Two nominally identical assets can therefore have different support sets. The correspondence also permits overlap: one carrier can support several functions, even when those functions cannot be supplied concurrently.

Actual deployment is represented by a feasible allocation state d . Let $\mathfrak{D}_t(\mathcal{B}_t)$ denote the set of allocation states compatible with the portfolio, support correspondence, and current concurrency or exclusivity constraints. The function-specific capability readouts introduced in Section 5 are refined in Equation 31.

$$\begin{aligned} \mathfrak{Q}_t &= \{(\mathcal{B}, d) : d \in \mathfrak{D}_t(\mathcal{B})\}, \\ \kappa_f : \mathfrak{Q}_t &\longrightarrow K_f. \end{aligned} \quad (31)$$

Equation 31 makes capability a function of a feasible portfolio–allocation pair rather than of a portfolio in isolation. The realized pair $(\mathcal{B}_t, d_t)$ was already carried by the governance state in Section 4. No common numerical scale across the codomains K_f is assumed.

A set of functions can now be tested for simultaneous supportability. For a declared function family $J \subseteq \mathcal{F}$, let $K_f^* \subseteq K_f$ denote the relevant sufficiency set for each $f \in J$. The jointly sufficient allocation set is defined in Equation 32.

$$\mathfrak{D}_t^*(J) = \{d \in \mathfrak{D}_t(\mathcal{B}_t) : \kappa_f(\mathcal{B}_t; d) \in K_f^* \text{ for every } f \in J\}. \quad (32)$$

A nonempty set in Equation 32 means that the declared functions can be supported simultaneously under at least one current allocation. Emptiness identifies a functional allocation conflict relative to the chosen thresholds and portfolio. The conflict is conditional on the representation: changing the time horizon, the resource carriers, the sufficiency sets, or the admissible allocation rules can change the result.

Observation and probing illustrate why this distinction matters. Passive observation can require access, sensing, analytical, interpretive, and communication capacity. Active probing can require those

capacities plus operational authority, implementation resources, containment capacity, and enough recovery support to manage an adverse response. A portfolio can therefore contain substantial observational capability while lacking the resources required for a diagnostically useful probe, or contain ample operational capacity while lacking the observation architecture needed to learn from the probe.

For a response or probe u , let $\mathcal{F}_u \subseteq \mathcal{F}$ denote the functions required for execution and let $K_{f,u}^{\text{req}} \subseteq K_f$ denote the acceptable capability region for each required function. The support set for u is defined in Equation 33.

$$\begin{aligned} \mathfrak{D}_t^{\text{supp}}(u; \mathcal{B}) &= \left\{ d \in \mathfrak{D}_t(\mathcal{B}) : \kappa_f(\mathcal{B}; d) \in K_{f,u}^{\text{req}} \text{ for every } f \in \mathcal{F}_u \right\}, \\ \mathfrak{D}_t^{\text{supp}}(u) &:= \mathfrak{D}_t^{\text{supp}}(u; \mathcal{B}_t). \end{aligned} \quad (33)$$

A response is functionally supportable at t only when the current-portfolio set in Equation 33 is nonempty. When the same notation is evaluated at a reachable future portfolio, the relevant future feasibility rules and time index are used; the time index can be suppressed when it is carried by the reachable portfolio-allocation state. This condition is narrower than normative admissibility and broader than possession of a single enabling asset. It states that the declared functional requirements can be jointly assembled under at least one feasible allocation.

Figure 2 summarizes the main structural distinction introduced in this section. Concrete carriers first determine which feasible allocations can be assembled. Those allocations generate function-specific capabilities, and only some capability configurations jointly support a declared response. Response coverage then depends not only on what is held immediately, but also on which resource operations can create later support within the relevant horizon.

Proposition 6.1 (Non-compensability under a declared requirement profile). *Let u be a response with required function family $\mathcal{F}_u$. If there exists $f \in \mathcal{F}_u$ such that no feasible allocation places $\kappa_f(\mathcal{B}_t; d)$ in $K_{f,u}^{\text{req}}$, then $\mathfrak{D}_t^{\text{supp}}(u) = \emptyset$, irrespective of capability levels in functions outside that unmet requirement.*

Proof. Every $d \in \mathfrak{D}_t^{\text{supp}}(u)$ must satisfy the requirement for each $f \in \mathcal{F}_u$ by Equation 33. If the requirement for one such f is unattainable under every feasible allocation, no element can satisfy all required conditions simultaneously. $\square$

Proposition 6.1 is an internal result of the requirement representation, not an empirical claim that every governance function is non-substitutable. It clarifies the condition under which aggregate abundance fails to compensate for a functional bottleneck: the missing function has been specified as a genuine requirement for the response under consideration.

6.2 Survival and Commitment Resources

Survival provisioning and selective commitment frequently draw on overlapping carriers. Personnel, fiscal capacity, transport, authority, communication channels, and political attention can maintain essential functions while also supporting interventions that reshape the trajectory. Allocation therefore creates an intertemporal problem even before resource depletion is considered: the same portfolio can support several functions individually while failing to support them jointly at a particular checkpoint.

Let $J_1, J_2 \subseteq \mathcal{F}$ denote two declared function families with their associated sufficiency sets. The paper uses *contemporaneous functional conflict* for the structure stated in Equation 34.

$$\mathfrak{D}_t^*(J_1) \neq \emptyset, \quad \mathfrak{D}_t^*(J_2) \neq \emptyset, \quad \mathfrak{D}_t^*(J_1 \cup J_2) = \emptyset. \quad (34)$$

Equation 34 describes a portfolio that can support either requirement family separately but cannot meet both simultaneously under the current allocation rules. The structure can arise from scarce shared carriers, exclusivity constraints, timing, authorization, or other institutional restrictions. It does not establish which function should receive priority.

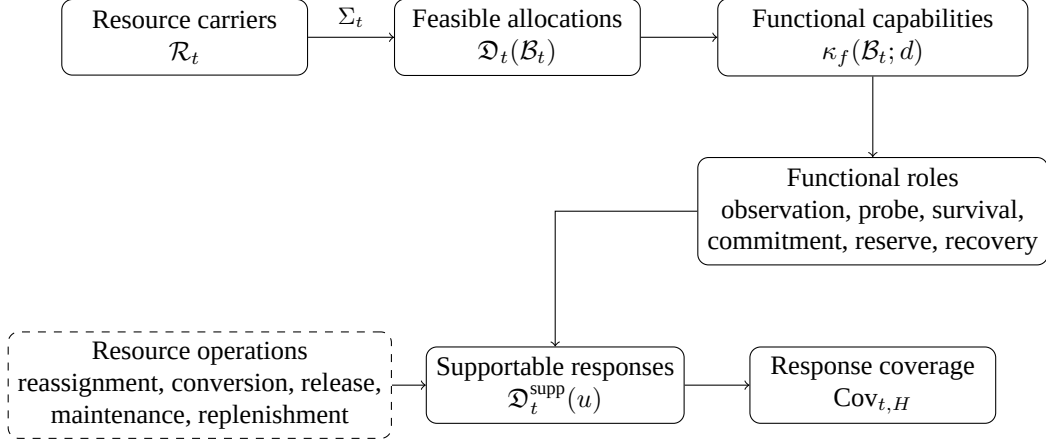


Figure 2: Illustrative resource-architecture pipeline from carriers to supportable responses. The figure emphasizes that supportability is not a property of aggregate stock alone: it depends on feasible allocation, function-specific capability, and the resource operations through which future coverage is created.

The distinction between reassignment and conversion is important in this setting. *Reassignment* changes the deployment of existing carriers while leaving the represented portfolio materially intact. *Conversion* changes the portfolio or the usable form of its capacities. Reassignment can include moving trained personnel from monitoring to emergency coordination. Conversion can include transforming financial reserve into physical supply, changing legal authority through an emergency authorization process, or adapting infrastructure for a new use. Conversion can require time, complementary resources, and irreversible sacrifice of the source function.

A generic conversion from support for function f toward support for function g is represented by the partial map in Equation 35.

$$\Gamma_{f \rightsquigarrow g}^\tau : \mathcal{B}_t \rightharpoonup \mathcal{B}_{t+\tau}^{(f \rightsquigarrow g)}. \quad (35)$$

Equation 35 includes a conversion time τ because a nominally convertible capacity can be useless for a time-sensitive response when the conversion cannot be completed before the relevant commitment window closes. The map is partial because technical, legal, logistical, or relational conditions can make conversion unavailable. It also avoids an implicit exchange-rate assumption: the notation states that a transformation exists, not that units of f and g possess a stable scalar equivalence.

The capability effects of conversion can extend beyond the two named functions. A conversion that increases survival provisioning can reduce reserve, observation, or recovery capability; a conversion that creates commitment capacity can generate future maintenance obligations; a conversion that repurposes recovery infrastructure for immediate survival can protect the present while weakening later reconstruction. These cross-functional effects should therefore be evaluated through the post-conversion portfolio rather than inferred from the label $f \rightsquigarrow g$ alone.

The survival corridor in Section 5 supplies one constraint on commitment. A response can be functionally supportable before execution and still undermine subsequent survival if its portfolio footprint removes capacities needed at later checkpoints. Conversely, a response that initially draws heavily on resources can improve survival by reopening supply, reducing exposure, or shortening the period over which emergency provisioning is required. The current section therefore distinguishes *pre-execution joint supportability* from *post-response functional viability*. Equation 33 addresses the first; the response footprint in Section 4 and the survival corridor address the second.

Hypothesis 6.2 (Allocation-conflict intensification under short commitment windows). When a time-sensitive response and essential survival provisioning depend on overlapping carriers whose reassignment or conversion requires non-negligible time, contraction of the response’s commitment window can

increase the practical severity of an existing functional allocation conflict. The direction and magnitude of the effect depend on the conversion architecture and cannot be inferred from resource quantity alone.

Hypothesis 6.2 is intentionally conditional. A shorter window can be irrelevant when dedicated capacities already support both functions, and rapid replenishment can relax the conflict. The hypothesis identifies a mechanism through which timing and functional composition interact: the same stock of resources can support a response under one conversion horizon and fail under another.

6.3 Reserve and Recovery Resources

Reserve capacity is often described as what remains unused. That description is insufficient for the present framework because an idle asset can be unavailable when needed, technically incompatible with the future task, legally encumbered, too slow to convert, or dependent on a bottleneck that fails during the transition. This paper therefore separates *held reserve*—currently uncommitted or releasable capacity preserved for future use—from the broader concept of *resource-architecture response coverage*, which can also depend on future replenishment, conversion, maintenance, or institutional change. The distinction prevents expected future inflows from being counted as though they were already held in reserve.

Let $(\mathcal{B}_t, d_t)$ denote the current portfolio-allocation state and let $\mathcal{Q}_t^{\mathcal{B}}$ denote the declared family of admissible resource-architecture operations. For a horizon H , write $(\mathcal{B}_t, d_t) \xrightarrow[\leq H]{\mathcal{Q}_t^{\mathcal{B}}} (\mathcal{B}', d')$ when the latter portfolio-allocation state can be reached within H through a path composed only of operations admitted by $\mathcal{Q}_t^{\mathcal{B}}$. These operations can include reassignment, conversion, replenishment, maintenance, release of previously committed capacity, and other portfolio changes represented in the application. The reachable resource architecture is stated in Equation 36.

$$\mathfrak{C}_{t,H}^{\mathcal{B}}(\mathcal{B}_t, d_t; \mathcal{Q}_t^{\mathcal{B}}) = \left\{ (\mathcal{B}', d') : (\mathcal{B}_t, d_t) \xrightarrow[\leq H]{\mathcal{Q}_t^{\mathcal{B}}} (\mathcal{B}', d') \right\}. \quad (36)$$

Equation 36 is model-relative. Its content depends on which conversion, replenishment, and institutional-change operations are admitted and on the time needed to execute them. It can therefore contract when a legal window closes or expand when new supply, authority, or coordination becomes available. Any empirical claim about coverage should state this operation repertoire rather than treating reachability as unconstrained.

For a declared family of possible future responses $\mathcal{U}$, resource-architecture response coverage is defined in Equation 37.

$$\text{Cov}_{t,H}(\mathcal{B}_t, d_t; \mathcal{U}, \mathcal{Q}_t^{\mathcal{B}}) = \{u \in \mathcal{U} : \exists (\mathcal{B}', d') \in \mathfrak{C}_{t,H}^{\mathcal{B}}(\mathcal{B}_t, d_t; \mathcal{Q}_t^{\mathcal{B}}) \text{ with } d' \in \mathcal{D}^{\text{supp}}(u; \mathcal{B}')\}. \quad (37)$$

In Equation 37, $\mathcal{D}^{\text{supp}}(u; \mathcal{B}')$ denotes the support set from Equation 33 evaluated at the future portfolio $\mathcal{B}'$. Coverage is therefore response-relative, horizon-relative, and operation-repertoire-relative. Held reserve can be one source of that coverage, but replenishment or institutional change can create coverage that was not present as reserve at time t . The next section will ask whether covered responses also rely on genuinely diverse pathways; coverage alone does not establish independence of failure modes.

Recovery resources are a special application of the same architecture. Let $\mathcal{U}_{\text{recover}}(V, H)$ denote the family of responses that can contribute to restoration of the declared functional target V within horizon H . The associated recovery coverage is defined in Equation 38.

$$\text{RecCov}_{t,H}(\mathcal{B}_t, d_t; V, \mathcal{Q}_t^{\mathcal{B}}) = \text{Cov}_{t,H}(\mathcal{B}_t, d_t; \mathcal{U}_{\text{recover}}(V, H), \mathcal{Q}_t^{\mathcal{B}}). \quad (38)$$

Equation 38 separates recovery capacity from exact reversal. The covered response family can include repair, reconstruction, substitution, institutional adaptation, relocation, or transition into another viable configuration, depending on the declared application. A portfolio can therefore possess low exact-reversal capacity while retaining substantial functional recovery coverage.

Table 5 summarizes the six resource functions used throughout the paper and the allocation question associated with each one. The table should be read as a functional diagnostic rather than a universal list of physical resource classes.

The formal distinction among these functions does not imply that governance should maximize each one independently. Requirements can conflict, conversion can be costly, and preserving reserve can impose present burdens. A portfolio with high observation and reserve capacity can still be unacceptable when survival needs are urgent; a portfolio concentrated on immediate survival can be appropriate under severe threat even when it reduces later recovery coverage. The framework identifies these tradeoffs so that the applicable empirical and normative criteria can evaluate them explicitly.

Hypothesis 6.3 (Functional composition and response coverage). For two portfolios with similar declared aggregate or coarse resource descriptions, differences in functional eligibility, allocation constraints, conversion time, and response-specific requirements can generate materially different resource-architecture and recovery coverage. The hypothesis is strongest in settings where several required functions are only partially substitutable and relevant commitment windows are finite.

Hypothesis 6.3 states the central analytical claim of this section in a testable form. It does not imply that functional diversification is always superior or that a universal optimal portfolio exists. The next section turns from allocation feasibility to architecture: whether the pathways that support several future responses are functionally diverse, redundant in useful ways, and sufficiently independent to survive correlated failure.

Table 5: Functional resource roles and associated allocation questions.

Function	Allocation question	Characteristic insufficiency in the present framework
Observation	Can relevant state or regime differences be detected and interpreted over the decision horizon?	Decisions proceed with inadequate discrimination among materially different response conditions.
Probe	Can bounded diagnostic perturbations be executed, observed, and contained?	Potentially informative experiments are unavailable or generate observations that cannot be safely interpreted.
Survival	Can declared essential functions remain above their sufficiency sets through the required checkpoints?	Immediate viability fails before later information or response capacity becomes usable.
Commitment	Can time-sensitive trajectory-shaping actions be assembled and executed before their windows close?	A response remains conceptually available but cannot be operationalized when required.
Reserve	Which currently held, uncommitted, or releasable capacities remain usable for materially relevant future responses?	Nominally unused resources can be inaccessible, incompatible, or too slow to deploy when needed.
Recovery	Can viable functions be restored, reconstructed, or substituted after disturbance or regime change?	Present stabilization consumes the capacities needed to construct a viable post-disturbance path.

7 Distributed Optionality and Resilience

This section turns from the feasibility of resource allocation to the architecture of future response. Its objective is to distinguish the existence of several supportable responses from the stronger condition that those responses remain available through materially different pathways and do not collapse under the same failure. The discussion first represents response-support pathways and their functional architectures, then separates redundancy from diversity, develops failure-conditioned response coverage, and finally identifies hidden common dependencies that can make apparently distributed capacity structurally concentrated. The section uses resilience in a limited sense consistent with the earlier literature: persistence, reorganization, and continued functional viability can matter even when exact return to a previous state is unavailable [1, 3]. Distributed optionality is treated as one possible architectural contributor to such resilience, not as a sufficient or universally desirable condition.

7.1 Functional Diversity in Response Support

Resource-architecture response coverage in Equation 37 identifies which future responses can be supported within a declared horizon through feasible changes in the resource architecture. That object does not record how support is assembled. Two covered responses can depend on the same resource carriers, the same conversion chain, the same institutional authorization, and the same logistical route. Conversely, one response can be supportable through several genuinely different arrangements. The present subsection therefore represents the pathways through which response support is realized.

For a response $u \in \mathcal{U}$, a *support pathway* is a finite sequence of admissible resource-architecture operations that begins from the current portfolio-allocation state and terminates in an allocation capable of supporting u . The family of such pathways within horizon H is defined in Equation 39.

$$\mathcal{P}_{t,H}(u; \mathcal{B}_t, d_t, \mathcal{Q}_t^{\mathcal{B}}) = \left\{ p : (\mathcal{B}_t, d_t) \xrightarrow{p} (\mathcal{B}', d'), d' \in \mathcal{D}^{\text{supp}}(u; \mathcal{B}'), \text{dur}(p) \leq H \right\}. \quad (39)$$

The notation $(\mathcal{B}_t, d_t) \xrightarrow{p} (\mathcal{B}', d')$ in Equation 39 means that p is composed only of operations in the declared repertoire $\mathcal{Q}_t^{\mathcal{B}}$, including any reassignment, conversion, replenishment, maintenance, release, or other resource operations admitted by the application. A path of zero resource operations is

permitted when u is already supportable under the current architecture. Equation 39 therefore refines coverage rather than changing its meaning: u belongs to the resource-architecture response coverage of Equation 37 exactly when at least one corresponding support pathway exists under the same declared resource operations and horizon.

The word *different* requires further discipline. Two paths can contain different operational steps while remaining functionally equivalent for the question under study. The paper therefore uses an application-defined architecture-signature map in Equation 40.

$$\text{Arch}_t : \bigcup_{u \in \mathcal{U}} \mathcal{P}_{t,H}(u; \mathcal{B}_t, d_t, \mathcal{Q}_t^{\mathcal{B}}) \longrightarrow \mathcal{X}_t. \quad (40)$$

The codomain $\mathcal{X}_t$ can record the distinctions relevant to the application, such as carrier classes, functional assignments, conversion chains, institutional routes, geographic channels, technologies, or response mechanisms. Equation 40 deliberately leaves the signature non-scalar. Its role is to prevent a purely syntactic difference between two operational sequences from being mistaken for meaningful functional diversity.

A family of pathways P is *architecture-diverse relative to* Arch_t when it contains at least two paths with different architecture signatures. The condition is weak by design. Diversity can improve the chance that different resources or mechanisms remain usable under changing conditions, but it does not establish that the pathways fail independently. Two architecturally different routes can still rely on the same communication backbone, payment rail, legal authority, fuel supply, cloud provider, transport hub, or trusted intermediary.

Functional diversity is therefore treated as a descriptive property of support architecture rather than a good to be maximized. Standardization can reduce coordination costs, dedicated infrastructure can outperform diversified substitutes, and emergency response can require concentration on a single effective mechanism. The analytical question is whether the degree and kind of diversity match the failures and transition conditions that the governance architecture is intended to survive.

7.2 Redundant Support Pathways

Redundancy concerns multiplicity of support pathways for a declared response or functional target. It differs from functional diversity because two redundant paths can have identical architecture signatures, while two architecture-diverse paths can support different responses rather than substitute for one another.

For a response u , an *architecture-distinct redundant family* is a subset $P_u \subseteq \mathcal{P}_{t,H}(u; \mathcal{B}_t, d_t, \mathcal{Q}_t^{\mathcal{B}})$ whose members have pairwise distinct architecture signatures. The condition is stated in Equation 41.

$$p, q \in P_u, \quad p \neq q \implies \text{Arch}_t(p) \neq \text{Arch}_t(q). \quad (41)$$

Equation 41 does not assign a scalar redundancy score. It supplies a test for whether several pathways represent distinct support architectures under the declared coding. A more refined application can place a similarity relation or distance on $\mathcal{X}_t$, but no such structure is required here.

Path redundancy can serve at least three different functions. First, several paths can provide continuity when one route becomes unavailable. Second, they can permit substitution across time when conversion windows differ. Third, they can support learning: observing which route remains viable can reveal information about the failure structure itself. These functions need not coincide. A route that is diagnostically informative can be too slow for survival provisioning, while a fast substitute can preserve immediate function without providing meaningful information about the underlying disturbance.

Redundancy also has costs. Maintaining several suppliers, legal authorizations, trained teams, physical routes, data systems, or recovery facilities can consume resources during periods in which only one route is used. The functional-distribution framework therefore does not infer that more redundant paths are always preferable. Their value depends on the failure environment, maintenance burden, conversion delay, and the consequences of losing the protected function.

The distinction between response redundancy and target redundancy is also useful. Several pathways can support the same response u , while a broader protected target V can be maintained through several substantively different responses $u_1, u_2, \dots$. The latter form is closer to optionality because the system retains more than one way to pursue a functional objective. Section 7 therefore treats response multiplicity and pathway multiplicity as separate layers of the architecture.

7.3 Failure-Mode Separation

Architecture diversity and redundancy remain incomplete descriptions until their dependency structure is specified. The same hidden dependency can disable several paths simultaneously. This subsection introduces a failure-relative representation that does not require probabilistic independence.

Let $\mathcal{Z}_t$ denote the declared family of critical dependency nodes at time t . A node can represent a physical facility, institutional authority, communication channel, supplier class, legal permission, information service, transport corridor, coordination body, or another condition whose loss can disable a support pathway. Each pathway has a dependency signature defined in Equation 42.

$$\text{Dep}_t : \bigcup_{u \in \mathcal{U}} \mathcal{P}_{t,H}(u; \mathcal{B}_t, d_t, \mathcal{Q}_t^{\mathcal{B}}) \longrightarrow 2^{\mathcal{Z}_t}. \quad (42)$$

Let $\mathcal{M}_t$ denote a declared family of failure modes. For each $m \in \mathcal{M}_t$, the disruption map $\Lambda_t(m) \subseteq \mathcal{Z}_t$ records the dependency nodes disabled or rendered unusable by that mode. A pathway remains viable under m when Equation 43 holds.

$$\text{Dep}_t(p) \cap \Lambda_t(m) = \emptyset. \quad (43)$$

Equation 43 is intentionally structural rather than probabilistic. It does not claim that failures are statistically independent, nor does it require probabilities to be known. It asks the narrower question of whether the represented pathway relies on a dependency disabled by the represented failure mode. The condition captures failures through declared dependency disablement only; applications in which a failure changes conversion time, capability thresholds, or the feasibility of resource operations should encode those effects in the pathway or failure representation rather than infer them from Equation 43 alone.

The resulting failure-conditioned response coverage is defined in Equation 44.

$$\text{Cov}_{t,H}^{(m)}(\mathcal{B}_t, d_t; \mathcal{U}, \mathcal{Q}_t^{\mathcal{B}}) = \{u \in \mathcal{U} : \exists p \in \mathcal{P}_{t,H}(u; \mathcal{B}_t, d_t, \mathcal{Q}_t^{\mathcal{B}}) \text{ such that } \text{Dep}_t(p) \cap \Lambda_t(m) = \emptyset\}. \quad (44)$$

Equation 44 reveals a distinction that baseline resource-architecture response coverage cannot show. Two portfolios can support the same response family before disturbance while retaining very different response sets after the same failure. This is the sense in which the paper uses *failure-mode separation*: relevant future responses are supported through dependency structures that do not all disappear under the same declared disruptions.

A governance application can make the continuity requirement more explicit by grouping future actions into materially distinct option classes. Let $\mathfrak{D}_t = \{O_\alpha\}_{\alpha \in A}$ be a declared family of nonempty subsets of $\mathcal{U}$, where each O_α represents a response class whose continued availability matters for the application. Examples could include immediate protection, relocation, substitution, restoration, or institutional revision, although the classes must be defined substantively rather than assumed from this paper. The architecture satisfies *single-mode option continuity* relative to $(\mathfrak{D}_t, \mathcal{M}_t)$ when the condition in Equation 45 holds.

$$\forall m \in \mathcal{M}_t, \quad \forall O_\alpha \in \mathfrak{D}_t, \quad O_\alpha \cap \text{Cov}_{t,H}^{(m)}(\mathcal{B}_t, d_t; \mathcal{U}, \mathcal{Q}_t^{\mathcal{B}}) \neq \emptyset. \quad (45)$$

Equation 45 is a demanding robustness criterion, not a universal governance requirement. Some applications need only one protected option class, some failure modes are too severe to design around,

and maintaining every option class through every modeled disruption can be prohibitively costly. Its analytical value is to expose the declared standard against which a portfolio is being called “distributed” or “resilient.”

Hypothesis 7.1 (Failure-conditioned divergence under similar baseline coverage). Portfolios with similar baseline resource-architecture response coverage can exhibit materially different failure-conditioned coverage when their support pathways differ in dependency overlap. The divergence should be most pronounced when several apparently distinct pathways share dependencies that recur across many pathways or protected option classes and whose disruption affects multiple functional roles at once.

Hypothesis 7.1 is empirical. It requires an application to identify dependencies, credible failure modes, pathway requirements, and the relevant horizon. The formalism does not infer the actual vulnerability of a real institution from architectural diversity alone.

7.4 Common Dependency Cores

Hidden common dependencies provide the limiting case of the previous analysis. A portfolio can be geographically dispersed, institutionally plural, or nominally redundant while still possessing a narrow dependency core. The relevant concentration is therefore relational rather than merely spatial.

For a nonempty pathway family P , define its common dependency core by Equation 46.

$$\text{Core}_t(P) = \bigcap_{p \in P} \text{Dep}_t(p). \quad (46)$$

Any dependency in Equation 46 is required by every represented pathway in P . A disruption that disables such a dependency therefore defeats the entire pathway family, provided the disruption map and dependency signatures are correctly specified. The result is immediate from the definitions but analytically important: multiplying visible paths does not remove a common point of failure.

Proposition 7.2 (Common-core collapse under a represented failure). *Let P be a nonempty family of support pathways and let $m \in \mathcal{M}_t$. If $\text{Core}_t(P) \cap \Lambda_t(m) \neq \emptyset$, then no pathway in P satisfies the viability condition in Equation 43 under failure mode m .*

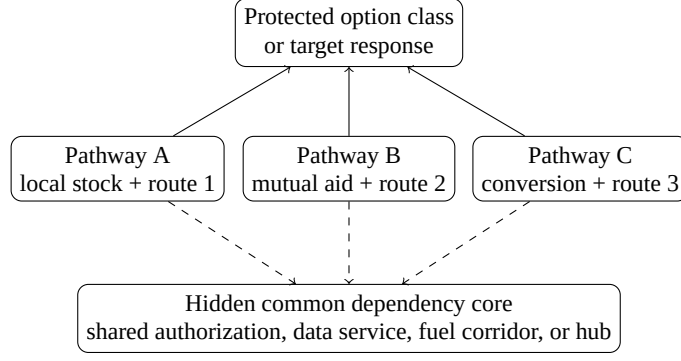
Proof. Choose $z \in \text{Core}_t(P) \cap \Lambda_t(m)$. By Equation 46, $z \in \text{Dep}_t(p)$ for every $p \in P$. Since $z \in \Lambda_t(m)$, each intersection $\text{Dep}_t(p) \cap \Lambda_t(m)$ is nonempty. Equation 43 therefore fails for every $p \in P$. $\square$

Proposition 7.2 is an internal consequence of the declared dependency representation. It does not establish that all important dependencies are observable or correctly modeled. Hidden dependencies are especially relevant because apparent diversification can coexist with unrecognized common exposure. Several suppliers can share one upstream manufacturer; multiple communication channels can rely on the same power system; decentralized institutions can depend on one authorization mechanism; and physically separated recovery sites can rely on the same data or identity infrastructure.

Figure 3 visualizes the point of Proposition 7.2. Several pathways can differ in surface architecture and still fail together because they pass through one shared enabling layer. The relevant concentration is therefore relational rather than merely organizational or geographic.

Table 6 summarizes four architectural properties that should remain distinct when interpreting distributed optionality.

The paper uses *distributed optionality* for the resulting architecture rather than for a single scalar index. Its descriptive content consists of the supported response family, the pathway families by which those responses can be assembled, their architecture signatures, their dependency signatures, and the way failure-conditioned coverage changes across the declared failure set. A compact representation is given in Equation 47.



A single represented failure that removes the common core can collapse all three apparently distinct pathways.

Figure 3: Illustrative distinction between visible pathway plurality and hidden common dependency. Apparent diversification can coexist with structural concentration when several pathways rely on the same enabling core.

Table 6: Distinct architectural dimensions of distributed optionality.

Dimension	Structural question	Limitation when considered alone
Spatial or organizational dispersion	Are capacities located in different places or organizations?	Dispersed units can depend on the same upstream infrastructure, authority, or supply chain.
Functional diversity	Do support pathways use materially different carrier, conversion, institutional, or response architectures?	Distinct architectures can still share a disabling dependency.
Path redundancy	Can the same response or protected target be supported through more than one pathway?	Several pathways can be redundant only in appearance when their dependency cores coincide.
Failure-mode separation	Do declared option classes retain viable pathways under the failures the architecture is intended to survive?	The result is conditional on the modeled failure family and can miss unknown or mis-specified dependencies.

$$\mathfrak{D}_{t,H}^{\text{dist}} = \left(\text{Cov}_{t,H}(\mathcal{B}_t, d_t; \mathcal{U}, \mathcal{Q}_t^{\mathcal{B}}), \{ \mathcal{P}_{t,H}(u; \mathcal{B}_t, d_t, \mathcal{Q}_t^{\mathcal{B}}) \}_{u \in \mathcal{U}}, \text{Arch}_t, \text{Dep}_t, \right. \\ \left. \{ \text{Cov}_{t,H}^{(m)}(\mathcal{B}_t, d_t; \mathcal{U}, \mathcal{Q}_t^{\mathcal{B}}) \}_{m \in \mathcal{M}_t} \right). \quad (47)$$

Equation 47 intentionally remains a profile. Compressing it to one number would require an explicit valuation of response classes, failure modes, pathway similarity, maintenance cost, and acceptable loss of option coverage. Those choices are empirical and normative inputs rather than consequences of the formalism.

The relation to resilience can now be stated cautiously. Distributed optionality can support persistence or reorganization when disturbance removes some pathways but leaves others capable of sustaining essential functions or constructing a viable successor configuration. It is neither necessary nor sufficient for every form of resilience. A highly specialized architecture can be resilient to a narrow, well-characterized disturbance, while a diversified architecture can fail when all paths depend on an unrecognized common bottleneck. The relevant governance question is therefore not whether capacity is simply centralized or decentralized, diversified or concentrated. It is whether the architecture preserves the response functions and recovery possibilities that matter under the transition and failure structures for which the system is being prepared.

Hypothesis 7.3 (Common-dependency fragility). When several nominally distinct response pathways rely on a small common dependency core, visible diversification can overstate the robustness of future

response capacity. The practical importance of the effect depends on whether credible failure modes intersect that core and on whether alternative pathways can be created within the relevant decision horizon.

Hypothesis 7.3 provides the bridge to the next part of the paper. Resource architecture determines which actions remain technically supportable, while evidence and model updating determine which of those actions remain justified as the response regime changes. The following section therefore returns to evidence-to-action relations only to the extent needed to connect regime change with the distributed option architecture developed here.

8 Evidence-to-Action near Regime Change

This section connects the resource architecture developed in Sections 5–7 to evidence-guided response under changing regimes. Its objective is deliberately narrower than the companion manuscript *Evidence-to-Action near Criticality: A Qualification for EBPM*. That work develops the distinction between locally informative evidence and the broader warrant required for intervention when the response regime can change. The present section inherits that distinction and asks a different question: how does an evidential update matter when the actions to which it could contribute are themselves conditioned by remaining functional capacity, commitment windows, and distributed support pathways? The discussion proceeds from transportability, to regime-sensitive response footprints, and finally to staged updating under changing evidence and capacity.

The main analytical point is that evidence quality and actionability can evolve in different directions. An observation can narrow the plausible regime family while waiting depletes the resources required for the responses that the new information would favor. Conversely, a new response pathway can become supportable through replenishment or institutional change even when diagnostic uncertainty remains substantial. Evidence-to-action analysis near regime change therefore requires a joint account of what the evidence supports and what the evolving portfolio still permits.

8.1 Evidence Transportability

Evidence is transportable only relative to a declared claim, regime distinction, horizon, and set of assumptions. A locally supported response claim can remain informative for one candidate regime and lose relevance for another if feedback structure, institutional implementation, affected population, recovery conditions, or strategic behavior changes materially. The present framework does not attempt to provide a general theory of external validity. It introduces only the amount of structure needed to connect transportability to functional resource distribution.

Let q denote an evidential claim used in the response analysis. Examples include a claim about the short-horizon effect of an intervention, the response of a protected function to a disturbance, the reliability of a supply substitution, or the recovery time associated with a particular repair strategy. Let $\mathcal{D}_q$ denote the declared regime–horizon domain within which the assumptions supporting q are treated as applicable. For the accessible-regime family in Equation 2, the regime-transport set of q is defined in Equation 48.

$$\text{Tr}_{t,H}(q) = \{g \in \mathcal{G}_t(H; \mathcal{P}_t) : (g, H) \in \mathcal{D}_q\}. \quad (48)$$

Equation 48 does not state that a claim is simply valid or invalid. It records the subset of the currently represented regime family over which the claim is being transported. The domain $\mathcal{D}_q$ can itself change when new evidence reveals a wider scope, identifies a previously unmodeled interaction, or shows that an assumption fails under conditions formerly treated as comparable. Likewise, the accessible-regime family can expand or contract as observations alter the modeled transition structure. Transportability is therefore indexed to the evidence and model in use rather than treated as a timeless property of q .

A claim is *transport-complete relative to the current regime family* when its transport set covers every currently represented regime. The condition is stated in Equation 49.

$$\text{Tr}_{t,H}(q) = \mathcal{G}_t(H; \mathcal{P}_t). \quad (49)$$

Failure of Equation 49 identifies a scope gap rather than an automatic reason for inaction. The uncovered regimes can be weakly plausible, the claim can remain sufficient for a limited decision, or urgent protection can be warranted despite incomplete transport. The value of the representation is diagnostic: it makes clear which part of the decision depends on extending a claim beyond the conditions for which its use is currently supported.

Transportability also needs to be connected to response support. Section 4 defines the bounded response set through declared footprint constraints, while Section 6 defines which responses are covered by the current resource architecture. The coarse repertoire $\mathfrak{A}_t$ in Section 4 records responses admitted by the current modeling and institutional frame; it does not by itself certify joint material support. Section 6 makes resource assembly and horizon-relative conversion explicit. The response family that is both bounded under the current analysis and supportable under this more explicit resource representation is therefore defined in Equation 50.

$$\mathfrak{A}_{t,H}^{\text{eff}} = \text{Cov}_{t,H} \left(\mathcal{B}_t, d_t; \mathfrak{A}_t^{\text{bd}}(H; \mathfrak{R}_{t,H}), \mathcal{Q}_t^{\mathcal{B}} \right). \quad (50)$$

Equation 50 is not a set of normatively warranted actions. The bounded set depends on declared constraints whose justification remains external to the formalism, while resource-architecture response coverage depends on the modeled resource operations and horizon. The object records a narrower intersection: responses that remain inside the declared footprint constraints and are supportable through the current portfolio architecture under the declared resource-operation repertoire.

The distinction between Equations 48 and 50 is central to this paper. An evidential update can improve confidence in which response would perform well while the effective response family contracts because time, reserve, authorization, infrastructure, or recovery capacity has been lost. Evidence can also weaken support for one intervention while replenishment opens several alternative responses. The paper therefore avoids treating stronger evidence as monotonically increasing the practical action set.

Remark 8.1 (Transport and support). A response can be strongly supported by a transported evidential claim yet be operationally unavailable, and a response can remain operationally available while the evidential claim previously used to justify it no longer transports across the currently plausible regime family. Evidence scope and response support are distinct dimensions of the same decision architecture.

8.2 Regime-Sensitive Intervention Effects

Transportability concerns whether a claim can be carried across represented regimes. A second issue concerns the response itself. The same named intervention can produce different state changes, portfolio demands, response-repertoire effects, and recovery consequences under different regimes. This is especially important for Paper IV because regime-sensitive intervention effects can change which functional resources should be held, converted, or protected.

For a candidate regime $g \in \mathcal{G}_t(H; \mathcal{P}_t)$, let the regime-conditioned response footprint be represented by Equation 51.

$$\text{Foot}_{t,H}^{(g)}(u; V) = \left(\omega_{t+1}^{(u,g)}, \mathcal{B}_{t+1}^{(u,g)}, d_{t+1}^{(u,g)}, \mathfrak{A}_{t+1}^{(u,g)}, \mathcal{R}_{t+1}^{(u,g)}(H; V) \right). \quad (51)$$

Equation 51 refines the response footprint in Equation 18 by making the represented regime explicit. The notation does not require regimes to be ontologically discrete or directly observed. It asks how the modeled consequences of the response differ under the candidate response structures currently retained for decision analysis.

A response is *regime-sensitive relative to the declared footprint* when at least two currently represented regimes generate different footprints. The condition is stated in Equation 52.

$$\exists g, g' \in \mathcal{G}_t(H; \mathcal{P}_t) \quad \text{such that} \quad \text{Foot}_{t,H}^{(g)}(u; V) \neq \text{Foot}_{t,H}^{(g')}(u; V). \quad (52)$$

Equation 52 is intentionally broad. The difference can lie in immediate system response, functional resource use, future response repertoire, or recovery structure. In many applications the most relevant difference is not the immediate output of u but the portfolio and pathway architecture left after execution. A measure can have similar short-run effects in two regimes while requiring very different recovery resources or creating different shared dependencies.

This distinction creates a direct bridge from evidence to functional allocation. If new observations shift weight away from a regime in which an intervention is resource-light and toward one in which the same intervention consumes scarce recovery capacity, the evidential update changes the resource problem even when the intervention label is unchanged. Similarly, evidence revealing that several responses share the same failure-sensitive dependency can change the distributed-optionality profile in Equation 47 without changing their nominal count.

Table 7 summarizes several ways in which a regime-relevant evidential update can alter the resource architecture. The table describes analytical channels rather than deterministic consequences.

The first row of Table 7 illustrates why the paper does not impose a universal preference for diversification. Better discrimination can sometimes justify concentrating resources on a narrower response architecture. The second and fourth rows illustrate the opposite possibility: improved knowledge can reveal that a seemingly adequate portfolio is more fragile than previously represented. Evidence can therefore support either concentration or distribution depending on what it reveals about regime structure, recovery, and dependencies.

Hypothesis 8.2 (Regime-sensitive resource demand). When the same candidate response has materially different portfolio and recovery footprints across plausible regimes, evidential changes in the represented regime family can alter which resource functions are binding even if the nominal response menu remains unchanged. The effect depends on the declared horizon, footprint representation, and resource-conversion architecture.

Hypothesis 8.2 is a bridge hypothesis. It does not assert that every regime update should trigger reallocation. It identifies a mechanism through which learning about the response regime can change the composition problem developed in Sections 6 and 7.

8.3 Staged Commitment and Model Updating

Staged response in Section 4 was introduced as a sequence of commitments separated by checkpoints at which observation can alter later action. The present subsection adds the resource-side condition required for those checkpoints to remain practically meaningful. A model update can improve diagnosis only after some of the original portfolio has already been consumed, converted, encumbered, or released. The relevant checkpoint state therefore needs to record evidence and capacity together.

For a common forward comparison horizon H , define the evidence–capacity state at checkpoint t_k by Equation 53.

$$\mathfrak{Z}_k = \left(H_k, \mathfrak{C}_{t_k}(H_k), \mathcal{B}_{t_k}, d_{t_k}, \mathfrak{D}_{t_k, H}^{\text{dist}}, \mathfrak{A}_{t_k, H}^{\text{eff}} \right). \quad (53)$$

The components of Equation 53 record the realized history, the updated criticality profile, the remaining resource portfolio and realized allocation, the distributed-optionality profile, and the currently effective response family. The notation extends rather than replaces the staged response rule in Equation 21. A staged decision rule can therefore be written in the reduced form stated in Equation 54.

$$u_k = \tilde{\pi}_k(\mathfrak{Z}_k), \quad u_k \in \mathfrak{A}_{t_k, H}^{\text{eff}}. \quad (54)$$

Equation 54 should not be read as an optimization rule. The selection map $\tilde{\pi}_k$ can represent political judgment, institutional procedure, robust decision logic, negotiated choice, or another application-specific selection process. The structural requirement is that later choice be conditioned on both updated diagnosis and the actions that remain functionally supportable.

Table 7: Illustrative channels from evidential update to functional resource consequences.

Evidential update	Change in represented response problem	Possible resource consequence
A formerly plausible regime is excluded	The candidate response family becomes more concentrated around a narrower set of dynamics.	Comparative analysis can rely on a narrower modeled dynamical family, while some reserves maintained only for the excluded regime can lose immediate relevance.
A previously omitted regime becomes plausible	Additional response footprints and recovery structures enter the decision problem.	Reserve, conversion, or recovery requirements can expand; apparent portfolio sufficiency can become conditional on one forecast.
Recovery is found to be slower or more resource intensive	The modeled recovery profile deteriorates for one or more responses.	Recovery capacity and survival provisioning can become more binding, reducing the effective value of aggressive probing or commitment.
A hidden common dependency is identified	Nominally distinct support pathways are revealed to share a disabling node.	Failure-conditioned coverage can contract even when baseline coverage and pathway count remain unchanged.
A commitment window is revised	The time available for reassignment, conversion, or staged learning changes.	A previously supportable response can become infeasible, or replenishment and coordination can make a later response newly supportable.

A useful failure mode of staged governance occurs when evidence improves after the response architecture has already contracted. To make this possibility explicit, consider two adjacent checkpoints evaluated over a common comparison family of candidate regimes Γ° and a common response taxonomy $\mathcal{U}^\circ$. Let $\mathcal{P}_k^\circ$ denote the observational partition induced by the evidence available at t_k over Γ° , and let $\mathfrak{A}_{t_k, H}^{\text{eff}, \circ}$ denote the effective responses at t_k after mapping them into $\mathcal{U}^\circ$. This common taxonomy is required because a raw subset comparison is not meaningful when action identities change across checkpoints. The paper calls the pair of changes in Equation 55 *evidence–capacity divergence*.

$$\mathcal{P}_{k+1}^\circ \prec \mathcal{P}_k^\circ \quad \text{and} \quad \mathfrak{A}_{t_{k+1}, H}^{\text{eff}, \circ} \subsetneq \mathfrak{A}_{t_k, H}^{\text{eff}, \circ}. \quad (55)$$

In Equation 55, $\prec$ denotes strict refinement of the observational partition as in Section 3. The first relation therefore represents improved discrimination over a fixed comparison family, while the second represents contraction of responses under a stable comparison taxonomy. The two relations can occur together because diagnostic learning and functional capacity evolve through different mechanisms.

Evidence–capacity divergence clarifies why a checkpoint can be epistemically successful yet operationally weak. The system can be better understood at t_{k+1} while the response favored by that understanding is no longer supportable, a relevant commitment window has closed, or every remaining pathway depends on one fragile common node. The converse can also occur: replenishment can expand the effective response family while the evidence remains too coarse to discriminate which branch is preferable. Adaptive governance requires attention to both trajectories.

The temporal relation between learning and capacity can therefore be expressed through an *actionable evidence window*. The concept is qualitative in the present paper: evidence becomes actionably useful when it arrives while materially different responses to which it is relevant remain inside their commitment windows and retain adequate portfolio support. No universal duration can be assigned because observation rates, dissipation rates, conversion times, and response requirements differ by application.

Hypothesis 8.3 (Actionable-evidence window). When diagnostic refinement requires time while relevant response capacities dissipate or commitment windows contract, the practical value of additional

evidence can depend on whether the update arrives before the associated response branches become unavailable. Under such conditions, allocating resources to observation and allocating resources to preserve later action are jointly rather than sequentially determined problems.

Hypothesis 8.3 does not imply that evidence should be rushed or that early action is generally preferable. Some responses should remain unavailable until evidential thresholds are met; some delay improves both diagnosis and supportability through coordination or replenishment; and some commitments are unacceptable even when they remain feasible. The hypothesis identifies a timing interaction: information has greater decision relevance when the capacities needed to act on it survive long enough to remain usable.

Section 8 therefore adds a portfolio qualification to evidence-to-action reasoning near regime change. Transportability, regime-conditioned footprints, and staged updating jointly connect diagnostic change to the response capacity that remains usable. The next section turns to empirical identification of transition-relevant conditions.

9 Identification of Near-Critical Conditions

This section develops the empirical discipline required before the resource architecture of Sections 2–8 is applied to a concrete system. Its objective is to distinguish a near-criticality hypothesis from a retrospective metaphor for instability, crisis, rapid change, or institutional stress. The section reviews six diagnostic families—recovery dynamics, fluctuation statistics, susceptibility, flickering, network indicators, and timescale deformation—and specifies how they can contribute to a mechanism-indexed attribution. The discussion treats these families as partially complementary sources of evidence whose interpretation depends on the transition mechanism, observed variables, sampling design, perturbation structure, and decision horizon.

Early-warning research provides a useful starting point because critical slowing down can precede several local bifurcations: as a dominant stabilizing mode weakens, recovery from small perturbations becomes slower, and under additional assumptions temporal autocorrelation and variance can rise [4, 8, 9]. The same literature also places strong boundaries around this inference. Regime shifts can arise through mechanisms that do not generate critical slowing down; observation error, changing noise structure, rapid forcing, spatial interaction, and short or poorly sampled time series can obscure or imitate conventional indicators [5, 8]. Model-based analyses further show that false-alarm and missed-detection rates can be substantial even under favorable settings, making uncertainty quantification part of the diagnostic problem rather than an optional refinement [6].

For Paper IV, these limitations have a direct governance implication. The functional portfolio should not be reorganized merely because one statistic trends in an intuitively alarming direction. A near-criticality attribution becomes decision-relevant only when the mechanism linking the observed change to transition susceptibility is stated, rival explanations are considered, and uncertainty about the attribution remains visible. The six diagnostic families below are therefore organized around the question each can answer and the assumptions under which the answer is informative.

9.1 Recovery Dynamics

Recovery dynamics provide the most direct empirical connection between resilience and critical slowing down. The basic idea is comparative rather than absolute: after perturbations of a declared type, does the system return toward the reference response regime more slowly than it did under otherwise comparable conditions? A trend toward slower local recovery can be consistent with weakening stability in classes of systems approaching particular bifurcations [4, 9]. It remains an indicator of a mechanism, rather than a universal measure of distance to every possible transition.

Suppose a local representation around a reference state admits a stochastic linear approximation over a limited observational window. A one-dimensional approximation is written in Equation 56.

$$d\xi_s = -r_t \xi_s ds + \sigma_t dW_s, \quad r_t > 0. \quad (56)$$

In Equation 56, s is local process time within the observational window indexed by governance time t , r_t is the local return rate, σ_t is the represented noise amplitude, and W_s is a Wiener process. When this approximation is appropriate, the characteristic recovery time is defined in Equation 57.

$$\tau_{\text{rec},t} = \frac{1}{r_t}. \quad (57)$$

A decline in r_t , equivalently an increase in $\tau_{\text{rec},t}$, is consistent with critical slowing down when the underlying mechanism is a gradual approach to a local loss of stability. The same observation can have other causes. The reference state can move during recovery; the perturbation can cross into a nonlinear region; recovery can be slowed by resource scarcity, institutional delay, or changing exogenous forcing; and the monitored variable can fail to align with the mode that is losing stability. The interpretation of Equation 57 therefore depends on a declared perturbation class, a stable enough comparison baseline, and evidence that the estimated return process is relevant to the hypothesized transition.

Recovery measurements also have a specific advantage for the present paper. They can sometimes be tied directly to functional targets. If the monitored quantity represents delivery of an essential service, restoration of a supply pathway, institutional processing capacity, or another protected function, a changing return rate can inform both the near-criticality hypothesis and the recovery component of the resource portfolio. The evidential roles should still be separated. Slow restoration of a service can reveal constrained repair capacity even when no dynamical critical transition is present.

Remark 9.1 (Recovery evidence). A measured increase in recovery time can support a near-criticality attribution when it is linked to an appropriate transition mechanism. Independently of that attribution, the same measurement can remain decision-relevant as evidence about the time and resources required to restore a protected function.

9.2 Variance and Autocorrelation

Variance and lagged autocorrelation are among the most widely discussed indirect indicators of critical slowing down. Their mechanistic interpretation can be seen in the local process of Equation 56. Under a stationary Ornstein–Uhlenbeck approximation with locally constant r_t and σ_t , the stationary variance is stated in Equation 58.

$$\text{Var}(\xi) = \frac{\sigma_t^2}{2r_t}. \quad (58)$$

For observations separated by interval $\Delta > 0$, the corresponding lag-one autocorrelation is stated in Equation 59.

$$\rho_t(\Delta) = \exp(-r_t \Delta). \quad (59)$$

Equations 58 and 59 explain why a declining return rate can, under this specific approximation, generate increasing variance and autocorrelation. They also expose the assumptions behind the inference. A change in σ_t can alter variance without any change in return rate. Changes in the temporal correlation of external forcing can affect autocorrelation. Detrending choices, observation error, sampling interval, moving-window length, and nonstationarity can alter both estimates. The indicator pair therefore acquires evidential force through consistency with a mechanism and data-generating model rather than through its numerical trend alone [5, 8].

The relationship between the two indicators can also differ when the relevant mechanism is flickering rather than critical slowing down. In an empirical lake study, Wang and colleagues reported rising variance accompanied by decreasing autocorrelation and skewness before a eutrophication transition, a

pattern they interpreted as consistent with flickering rather than the canonical critical-slowness-down pattern [7]. This example is useful because it illustrates why an indicator family should be read jointly with a hypothesized mechanism.

A further limitation concerns forecasting. Relative trends can be informative even when no absolute critical threshold is known, yet the location and timing of the transition generally remain uncertain. Boettiger and Hastings show that common indicators can exhibit substantial reliability–sensitivity tradeoffs and argue for explicit characterization of error rates [6]. For governance applications, this implies that variance and autocorrelation should be accompanied by uncertainty intervals, alternative preprocessing choices, null or rival models where feasible, and sensitivity to observation windows.

Caution 9.2 (Indicator inversion). A rising variance or autocorrelation series is not equivalent to an identified critical transition. The same observed trend can arise from changing disturbance statistics, sampling structure, transient dynamics, or other forms of nonstationarity. Conversely, a relevant transition can occur without the canonical trend when the transition mechanism does not produce critical slowing down or when the signal is masked.

9.3 Susceptibility

Susceptibility concerns how strongly a system responds to perturbations. Section 2 already treats sensitivity as directional and horizon-dependent. Identification therefore requires a perturbation–response design rather than a single volatility statistic. In empirical settings, perturbations can be naturally occurring shocks, controlled probes where ethically and institutionally permissible, policy discontinuities, or other changes for which a response contrast can be estimated.

Let v denote a declared perturbation direction, ϵ its scale, and Π_H a readout over horizon H . When the state representation and readout metric d_Π make such a comparison meaningful, a finite-difference susceptibility estimate is defined in Equation 60.

$$\chi_{t,H}(v; \epsilon) = \frac{d_\Pi(\Pi_H(\omega_t^{\epsilon v}), \Pi_H(\omega_t))}{|\epsilon|}. \quad (60)$$

Equation 60 is intentionally indexed by direction, perturbation scale, horizon, and readout. A system can become highly susceptible along one mode while remaining insensitive along another. Apparent amplification can also reflect a change in exposure, measurement, or perturbation composition rather than a reduction in dynamical stability. Repeated or comparative estimates are therefore more informative when the perturbation class remains sufficiently comparable and the response metric is tied to the hypothesized mechanism.

Susceptibility evidence can sometimes reveal transition-relevant structure earlier than passive fluctuation statistics because it asks the system a controlled response question. That advantage comes with the probe problem developed in Section 3: the perturbation can alter the state, consume resources, create distributional burdens, or close future options. Identification and intervention are therefore coupled. Where active probing is unacceptable, natural perturbations or quasi-experimental contrasts can provide weaker but safer evidence.

The governance interpretation also requires restraint. High susceptibility can indicate leverage, fragility, or both. It does not determine whether a response should be amplified, buffered, redirected, or avoided. The same observation that strengthens the near-criticality hypothesis can increase the need to preserve recovery capacity because an error in direction or scale may have more persistent consequences.

9.4 Flickering

Flickering refers to repeated switching between distinguishable state regions or regimes before a more persistent transition. In systems with alternative states and sufficiently strong perturbations, trajectories can move back and forth across a basin boundary while the underlying forcing continues to change. Such

behavior can provide information about reduced separation between regimes, but its interpretation differs from canonical critical slowing down [7, 8].

Suppose an empirically justified classifier c maps observed configurations into K state classes. For observations $\omega_{t_0}, \dots, \omega_{t_n}$ within a declared window, the observed switching count is defined in Equation 61.

$$N_{\text{switch}} = \sum_{k=0}^{n-1} \mathbf{1}[c(\omega_{t_{k+1}}) \neq c(\omega_{t_k})]. \quad (61)$$

Equation 61 becomes diagnostically meaningful only when the classes have substantive and statistical support and when comparisons control for observation-window length and sampling frequency. Where those quantities vary, a normalized switching rate or a model of residence times is preferable to raw counts. A high switching count generated by an unstable clustering algorithm, changing measurement definitions, seasonal movement, or strategic reclassification is weak evidence for dynamical flickering. Likewise, genuine flickering can be missed when the sampling interval is too coarse to observe short excursions.

Flickering analysis can be enriched by residence-time distributions, transition asymmetry, multimodality, or state-dependent recovery after switches. These extensions help separate frequent boundary crossing from simple high-frequency noise. They remain mechanism-specific. A system can approach a transition without observable flickering, and switching can occur because of stochastic forcing even when a deterministic threshold is not being approached [8].

For Paper IV, flickering matters because it can change the practical meaning of reserve and commitment. Repeated excursions can repeatedly activate emergency resources, shorten maintenance cycles, or reveal that nominally distinct regimes already require concurrent support. A resource architecture designed around one stable baseline can therefore become fragile before a persistent transition is formally identified.

9.5 Network Indicators

Many governance systems are high-dimensional and networked. Infrastructure, supply, finance, communications, administration, care, and emergency response depend on interactions among heterogeneous nodes rather than on one aggregate state variable. Network structure can shape robustness, cascading failure, recovery, and the location of transition-sensitive modes, and network-resilience research has developed corresponding analytical and early-warning approaches [10]. The existence of these approaches does not supply a universal network indicator of political or institutional criticality.

A network diagnostic should distinguish at least three objects. The first is the interaction architecture itself: topology, weights, directionality, multiplex coupling, and interdependence. The second is the dynamics operating on that architecture. The third is the observation design: which nodes, edges, flows, or latent variables are actually measured. A topological statistic can change while the system remains dynamically stable, and a dynamically important mode can change with little visible alteration in coarse topology.

Where a local dynamical model is available, changes in the dominant stability mode of a network Jacobian can provide a recovery-oriented indicator analogous to Section 9.1. Where the full model is unavailable, multivariate correlation structure, sentinel-node signals, spatial coherence, cascade propagation, or dynamical-network-marker approaches can provide alternative evidence. Recent reviews emphasize that network early-warning methods remain closely tied to model class, dimensionality, data availability, and the relation between topology and node dynamics [10].

The distributed-optionality framework adds a second network layer that is analytically distinct from dynamical criticality. Section 7 represents hidden common dependencies and failure-conditioned response coverage. A growing dependency core, declining pathway diversity, or rising cascade exposure can indicate resource-architecture fragility even when there is insufficient evidence for a bifurcation-type

transition. These measures should therefore be reported as architecture diagnostics unless a transition mechanism linking them to near criticality is independently supported.

Remark 9.3 (Network fragility and criticality). Evidence that a network has concentrated dependencies, cascade vulnerability, or low redundancy can justify resilience-oriented resource attention without establishing that the network is near a critical transition. The near-criticality claim requires an additional dynamical mechanism connecting the observed architecture to transition susceptibility over the relevant horizon.

9.6 Timescale Deformation

Critical slowing down is itself a change in timescale, but governance operates with several interacting clocks. Recovery, forcing, observation, decision, replenishment, implementation, and institutional revision can evolve at different rates. A near-criticality diagnosis can therefore benefit from tracking whether previously useful separations among these timescales are changing, even when no single early-warning statistic is decisive.

Let the relevant timescale profile be represented by Equation 62.

$$\mathfrak{T}_t = (\tau_{\text{rec},t}, \tau_{\text{force},t}, \tau_{\text{obs},t}, \tau_{\text{exec},t}, \tau_{\text{opp},t}, \tau_{\text{repl},t}). \quad (62)$$

The entries in Equation 62 respectively denote characteristic times for recovery, material change in the relevant external or endogenous forcing, obtaining decision-relevant observations, executing a response, remaining time before a declared response opportunity materially narrows or closes, and replenishing critical resources. Their meanings are application-specific and can be represented by intervals or distributions rather than point estimates.

A clean fast-slow approximation becomes less reliable when timescales that were previously well separated become comparable. For example, if recovery becomes slower while external forcing accelerates, the ratio in Equation 63 increases.

$$\vartheta_t^{\text{rf}} = \frac{\tau_{\text{rec},t}}{\tau_{\text{force},t}}. \quad (63)$$

Likewise, the relation between observation time and the remaining response opportunity can be summarized by the ratio in Equation 64.

$$\vartheta_t^{\text{oo}} = \frac{\tau_{\text{obs},t}}{\tau_{\text{opp},t}}. \quad (64)$$

Equations 63 and 64 do not define universal critical thresholds. They expose timing relations that can alter the interpretation of other evidence. A rising ϑ_t^{rf} can mean that recovery is losing pace relative to the forcing that moves the system. A high ϑ_t^{oo} can mean that obtaining the declared diagnostic update consumes a large fraction of the remaining response opportunity. Both relations connect directly to the dissipative-delay analysis of Section 5.

Timescale deformation can also generate misleading conventional indicators. If sampling frequency remains fixed while recovery time changes, autocorrelation estimates can move partly because the observation interval becomes different relative to the system's intrinsic timescale. If the forcing timescale changes rapidly, a stationary local approximation can become inappropriate before the analyst has enough data to estimate a trend. Timescale analysis should therefore accompany, rather than merely follow, statistical early-warning analysis.

The six diagnostic families can now be assembled without converting them into a single criticality score. Table 8 summarizes their mechanistic basis, principal empirical requirements, and characteristic interpretive limits.

Rather than aggregating Table 8 into a scalar index, this paper represents a diagnostic record through Equation 65.

Table 8: Diagnostic families for a conditional near-criticality attribution. Each family is mechanism-dependent and can remain informative even when the overall near-criticality hypothesis is unresolved.

Family	Mechanistic question	Evidence requirement	Characteristic limitation
Recovery dynamics	Is local restoration after comparable perturbations becoming slower?	Perturbation–recovery observations or an identified local model.	Slow recovery can arise from changing resources, forcing, or reference states without a critical transition.
Variance and autocorrelation	Are fluctuation statistics changing as expected under the proposed slowing mechanism?	Sufficiently sampled, appropriately detrended time series with uncertainty analysis.	Changing noise, observation error, window choice, and nonstationarity can generate false or missing signals.
Susceptibility	Is response amplification increasing along decision-relevant perturbation directions?	Comparable natural or designed perturbations and declared readouts.	Amplification is directional and can reflect changing exposure or composition rather than stability loss.
Flickering	Are trajectories increasingly switching among empirically supported state regions?	Defensible state classification and sampling fast enough to resolve excursions.	Switching can be noise-driven, seasonal, classificatory, or absent under genuine transitions.
Network indicators	Are transition-sensitive modes, correlations, or cascade structures changing in a networked system?	Network observations plus a model connecting topology and node dynamics.	Topological fragility and dynamical near-criticality are related only under additional assumptions.
Timescale deformation	Are recovery, forcing, observation, execution, response-opportunity, or replenishment times becoming less separated?	Comparable estimates of process and governance timescales.	Timescale convergence is a broad coordination problem and does not identify a transition mechanism by itself.

$$\mathcal{D}_t^{\text{crit}}(H) = \left(E_t^{\text{rec}}, E_t^{\text{fluc}}, E_t^{\text{sus}}, E_t^{\text{flick}}, E_t^{\text{net}}, E_t^{\text{time}}; \mathcal{M}_t, \mathcal{U}_t \right). \quad (65)$$

In Equation 65, the E terms denote the evidence assembled from the six diagnostic families, $\mathcal{M}_t$ is the set of transition mechanisms retained as plausible, and $\mathcal{U}_t$ records material uncertainties in measurement, model form, sampling, mechanism attribution, and horizon. The tuple is a reporting architecture. It does not imply commensurability among evidence families or prescribe a threshold at which the near-criticality hypothesis becomes true.

Hypothesis 9.4 (Mechanism-indexed diagnostic conjunction). A near-criticality attribution is more defensible when multiple diagnostic families provide mutually compatible evidence for a stated transition

mechanism and when principal rival explanations and measurement uncertainties have been examined. The relevant combination depends on the mechanism and observation architecture; disagreement among indicators is itself diagnostic information rather than an automatic reason to average them.

Hypothesis 9.4 is consistent with methodological reviews that recommend combining approaches and emphasize conceptual, operational, and statistical limitations rather than relying on one generic indicator [5, 8]. The hypothesis also preserves the possibility that strong mechanism-specific evidence can exist even when one conventional indicator is absent.

For the resource-governance framework, the practical output of Section 9 is therefore a qualified diagnostic profile rather than a declaration of crisis. The profile can update the regime family, susceptibility representation, recovery structure, observation strategy, and effective response set developed earlier in the paper. It can also remain unresolved. Section 10 turns from diagnosis to coordination across scales, where local and system-level signals, resource dependencies, and decision authority can differ even when they refer to the same evolving transition.

10 Multi-Scale Coordination

This section extends the functional-resource and distributed-optionality framework across multiple governance scales. Its role is to distinguish three questions that become entangled when a near-critical configuration spans local, regional, sectoral, and system-wide processes: where transition-relevant information is observable, where the resources required for response are located, and where authority or coordination capacity resides. The objective is to specify conditions under which distributed capacity and selective coordination can be combined without treating either decentralization or centralization as a general solution. The section proceeds from scale-indexed diagnostic and capacity records to coordination interfaces, selective central coordination, and cross-scale resource mobilization.

Research on adaptive and polycentric governance already provides strong reasons to take multi-level structure seriously. Adaptive-governance scholarship emphasizes networks, bridging organizations, and interaction across organizational levels during periods of abrupt change [11]. Work on resource-governance regimes similarly treats adaptive capacity as partly dependent on multi-level learning and on the interaction of hierarchies, markets, and networks [12]. Polycentric analysis shows how multiple centers of decision can support experimentation and learning at several scales while still leaving roles for wider coordination [13]. The present paper uses these traditions as background rather than deriving its framework from any one institutional form. Its narrower concern is how scale affects the supportability of future responses under conditional near-criticality.

A multi-scale formulation is needed because the diagnostic record of Section 9, the resource portfolio of Section 6, and the distributed-optionality profile of Section 7 need not align at the same organizational level. A locally visible loss of recovery capacity can require resources held at a higher level. A system-wide aggregate can remain stable while one locality approaches a functional threshold. Several local units can each support an intervention independently while lacking the coordination, interoperability, or common authorization needed for joint execution. The relevant object is therefore the relation among scale-specific capacities rather than a presumption that one scale contains the complete decision problem.

10.1 Scale-Indexed Diagnostic and Capacity Records

Let $\mathcal{L}_t$ denote a finite family of governance units or analytical scales relevant at time t . A member $\ell \in \mathcal{L}_t$ can represent a locality, organization, sector, jurisdictional level, infrastructure domain, or another unit for which diagnostic and resource records can be meaningfully constructed. The family need not form a simple hierarchy. Lateral, overlapping, and nested relations can coexist.

For each ℓ , collect the local diagnostic, portfolio, effective-response, and distributed-optionality objects into the scale-indexed governance record defined in Equation 66.

$$\mathfrak{X}_{t,H}^{(\ell)} = \left(\mathfrak{D}_t^{\text{crit},(\ell)}(H), \mathcal{B}_t^{(\ell)}, d_t^{(\ell)}, \mathfrak{A}_{t,H}^{\text{eff},(\ell)}, \mathfrak{D}_{t,H}^{\text{dist},(\ell)} \right). \quad (66)$$

Table 9: Multi-scale coordination functions and characteristic failure modes. The table treats coordination as a differentiated set of functions rather than as a synonym for hierarchical control.

Function	Potential contribution	Characteristic failure	Relevant safeguard or diagnostic
Local sensing	High-context observation and rapid detection of heterogeneous change	Fragmented visibility; incompatible measurements; local blind spots	Common metadata, cross-site comparison, retained local detail
Cross-scale integration	Comparison of signals and recognition of coupled exposure	Aggregation loss; delayed escalation; false system-wide averaging	Explicit uncertainty, discordance records, reversible aggregation
Common standards	Interoperability of data, logistics, legal procedures, or emergency protocols	Standard mismatch with local conditions; lock-in	Modular standards, exception procedures, periodic revision
Resource pooling	Mobilization of scarce personnel, liquidity, materials, or infrastructure	Donor depletion; bottleneck transfer; queueing delay	Donor-safety constraints, priority rules, commitment-window analysis
Mutual aid	Lateral substitution across peer units	Correlated exposure; simultaneous demand; hidden common supplier	Dependency mapping and failure-conditioned coverage
Central emergency coordination	Rapid synchronization where cross-scale coupling is strong	Single-point failure; information overload; excessive closure of local options	Backup coordination paths, distributed execution, bounded mandate

Equation 66 carries the realized local allocation state $d_t^{(\ell)}$ alongside the portfolio because supportability depends on how locally available resources are assembled at the checkpoint. It is a bookkeeping device. It does not assume that the same variables, thresholds, or response classes are meaningful at every scale. A city-level survival function, a national fiscal reserve, and a regional transmission-network recovery capacity can belong to the same multi-scale problem while requiring different empirical representations.

The first coordination difficulty is epistemic. An aggregate record can be useful without being a sufficient statistic for every local response problem. Let $C \subseteq \mathcal{L}_t$ be a collection of units whose records are integrated for a declared coordination task. A partial integration map is represented in Equation 67.

$$\mathcal{I}_{t,H}^C : \prod_{\ell \in C} \mathfrak{x}_{t,H}^{(\ell)} \rightarrow \mathfrak{Y}_{t,H}^C. \quad (67)$$

The codomain $\mathfrak{Y}_{t,H}^C$ in Equation 67 is a task-specific coordination record rather than a claim that the integration map reconstructs one objectively complete macrostate. The map is partial because records may be incomparable, temporally misaligned, or unavailable. It can also be lossy. Averaging a set of local recovery rates, for example, can conceal a locality whose essential function is already outside its survival corridor.

The same caution applies in the opposite direction. A local signal can be genuine while remaining insufficient for a system-wide near-criticality attribution. Section 9 therefore carries over at every scale: mechanism, horizon, readout, uncertainty, and rival explanations should remain visible. Multi-scale coordination adds a further requirement that disagreement across records be retained long enough to determine whether it reflects measurement error, legitimate heterogeneity, asynchronous dynamics, or coupled regime change.

Remark 10.1 (Scale discordance). A difference between scale-indexed diagnostic records is not, by itself, an inconsistency to be removed. It can indicate heterogeneous exposure, different recovery times,

distinct forcing, asynchronous transitions, or incompatible observation architectures. A coordination process should therefore preserve the location and source of diagnostic discordance where those differences can affect response choice.

A second difficulty concerns temporal alignment. The characteristic timescales in Equation 62 can differ across ℓ . A local operational unit can face a short commitment window while a higher-level institution updates slowly because information collection, authorization, or procurement takes longer. A multi-scale architecture can therefore possess adequate total resources and accurate retrospective diagnosis while still failing to coordinate them within the horizon over which the local response remains feasible.

10.2 Coordination Interfaces and Joint Feasibility

Coordination requires more than the coexistence of capable units. Information, resources, authority, standards, and execution rights are mediated through interfaces that can themselves become bottlenecks. Represent the coordination architecture at time t by the labeled directed graph in Equation 68.

$$\mathcal{C}_t = (\mathcal{L}_t, E_t, \chi_t), \quad \chi_t : E_t \longrightarrow 2^{\mathcal{F}_{\text{coord}}}. \quad (68)$$

In Equation 68, E_t contains available coordination interfaces and $\mathcal{F}_{\text{coord}}$ is a declared family of interface functions, such as information exchange, resource transfer, authorization, mutual aid, standard setting, or conflict resolution. The labeling map χ_t records which functions a particular interface can support. The graph is not assumed to be centralized, connected, or static.

For a response u , let $\mathcal{L}_t(u) \subseteq \mathcal{L}_t$ denote the units whose resources, authority, or execution are required for implementation. For each $\ell \in \mathcal{L}_t(u)$, write $\mathfrak{D}_t^{\text{supp},(\ell)}(u)$ for the scale-specific analogue of the support set in Equation 33. Each required unit can have a nonempty local support set while the response still lacks a jointly compatible configuration. Let $\mathfrak{J}_{t,H}(u)$ denote the family of tuples of local allocation states and coordination-interface uses that jointly satisfy the response requirements. Write $\text{JSupp}_{t,H}(u) = 1$ when the response is jointly supportable. The condition is defined in Equation 69.

$$\text{JSupp}_{t,H}(u) = 1 \iff \mathfrak{J}_{t,H}(u) \neq \emptyset. \quad (69)$$

The definition in Equation 69 adds compatibility constraints to the local support sets of Section 6. Compatibility can concern common technical standards, synchronized timing, legal authorization, shared infrastructure, mutually exclusive resource claims, or sequencing requirements.

Proposition 10.2 (Local and joint supportability). *If $\text{JSupp}_{t,H}(u) = 1$ in Equation 69, then every required unit $\ell \in \mathcal{L}_t(u)$ has a nonempty local support set. The converse is not guaranteed by local nonemptiness alone: it additionally requires at least one tuple of locally supporting allocations and coordination-interface uses that satisfies the declared cross-scale compatibility conditions.*

Proof. Any element of $\mathfrak{J}_{t,H}(u)$ contains, by construction, a supporting local allocation for every required unit, so joint supportability implies local nonemptiness. Conversely, nonempty local support sets establish only the existence of supporting allocations unit by unit. If no selection of those allocations can be combined with admissible coordination interfaces while satisfying the declared synchronization, authorization, interoperability, or shared-resource constraints, then $\mathfrak{J}_{t,H}(u) = \emptyset$ even though every local support set is nonempty. $\square$

Timing creates a second joint-feasibility constraint. Let $\text{Lat}_t(u; \mathcal{C}_t)$ denote the critical-path latency of the declared coordination workflow for u , including the information, authorization, transfer, and synchronization steps represented in the application. Let $\Delta_t(u)$ denote an application-specific remaining coordination horizon within the response opportunity identified by the commitment-window analysis of Section 5; it records how much additional coordination delay the current opportunity can tolerate under the declared continuation policy. The coordination timing condition is stated in Equation 70.

$$\text{Lat}_t(u; \mathcal{C}_t) \leq \Delta_t(u). \quad (70)$$

Equation 70 does not prescribe a universal latency model. In parallel workflows, Lat_t can be computed from the relevant critical path; in institutional applications it can be estimated empirically from escalation, authorization, procurement, and mobilization times. Its analytical role is to make explicit that coordination occurring after a response branch has closed does not by itself restore the earlier action opportunity.

The effective response family can now be refined once more. Define the coordination-feasible response family by Equation 71.

$$\mathfrak{A}_{t,H}^{\text{coord}} = \left\{ u \in \mathfrak{A}_{t,H}^{\text{eff}} : \mathfrak{J}_{t,H}(u) \neq \emptyset \text{ and } \text{Lat}_t(u; \mathcal{C}_t) \leq \Delta_t(u) \right\}. \quad (71)$$

Equation 71 shows why additional organizational layers can either expand or contract effective optionality. A new interface can make previously fragmented resources jointly usable. The same interface can also introduce delay, authorization dependencies, or common bottlenecks that remove responses from the time-feasible family.

Figure 4 illustrates the distinction between coordination and control. A coordinating layer can aggregate information, issue interoperable standards, or mobilize pooled resources while execution and some fallback pathways remain distributed. The architecture can therefore combine vertical and lateral links rather than forcing all response capacity through one chain.

10.3 Selective Central Coordination

Selective central coordination refers here to the use of a wider-scope coordinating unit for functions that require integration across several otherwise distributed units. The concept is functional rather than constitutional. A coordinating unit can be governmental, inter-organizational, infrastructural, contractual, or temporary, and the same system can use different coordinating units for different functions.

Wider-scope coordination can become especially relevant when the response problem contains cross-scale coupling that cannot be resolved through independent local action alone. Examples include shared network congestion, incompatible local standards, emergency allocation of scarce common resources, synchronized containment, or a need to compare signals whose meaning emerges only across several sites. Folke and colleagues emphasize the role of bridging organizations and cross-level networks in adaptive governance, while Pahl-Wostl highlights multi-level learning and the interaction of multiple governance modes [11, 12]. Ostrom’s polycentric account is similarly useful because it treats multiple centers of action and broader coordination as potentially complementary rather than mutually exclusive [13].

The same coordinating layer can, however, create a common dependency. If every support pathway for a protected option class requires one coordinating authority, data service, communications backbone, or authorization channel, that component enters the common dependency core defined in Equation 46. Proposition 7.2 then applies directly to any represented failure mode that disables the common component. Selective central coordination therefore changes both the feasible-response set and its failure structure.

This tradeoff can be represented without reducing it to one scalar score. Let c denote a proposed coordination arrangement for response u . Its coordination footprint is the ordered record defined in Equation 72.

$$\text{CFoot}_{t,H}(c; u) = (\text{Lat}_t(c; u), \text{InfoRet}_t(c; u), \text{Mobil}_t(c; u), \text{DepAdd}_t(c; u), \text{Fallback}_t(c; u)). \quad (72)$$

The components in Equation 72 are application-specific and need not share a numerical scale. They record, respectively, coordination latency, preservation of action-relevant local information, added mobilization capacity, new dependency exposure, and fallback pathways available if the arrangement fails.

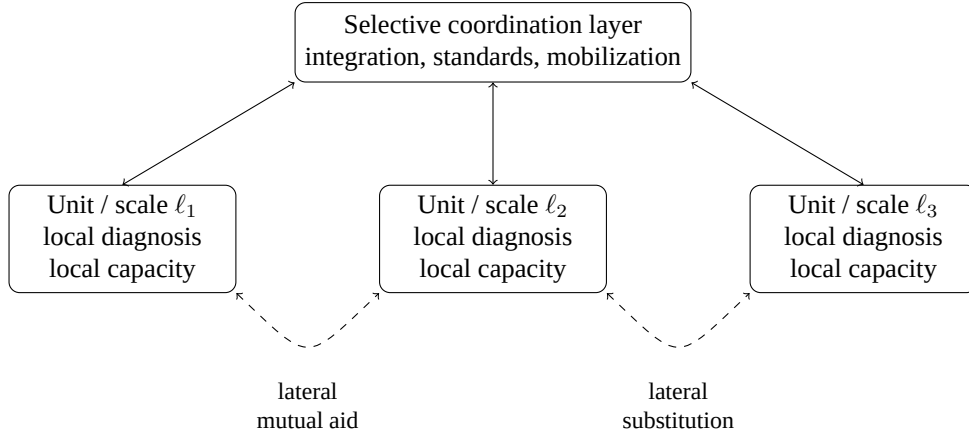


Figure 4: Illustrative multi-scale architecture with distributed local capacity, lateral pathways, and a selective coordination layer. The diagram represents one possible architecture rather than a preferred institutional form. Central integration can add cross-scale functions while lateral pathways preserve alternatives when the coordinating layer is delayed or unavailable.

The object is descriptive. A normative or operational decision still requires an explicit criterion for which components matter and how conflicts among them should be handled.

Hypothesis 10.3 (Selective coordination under cross-scale coupling). When a response depends on strongly coupled resources or synchronized actions across several units, and when coordination latency remains inside the relevant commitment window, adding an integration or mobilization layer can expand the coordination-feasible response family. The benefit can be reduced or reversed when aggregation removes action-relevant heterogeneity, the coordinating layer becomes a dependency shared by many protected response pathways, or the added latency exceeds the response window.

Hypothesis 10.3 is conditional and empirically testable. It does not establish a general preference for hierarchical consolidation. The relevant comparison is between concrete coordination architectures under declared failure modes, information requirements, resource constraints, and response horizons.

A useful design implication follows from Section 7. Central information integration can coexist with distributed execution, and centralized emergency mobilization can coexist with lateral mutual-aid paths or local fallback authority. Such combinations can reduce duplication for some functions while preserving failure-mode separation for others. Whether they succeed depends on the actual dependency graph rather than on the institutional label “centralized” or “decentralized.”

10.4 Cross-Scale Resource Mobilization and Failure Containment

The final multi-scale problem concerns movement of scarce resources across units. A higher-level pool or neighboring unit can rescue a local survival corridor, yet the transfer can simultaneously deplete the donor, consume transport capacity, or create a new dependency. Cross-scale mobilization should therefore be represented as a portfolio transformation rather than as costless redistribution.

For two units $\ell, m \in \mathcal{L}_t$, let a cross-scale transfer over delay τ be represented by the partial map in Equation 73.

$$\mathcal{T}_{\ell \rightsquigarrow m}^{\tau} : (\mathcal{B}_t^{(\ell)}, \mathcal{B}_t^{(m)}) \rightarrow (\mathcal{B}_{t+\tau}^{(\ell|m)}, \mathcal{B}_{t+\tau}^{(m|\ell)}). \quad (73)$$

The notation in Equation 73 allows the donor and recipient portfolios to change differently. Transfer can consume fuel, time, personnel, legal capacity, or reserve headroom in addition to the resource being moved. The map can also be undefined when interoperability, authority, transport, or timing requirements are absent.

A transfer that rescues the recipient can still undermine the donor's essential functions. Let $\mathcal{F}_\ell^*$ denote the donor's declared essential function family after transfer. The transfer is donor-safe relative to those functions when the condition in Equation 74 holds for some feasible post-transfer allocation $d^{(\ell)}$.

$$\exists d^{(\ell)} \in \mathcal{D}_{t+\tau} \left(\mathcal{B}_{t+\tau}^{(\ell|m)} \right) \quad \text{such that} \quad \kappa_f \left(\mathcal{B}_{t+\tau}^{(\ell|m)}; d^{(\ell)} \right) \in K_f^* \quad \forall f \in \mathcal{F}_\ell^*. \quad (74)$$

Equation 74 supplies a structural safeguard against solving one local bottleneck by silently exporting functional failure to another unit. The sufficiency regions remain application-specific and can incorporate distributional or legal constraints in addition to physical survival requirements.

Transfers can also change failure-mode dependence. If several local units are repeatedly stabilized from one common reserve or routed through one logistics hub, the reserve or hub can become a common dependency even when the recipient units remain geographically dispersed. Conversely, lateral transfers among units with genuinely different dependency structures can increase failure-conditioned coverage. Multi-scale coordination therefore interacts directly with the common-core analysis of Section 7.

The same reasoning applies to information and authority. Escalating every decision to one center can create a coordination queue whose delay closes local commitment windows. Delegating every decision locally can leave coupled externalities unresolved. A multi-scale architecture can instead allocate different functions to different levels: local observation and immediate protective action, cross-scale information integration, wider resource pooling, common interoperability standards, and explicitly bounded emergency authority. Table 9 summarizes these functions without implying that the same institutional allocation is appropriate in every domain.

Hypothesis 10.4 (Scale-matched functional allocation). Relative to an otherwise comparable architecture with substantial timing, capacity, authorization, or failure-exposure mismatches, a multi-scale governance architecture can preserve a broader set of usable future responses when critical functions are assigned to units whose characteristics are compatible with those functions' response timescales, while cross-scale interfaces remain available for functions that exceed local capability. The hypothesis permits different functions to be concentrated, distributed, or redundantly supported under the same overall architecture.

Hypothesis 10.4 provides the section's connection to Paper IV's larger argument. Functional resource distribution concerns more than how much capacity is allocated to observation, survival, reserve, or recovery. It also concerns where that capacity is situated, which interfaces make it jointly usable, how quickly coordination can occur, and whether the architecture retains fallback paths when one level or interface fails. Multi-scale coordination is therefore one component of distributed optionality rather than a separate institutional principle.

11 Illustrative Survival and Governance Cases

This section applies the preceding framework to four stylized governance cases. Its role is analytical rather than empirical: the cases are constructed to expose different combinations of diagnostic uncertainty, resource dissipation, functional conflict, hidden dependency, coordination latency, and recoverability. They do not describe particular jurisdictions, infer that any contemporary system is near criticality, or prescribe a preferred institutional design. The objective is to show how the same formal vocabulary can distinguish cases that would look similar if governance capacity were represented only by aggregate resources or by a binary choice between intervention and waiting.

For comparison, collect the principal objects relevant to a case c at time t in the case record defined in Equation 75.

$$\mathfrak{J}_{t,H}^{(c)} = \left(\mathfrak{D}_t^{\text{crit},(c)}(H), \mathcal{B}_t^{(c)}, \mathfrak{A}_{t,H}^{\text{eff},(c)}, \mathfrak{D}_{t,H}^{\text{dist},(c)}, \mathcal{C}_t^{(c)} \right). \quad (75)$$

The record in Equation 75 combines the diagnostic record of Equation 65, the functional portfolio of Equation 1, the effective response family of Equation 50, the distributed-optionality profile of Equation 47, and the coordination architecture of Equation 68. The object is intentionally incomplete. A real application would additionally require domain-specific causal models, legal and institutional constraints, distributional analysis, affected-party participation, and empirical calibration of resource and response timescales.

11.1 Coupled Urban Infrastructure Stress

Consider a stylized urban service system in which electricity, water pumping, communications, transport access, and emergency logistics are mutually dependent. A disturbance initially appears as a loss of electrical supply in part of the network. Two broad regime interpretations remain plausible. Under one interpretation, the disturbance is temporary and ordinary backup capacity is sufficient until restoration. Under another, the loss of electricity degrades communications and pumping, impedes fuel delivery and maintenance access, and thereby participates in a wider service cascade. The case is useful because the observed initiating event can be similar while the future resource requirements differ substantially across the candidate regimes.

The diagnostic problem first concerns regime discrimination. Passive monitoring can reveal outage duration, load redistribution, storage levels, communications quality, and restoration progress. Some observations can also be generated by ordinary operational changes that function as bounded probes, provided the resulting perturbation remains inside declared recovery constraints. Section 3 implies that increased observation is valuable only insofar as the observations discriminate among relevant regime hypotheses. A growing volume of telemetry can coexist with poor regime-level visibility when the same visible symptoms are compatible with both temporary disruption and cascading degradation.

The resource problem is more revealing. Suppose several nominal backup pathways exist for water pumping and communications. One pathway uses fixed backup generation, another mobile generation, and another reroutes service through an adjacent district. If all three require the same fuel-distribution corridor or the same communications service for dispatch and authorization, their architecture signatures can differ while their dependency signatures share a common component. The common-core result in Proposition 7.2 then applies under a failure mode that disables that component. The number of nominal backup plans therefore overstates failure-conditioned coverage.

The case also illustrates functional noncompensability. A large fiscal reserve does not immediately substitute for unavailable electrical switching equipment, trained repair personnel, physical access, or a functioning communications link. Equation 32 requires a jointly feasible allocation across the functions required by the contemplated response. Aggregate resource abundance can consequently coexist with local operational scarcity.

Waiting can have mixed effects. Additional observation can distinguish an ordinary restoration trajectory from a cascade, while battery reserves, potable-water storage, staff endurance, and accessible fuel can decline during the same interval. The waiting update in Equation 23 therefore changes both knowledge and the portfolio. If a later intervention depends on one of the depleted functions, the effective response family in Equation 50 can contract even as the diagnostic record improves.

A multi-scale architecture can enlarge the response family through mutual aid, shared repair teams, pooled reserve equipment, or wider information integration. Yet the coordination interface can itself become a bottleneck when every transfer requires one authorization channel or logistics hub. The relevant question is therefore whether wider coordination changes the support pathway family and its dependency structure, not whether the architecture carries a centralized or decentralized label.

11.2 Regional Provisioning under a Closing Logistics Window

Consider a stylized region facing a sudden increase in demand for essential consumables while the duration and geographical concentration of that demand remain uncertain. The resource portfolio includes

Table 10: Structural comparison of the four illustrative cases. The cases are stylized analytical constructions, not empirical diagnoses or policy recommendations.

Case	Principal uncertainty	Resource architecture issue	Main structural lesson
Coupled urban infrastructure	Temporary disturbance versus self-reinforcing service cascade	Backup systems share fuel, communications, access, or maintenance dependencies	Visible redundancy can coexist with a disabling common dependency core
Regional provisioning	Duration and spatial distribution of demand under a finite logistics window	Survival stocks, transport, personnel, and reserve capacity are time-sensitive and only partly substitutable	Better demand information can arrive after some response branches have become infeasible
Federated information and coordination	Whether disagreement reflects local heterogeneity, measurement failure, or wider regime change	Multiple decision centers can rely on one identity, data, communications, or authorization layer	Organizational plurality does not guarantee failure-mode separation
Shared water reserve	Temporary inflow shock versus persistent change in replenishment conditions	Present release supports survival while retained storage supports future response and recovery	Present protection and future optionality can draw on the same finite stock

current stocks, replenishment contracts, transport capacity, storage, trained personnel, liquidity, information systems, and reserve arrangements with neighboring units. Several of these resources are time-sensitive. Inventories are consumed, personnel can fatigue, transport slots expire, and upstream suppliers can become constrained as other regions draw on the same sources.

The diagnostic value of waiting is immediate. A longer observation interval can improve estimates of demand location, consumption rates, and the duration of disruption. The resource cost of waiting is equally immediate. Section 5 implies that these two trajectories should be represented separately. A decision can therefore occur at a later time with a narrower uncertainty set but a smaller family of supportable actions.

Let u^{bulk} denote a large replenishment action whose execution depends on a finite transport or procurement window. Its commitment window $\mathcal{T}_{u^{\text{bulk}}}^x(H)$ is defined by Equation 29. Suppose improved demand discrimination occurs only after the last checkpoint in that window. The later evidence can still be epistemically valuable: it can guide allocation of the resources that remain, reveal which earlier assumptions were wrong, and improve recovery planning. It cannot retroactively restore the expired transport slot. This is an instance of evidence-capacity divergence rather than evidence failure.

The same case makes resource conversion friction visible. Financial reserves can support later procurement only if suppliers, transport, authorization, and delivery time remain available. Spare vehicles can increase logistics capacity only when operators, fuel, access, and maintenance are jointly supportable. The conversion map in Equation 35 therefore represents a time-dependent transformation rather than an instantaneous exchange among fully substitutable resource categories.

Cross-scale transfers add another constraint. A neighboring unit can release stocks or transport capacity to preserve the recipient's survival corridor, but Equation 74 requires attention to the donor's own essential functions. A transfer that prevents one local failure can otherwise export vulnerability to the donor, especially when both units face correlated demand or depend on the same upstream supplier.

The case therefore distinguishes reserve quantity from reserve architecture. A larger nominal reserve can remain fragile when it is concentrated in one facility, reachable only through one transport route, or convertible only through a narrow institutional process. A smaller but functionally diverse portfolio can support more response pathways when it preserves alternative logistics, authorization, and replenishment structures. This comparison is structural rather than normative; distributional priority, rights, and

acceptable exposure require separate evaluation.

11.3 Federated Information and Coordination Capacity

Consider a governance system with several local decision units, each capable of monitoring conditions and initiating some protective responses. The units exchange information through a common data service, rely on a shared identity or authorization layer for some actions, and can request resources from a wider coordinating body. At first sight the system appears distributed because decision authority and operational staff are geographically and organizationally dispersed.

The framework distinguishes this organizational dispersion from distributed optionality. If the local units' principal support pathways all require the same data service, identity system, communications backbone, or approval mechanism, that component enters the common dependency core. A single represented failure mode can then remove several apparently independent response paths at once. The failure-conditioned coverage of Equation 44 captures this distinction more directly than a count of organizations or sites.

The case also exposes a multi-scale epistemic problem. Local records can disagree because conditions genuinely differ, because observation systems use different measurements, or because one unit is detecting a change that has not yet propagated elsewhere. Remark 10.1 implies that immediate aggregation can destroy information relevant to response. A wider coordinating unit can nevertheless be necessary to detect common exposure, compare timing, or recognize that several local anomalies depend on the same upstream cause.

Selective central coordination changes both capability and dependency. A common coordination layer can establish interoperable standards, pool scarce specialists, and reduce incompatible local actions. It can also create a queue, a single authorization point, or an information-processing bottleneck. The coordination footprint in Equation 72 makes these effects jointly visible without assigning one scalar score.

A useful contrast involves two architectures. In the first, local units retain bounded fallback authority, local copies of essential information, and lateral mutual-aid interfaces even when the common coordination layer is unavailable. In the second, every meaningful response requires successful access to the central service. Both architectures can use the same nominal number of local units. Their distributed-optionality profiles differ because their dependency signatures and failure-conditioned coverage differ.

This case therefore illustrates why “decentralized” and “centralized” are too coarse for the present problem. The analytically relevant questions concern which functions are distributed, which are integrated, what dependencies the interfaces create, how rapidly coordination occurs, and whether response pathways survive when one layer is unavailable.

11.4 Shared Water Reserve under an Uncertain Inflow Regime

Consider a stylized multi-unit water system that begins with a finite stored reserve and uncertain future inflow. The candidate regime family contains at least two interpretations: a temporary inflow deficit followed by ordinary replenishment, and a more persistent change in replenishment conditions. Current release supports drinking-water provision, sanitation, ecological or operational requirements, and other declared essential functions. Retained storage supports later survival, buffering, and recovery. The same physical stock therefore contributes to several functions whose temporal requirements can conflict.

The diagnostic problem is deliberately modest. Lower inflow, rising variability, or changing recovery behavior can motivate investigation of regime change, but Section 9 does not allow these observations to prove near criticality by themselves. A domain-specific application would need a mechanistic model, observation uncertainty, alternative explanations, and an explicit horizon. The stylized case assumes only that several materially different replenishment regimes remain plausible for the decision problem.

The resource conflict arises because current protection and future optionality draw on the same reserve. Releasing more storage now can preserve present essential functions or reduce immediate harm

while decreasing the reserve available if low inflow persists. Conserving more storage can preserve future buffering capacity while increasing present scarcity or distributional burden. Section 6 represents this as a joint allocation problem rather than as a choice determined by one scalar notion of resilience.

The functional-survival corridor in Equation 28 is useful because survival need not mean preservation of the initial operating state. A reduced service configuration can remain inside declared sufficiency sets for essential functions while conserving enough reserve to preserve later responses. Conversely, a policy that maintains the original service level for several periods can remain outside a defensible survival architecture if it consumes the capacity needed for a plausible persistent-deficit regime. Which sufficiency sets and burdens are acceptable remains a normative and institutional question outside the structural formalism.

Cross-scale coordination becomes relevant when stored water, treatment capacity, pumping capacity, or emergency supply can move among units. A transfer can increase the recipient's survival coverage while reducing the donor's reserve and changing dependency on shared transport or energy infrastructure. The donor-safety condition of Equation 74 therefore applies alongside the common-dependency analysis of Section 7.

The case also clarifies recoverability. Exact restoration of an earlier storage level may be impossible over the relevant horizon. A governance architecture can nevertheless preserve recovery capacity by maintaining treatment equipment, alternative intake options, monitoring, maintenance capability, financial and legal capacity, and coordination relationships. Recoverability therefore concerns the ability to construct viable future service configurations rather than the guaranteed return of the physical system to its initial state.

11.5 Cross-Case Structural Comparison

The four cases share a common analytical structure while differing in which constraint is dominant. In the infrastructure case, hidden common dependencies can invalidate visible redundancy. In the provisioning case, information improves while commitment windows close. In the federated-coordination case, institutional plurality can coexist with concentrated infrastructural dependence. In the water-reserve case, present survival and future optionality compete for the same finite stock.

These differences matter because no single resource rule follows from the framework. A policy of maximizing reserves can fail when immediate survival collapses first. A policy of maximizing current service can fail when it exhausts recovery capacity. A policy of decentralizing resources can leave shared dependencies untouched. A policy of centralizing coordination can solve interoperability problems while creating one disabling bottleneck. A policy of waiting for better evidence can improve discrimination while allowing response branches to expire. The framework therefore organizes tradeoffs and failure structures rather than supplying a universal allocation formula.

The cases also show why the effective response family is a more useful operational object than a nominal action list. In each case, an action can remain legally or conceptually imaginable while becoming unsupported because a required resource, interface, dependency, or commitment window has changed. The relation among Equations 50, 44, and 71 captures three successive filters: portfolio support, failure-mode survival, and coordination feasibility.

A final distinction concerns temporal asymmetry. Resources used for present survival can sometimes be replenished; some commitments can be reversed; some coordination failures can be bypassed. Other losses can close pathways for the relevant horizon. Paper IV therefore treats optionality as a property of a changing support architecture rather than as a stock that can simply be maximized once. The empirical task is to identify which dependencies, conversions, and windows are actually operative in the domain under study. The normative task is to determine which functions, populations, rights, burdens, and future opportunities should be protected when they cannot all be preserved simultaneously.

12 Discussion and Limitations

This section consolidates the analytical contribution of the paper and states the limits under which its formal vocabulary should be interpreted. Its role is to separate three levels that can otherwise become conflated: structural descriptions of supportability, empirical claims about near-critical systems, and normative judgments about legitimate governance. The discussion first identifies the contribution specific to this paper, then examines normative non-closure, empirical identification, resource and dependency representation, multi-scale boundaries, and the relation to the two companion manuscripts on governance and evidence near criticality. The objective is to make the framework easier to criticize and operationalize by stating explicitly what its constructions do and do not establish.

12.1 Analytical Contribution and Scope

The paper's central contribution is a resource-architectural account of governance capacity under conditional near-criticality. Earlier sections treat governance capacity as more than an aggregate stock. A portfolio can contain resources that support observation, probing, survival, commitment, reserve, and recovery to different degrees; these functions can overlap, compete, require conversion, and depend on common infrastructure. The framework therefore shifts attention from the quantity of available resources toward the composition of support pathways through which future responses remain executable.

Three distinctions organize that contribution. First, resource abundance is separated from joint functional supportability. A system can possess substantial nominal resources while lacking a feasible allocation for a response whose requirements must be met simultaneously. Second, visible diversity is separated from failure-mode separation. Several pathways can remain exposed to one common dependency and disappear together under a represented failure. Third, informational improvement is separated from action-capacity preservation. Observation can refine the diagnostic record while dissipative delay, commitment-window closure, or resource reallocation reduces the effective response family.

These distinctions support the paper's use of *distributed optionality*. The term denotes a property of an evolving support architecture in which materially different future responses remain backed by functionally diverse and sufficiently non-coincident pathways. It does not denote the number of nominal choices, geographical dispersion by itself, or a general preference for postponing commitment. Optionality is distributed only relative to declared response families, resource functions, dependency representations, failure modes, horizons, and coordination conditions.

The framework remains architectural rather than optimizing. It identifies feasible allocations, pathway structures, dependency cores, commitment windows, recovery coverage, and coordination constraints. It does not derive a universally optimal portfolio, an optimal intervention time, or a scalar resilience objective. Such results would require additional assumptions about probabilities, losses, social objectives, rights, authority, distribution, and the value assigned to different future capabilities. The absence of a universal optimum is therefore part of the framework's scope rather than a missing theorem that can be supplied without further normative and empirical structure.

Table 11 makes the division of analytical labor explicit. The three manuscripts form a sequence of questions rather than three competing theories. The first develops the response problem, the second isolates the evidence-to-action problem, and the present paper develops the resource-support problem that remains after response sensitivity and evidential instability are acknowledged.

12.2 Normative Non-Closure and Distributional Structure

The formal constructions in this paper do not determine which functions deserve protection, whose survival claims have priority, which risks are acceptable, or how burdens should be distributed. Those judgments enter through objects that the framework deliberately leaves application specific: the essential-function family, sufficiency sets, footprint constraints, protected response classes, transfer rules, and the institutional authority to define or revise them. Changing these specifications can change which continuation histories count as survival-supporting and which responses count as bounded or acceptable.

Table 11: Distinct analytical roles of the three near-criticality manuscripts. The boundaries are functional rather than absolute; concepts can interact across the manuscripts without collapsing their principal questions.

Manuscript	Principal question	Primary analytical objects	Boundary retained in the present paper
Governance Near Criticality	How should political response be conceptualized when susceptibility and trajectory consequences can be unusually high?	Perturbation–response relations, restraint, reversibility, trajectory closure, future option space, legitimacy	Paper IV inherits this response problem and does not re-derive its general normative vocabulary
Evidence-to-Action near Criticality	How can evidence remain locally informative while the warrant for intervention changes with the response regime?	Regime transport, evidential validity, reversibility, action warrant, adaptive updating	Paper IV uses these distinctions only where changing evidence interacts with resource support and pathway closure
Present paper	How can heterogeneous governance capacity be composed when diagnosis is incomplete, waiting dissipates resources, and future responses depend on non-substitutable functions?	Functional portfolios, feasible allocations, support pathways, dependency cores, failure-conditioned coverage, commitment windows, coordination feasibility	The paper stops short of deriving a universal response ranking or normative allocation rule

Distributed optionality is therefore not a freestanding normative good. Maintaining additional pathways can consume resources needed for present protection, preserve harmful options, entrench veto points, or shift burdens onto actors whose capacities are being held in reserve for others. Conversely, closing some pathways can be justified when continued availability itself creates severe exposure or violates rights. The structural statement that one architecture preserves more represented options does not establish that it is more just or legitimate.

The same limitation applies to reserve and recovery capacity. A portfolio that preserves substantial future recovery capability can impose serious present deprivation if current provisioning is reduced to protect reserves. A portfolio that maximizes immediate survival can impose future vulnerability on later populations or neighboring units. Donor-safety constraints in cross-scale transfer protect only the declared essential capability of the donor within the model; they do not resolve questions of distributive justice, historical entitlement, democratic authorization, intergenerational obligation, or the distribution of uncertainty.

Power also enters the framework through more than resource possession. Actors can influence which functions are declared essential, which dependencies are recorded, which failure modes are considered credible, whose observations enter the diagnostic record, and which responses are legally or politically executable. A formally broad response repertoire can therefore coexist with highly unequal standing or control over activation. The present paper represents some of these effects indirectly through authorization, coordination, and supportability, but it does not supply a general theory of power, legitimacy, or procedural justice.

For that reason, the resource architecture should be read as a substrate for normative analysis. It can reveal that a proposed policy protects one group by consuming a shared recovery resource, that an apparently diversified system relies on one common dependency, or that a delayed decision removes a later option. The judgment that follows requires additional moral, legal, political, and institutional argument.

12.3 Empirical Identification and Model Dependence

Every substantive application depends on a representation of the system, the candidate regime family, the relevant horizon, and the diagnostic mechanisms under consideration. Section 9 therefore treats criticality attribution as mechanism indexed and uncertainty preserving. Rising autocorrelation, variance, recovery time, susceptibility, flickering, network fragility, or timescale deformation can be informative under specific models while remaining ambiguous under others. The framework does not convert their conjunction into a universal test of near criticality.

Model dependence extends beyond diagnosis. The accessible-regime family can change when new variables, mechanisms, or boundary conditions are introduced. Recovery can appear possible under a coarse functional readout and unavailable under a more demanding one. A pathway can look independent until an omitted supplier, legal dependency, identity service, or coordination layer is added to the dependency representation. Failure-conditioned coverage is therefore conditional on the modeled failure family rather than a guarantee against unknown disruptions.

The response-coverage object is also conditional on the declared resource-operation repertoire $\mathcal{Q}_t^{\mathcal{P}}$. Replenishment, conversion, maintenance, institutional change, and release from prior commitments enlarge reachability only when those operations are represented as admissible and executable within the horizon. Coverage should therefore not be read as a property of the portfolio alone. Cross-time claims that an effective response family has expanded or contracted require a stable response taxonomy or an explicit mapping between response identities at the two checkpoints; otherwise set inclusion can confuse reclassification with genuine gain or loss of action capacity.

Horizon choice creates a similar dependence. A resource can appear substitutable over a long horizon and non-substitutable over an emergency horizon because conversion or replenishment requires time. A response can be reversible over one interval and effectively irreversible over another. A commitment window can reopen after replenishment or institutional change. Claims about survival, reserve, recovery, and optionality should consequently state the temporal horizon over which their support relations are evaluated.

Empirical operationalization also requires observability that the abstract framework does not assume. Resource inventories can be incomplete, private, strategically withheld, or difficult to compare. Dependency structures can be latent. Institutional capacity can change during the observation process. The system can respond to the publication of diagnostic information or to visible preparation for intervention. These features make parameter estimation and causal attribution separate research tasks rather than consequences of the formal notation.

The paper's formal propositions are therefore internal conditional results. They state what follows when the relevant sets, maps, dependencies, and admissibility relations are specified as assumed. They do not establish that a real political or social system possesses those structures with the required fidelity. Empirical work must determine whether a proposed representation is sufficiently informative for the decision problem and whether rival representations change the conclusion materially.

12.4 Resource Representation and Institutional Endogeneity

The functional portfolio is intentionally heterogeneous, but its categories remain analytical abstractions. A single resource carrier can support several functions simultaneously, and several carriers can combine nonlinearly to support one function. Institutional authority, trust, trained personnel, physical infrastructure, data access, fiscal liquidity, and logistical capacity differ in divisibility, replenishment, ownership, and transferability. The support correspondence in Section 6 records functional eligibility without claiming that these properties share one measurement scale.

The same caution applies to conversion maps. Resource conversion is modeled as partial and time dependent because conversion can require legal authorization, technical transformation, transport, procurement, learning, or coordination. Real conversions can also impose distributional burdens, destroy qualities not represented by the target function, or create dependencies that become visible only later. A formal map from one functional role to another therefore records feasibility under declared conditions;

it does not imply lossless substitution or social equivalence between the resources involved.

Response repertoires are also endogenous. Law, legitimacy, technology, organizational learning, coalition structure, market access, and prior decisions can create or eliminate feasible responses. The framework captures some of this endogeneity through changing portfolios, commitment windows, coordination interfaces, and state-dependent supportability. It remains possible, however, for a real intervention to change the institutional rules that determine the repertoire itself in ways that are not represented by the current state variables. Applications involving such reflexivity require an expanded state representation rather than treating the existing response family as fixed background.

A related limitation concerns maintenance. Distributed architectures can require duplicated infrastructure, interoperability work, inventories, training, testing, and periodic coordination. Redundancy can therefore carry substantial carrying costs. The present framework can represent those costs through portfolio updates and dissipative continuation, but it does not estimate them automatically. An architecture with greater failure-mode separation can be less sustainable if its maintenance burden depletes the very capacities it is meant to preserve.

Table 12 summarizes the distinction between structural representation and substantive application. The formal objects can organize evidence and expose missing assumptions, but their empirical and normative content must be supplied in the domain where the framework is used.

12.5 Multi-Scale Boundaries and Coordination Risks

Section 10 treats scale as part of the governance problem because observation, resources, authority, and response times can differ across units. The resulting framework nevertheless simplifies several cross-scale difficulties. Geographic, administrative, ecological, infrastructural, and temporal scales need not coincide. A local unit can be nested administratively within one jurisdiction while depending materially on infrastructure located elsewhere. A resource transfer can be local in space and cross-scale in authority. The choice of governance units is therefore itself an analytical decision.

Coordination can also generate strategic behavior that is not modeled explicitly. Units can under-report capacity to preserve local reserves, overstate need to obtain transfers, delay disclosure, or rely on expectations that another unit will provide backup. Shared reserves can generate free-riding or withholding incentives. Central coordination can alter those incentives while creating new informational and authorization bottlenecks. Modeling such behavior requires game-theoretic, institutional, historical, or qualitative extensions rather than treating the coordination graph as a complete account of collective action.

Correlated failures provide another boundary. Section 7 represents declared failure modes and shared dependencies, yet real failures can combine mechanisms or propagate through dependencies that were individually considered unlikely. A portfolio robust to each modeled single failure can remain vulnerable to compound events. Single-mode option continuity should therefore be interpreted as one stress-test criterion rather than a general theorem of resilience.

The paper also avoids deriving a universal scale of coordination. Some functions can benefit from local autonomy because response latency matters and local information is rich. Others can require wider integration because resources, externalities, standards, or correlated risks cross local boundaries. The appropriate distribution of functions is contingent on those structural properties and on institutional legitimacy. Scale-matched allocation is therefore a hypothesis for inquiry, not a prescription for a particular constitutional form.

12.6 Research Programme and Operationalization

The framework can support empirical research through progressive operationalization rather than immediate full-system estimation. One starting point is a narrowly defined response problem with a small number of essential functions, a declared horizon, and a limited candidate regime family. Analysts can then identify the resources required by each response, map conversion and replenishment delays, enu-

Table 12: Principal scope boundaries of the framework and the additional work required for application.

Framework object	What the object can represent	Additional work required for substantive use
Near-critical diagnostic record	Mechanism-indexed evidence, uncertainty, and competing regime interpretations	Domain-specific identification, measurement validation, rival-mechanism testing, and horizon specification
Functional resource portfolio	Heterogeneous support roles and conflicts among governance functions	Measurement of actual capacities, ownership, accessibility, quality, and replenishment dynamics
Support and conversion maps	Feasible allocation, reassignment, and conversion relations under declared conditions	Empirical conversion time, loss, transaction cost, institutional permission, and distributional burden
Distributed-optionality profile	Coverage, pathway diversity, dependencies, and failure-conditioned survival of options	Selection of relevant response classes, dependency discovery, failure-mode construction, and maintenance-cost estimation
Multi-scale coordination architecture	Information, transfer, authorization, standards, latency, and fallback relations across units	Institutional mapping, interoperability analysis, authority and legitimacy assessment, and correlated-failure analysis
Survival and recovery targets	Functional sufficiency and recoverability over a declared horizon	Normative justification of protected functions, populations, thresholds, rights, and acceptable burdens

merate major dependencies, and test whether nominally distinct pathways survive selected failure modes. This produces an auditable support architecture even before a complete dynamical model is available.

A second route is retrospective comparison. Historical episodes can be reconstructed to ask which response branches were actually supportable at successive checkpoints, which resources or interfaces became binding, and whether improved information arrived before or after relevant commitment windows closed. Such analysis would not prove near criticality by itself. It could nevertheless test narrower propositions about dissipative delay, hidden dependencies, resource non-substitutability, coordination latency, and evidence–capacity divergence.

A third route is prospective stress testing. Institutions can compare portfolios under alternative regime hypotheses and failure families, examining how the effective response family changes when a dependency is removed, a conversion takes longer than expected, or observation consumes more capacity than assumed. The objective would be to identify structurally consequential assumptions rather than to certify one architecture as robust in every future.

Across these approaches, the framework is most useful when it makes disagreement more explicit. Disagreement can concern the criticality mechanism, the relevant horizon, the sufficiency threshold for an essential function, the completeness of the dependency map, the legitimacy of a transfer, or the value of preserving a future pathway. These are different disagreements and call for different forms of evidence and judgment. Keeping them separate is a principal methodological advantage of the resource-architectural approach.

The paper therefore closes its discussion with a limited research claim. Governance near a plausible critical transition can be studied as a problem of maintaining supportable functions and response pathways under evolving diagnostic uncertainty, resource dissipation, and institutional interdependence. The framework provides a vocabulary for that study. Its adequacy depends on the quality of the empirical representation, the explicitness of the normative commitments, and the willingness to revise the model when omitted dependencies or alternative mechanisms become visible.

13 Conclusion

This paper has examined a resource problem that arises once governance near a plausible critical transition is treated as more than a problem of choosing an intervention. When the future response regime remains uncertain, observation and probing can become valuable; when the system is dissipative, delay can simultaneously consume the capacities required for protection, commitment, and recovery. The resulting governance problem concerns the composition of response capacity over time. The paper has developed a structural vocabulary for that problem through functional resource distribution and distributed optionality, while retaining the conditional status of the near-criticality hypothesis and the normative openness of the allocation problem.

The analysis began by treating near criticality as a model-relative diagnostic profile rather than a scalar condition. Candidate regimes, direction- and horizon-sensitive response properties, and function-relative recovery structures can jointly make the resource problem more consequential without establishing a universal criticality index. Section 9 later made the corresponding empirical discipline explicit. Recovery dynamics, fluctuation statistics, susceptibility, flickering, network structure, and timescale deformation can contribute evidence under particular mechanisms, while disagreement among indicators, alternative explanations, measurement limitations, and model uncertainty remain part of the diagnostic record. Political crisis, rapid change, or institutional stress therefore remain insufficient by themselves to establish the near-critical condition assumed in the paper's conditional arguments.

Sections 3 and 4 then located observation and response inside the evolving governance architecture. Regime-level visibility depends on the observation architecture and can remain coarse even when the consequences of misclassification are large. Perturbations can sometimes refine diagnosis, yet probes are themselves interventions that can consume resources and alter the system they are intended to reveal. Response was consequently represented as a joint transformation of system configuration, functional resource portfolio, and future response repertoire. This representation separates intervention magnitude from commitment depth: a materially small act can strongly narrow later pathways, while a larger temporary intervention can remain comparatively revisable if adequate exit and recovery capacities are preserved.

The temporal problem developed in Section 5 follows from the same architecture. Waiting was represented as a continuation policy rather than as absence of action. Monitoring, buffering, maintenance, provisioning, coordination, and replenishment can continue while a larger commitment is deferred. These activities can improve diagnosis while depleting survival, reserve, or recovery capacity. The resulting evidence–capacity divergence is central to the paper: a system can become better understood while the family of materially supportable responses becomes smaller. The practical value of additional information therefore depends partly on whether the capabilities needed to use that information remain available when it arrives.

Section 6 developed the resource side of this argument. The functional portfolio distinguishes observation, probing, survival, commitment, reserve, and recovery as analytical roles without assuming additivity, independence, or lossless substitutability. Identifiable resource carriers can support several functions, compete across allocations, or require conversion before they become useful elsewhere. Feasible allocation and joint sufficiency matter because nominally abundant resources can still fail to support a response whose requirements must be met simultaneously. Conversely, comparatively limited resources can preserve a wider effective response family when they are accessible, appropriately composed, and convertible within the relevant time window.

The concept of distributed optionality in Section 7 adds an architectural qualification to resource coverage. A response repertoire is not robust merely because it contains several nominal alternatives. Alternative pathways can share the same supplier, communication system, legal authorization, identity infrastructure, technical standard, or coordinating institution. The analysis therefore distinguished baseline coverage, architecture-distinct redundancy, dependency structure, and failure-conditioned coverage. The common-dependency result formalizes a simple but consequential point: visible diversification can leave a response family jointly vulnerable when every pathway passes through the same disabling de-

pendency. Distributed optionality accordingly concerns materially different future responses supported through sufficiently non-coincident pathways, not the number of options listed in advance.

Section 8 connected this architecture to evidence without reproducing the broader evidence-to-action argument developed elsewhere. Evidence can change the modeled regime family, the estimated recovery structure, or the expected resource demands of a response. Resource dissipation and pathway closure can change the effective response family at the same time. These trajectories need not move together. Improved evidence can support stronger commitment, more selective intervention, continued observation, or withdrawal from a formerly plausible action depending on what the evidence reveals about response conditions and which capacities remain supportable. The framework therefore treats evidence as one input into an evolving evidence–capacity state rather than as a direct instruction for intervention intensity.

The multi-scale analysis in Section 10 further shows why distributed capacity does not imply a general preference for decentralization. Local units can each possess feasible component responses while the combined response remains infeasible because of incompatible standards, authorization, shared-resource conflicts, or coordination latency. Selective central coordination can make otherwise fragmented resources jointly usable, integrate information, or mobilize emergency capacity. The same coordinating layer can also introduce delay, information loss, or a common point of failure. Cross-scale allocation therefore remains function specific. Observation, provisioning, authorization, reserve maintenance, and recovery can each have different appropriate scales under different horizons and dependency structures.

The stylized cases in Section 11 demonstrate how these distinctions interact. Coupled urban infrastructure can contain many visible backups while relying on one hidden fuel, communication, or dispatch dependency. Regional provisioning can gain information about demand while inventories and logistics windows deteriorate. Federated information systems can appear institutionally plural while resting on concentrated infrastructural services. A shared water reserve can protect current survival while simultaneously reducing future buffering and recovery capacity. None of these cases yields a universal allocation rule. Together they show why the relevant governance object is an evolving architecture of functions, dependencies, timing constraints, and recovery possibilities rather than a single stock of resources or a single preferred response mode.

The resulting contribution is therefore limited but structurally specific. The framework can represent which functions compete for the same carriers, which responses require simultaneous support, which pathways share hidden dependencies, which options are lost or gained during delay, which evidence arrives before or after a commitment window closes, and which coordination interfaces enable or obstruct joint action. These objects can support comparison, stress testing, retrospective reconstruction, and empirical operationalization. They do not determine which function should receive priority, which losses are acceptable, whose survival claims dominate, which future pathways deserve preservation, or which institution possesses legitimate authority to allocate scarce capacity.

This normative non-closure is especially important for the language of survival and optionality. Functional survival concerns the persistence of declared capabilities, not the preservation of every existing institution or regime. Recoverability concerns the capacity to construct a viable subsequent path, not necessarily restoration of a prior state. Distributed optionality concerns supportable future responses, not the indefinite preservation of every possible action. Each of these objects depends on declared horizons, sufficiency conditions, resource representations, failure families, and normative specifications. Their value can change when present deprivation, rights, distributive burdens, democratic authorization, inter-generational claims, or severe irreversible harms are introduced into the judgment.

Within these limits, the paper suggests a particular way to formulate governance near uncertain regime change. The relevant question is not only how strongly a system should be steered, nor only how much evidence should be gathered before action. It is also how observation, experimentation, present protection, selective commitment, reserve, and recovery remain jointly supportable while time passes and the response architecture changes. That question becomes especially salient when resources are heterogeneous, substitution is incomplete, hidden dependencies matter, and information can improve after some actions have already ceased to be feasible.

The paper therefore closes with a conditional orientation rather than a general prescription. Under a

defensible near-criticality hypothesis, governance capacity can be studied as an evolving support architecture in which diagnosis, resource composition, delay, dependency, coordination, and recovery interact. Preserving this architecture can sometimes favor diversification, sometimes concentration, sometimes staged action, sometimes decisive commitment, and sometimes continued observation. The framework's role is to make the structural conditions of those alternatives explicit. Empirical evidence and normative judgment remain necessary to determine which architecture, response, or sacrifice is warranted in any particular case.

References

- [1] C. S. Holling. "Resilience and Stability of Ecological Systems." *Annual Review of Ecology and Systematics*, 4:1–23, 1973. doi:10.1146/annurev.es.04.110173.000245.
- [2] Marten Scheffer, Steve Carpenter, Jonathan A. Foley, Carl Folke, and Brian Walker. "Catastrophic shifts in ecosystems." *Nature*, 413:591–596, 2001. doi:10.1038/35098000.
- [3] Carl Folke. "Resilience: The emergence of a perspective for social–ecological systems analyses." *Global Environmental Change*, 16(3):253–267, 2006. doi:10.1016/j.gloenvcha.2006.04.002.
- [4] Marten Scheffer, Jordi Bascompte, William A. Brock, Victor Brovkin, Stephen R. Carpenter, Vasilis Dakos, Hermann Held, Egbert H. van Nes, Max Rietkerk, and George Sugihara. "Early-warning signals for critical transitions." *Nature*, 461:53–59, 2009. doi:10.1038/nature08227.
- [5] Vasilis Dakos, Stephen R. Carpenter, William A. Brock, Aaron M. Ellison, Vishwesha Guttal, Anthony R. Ives, Sonia Kéfi, Valerie Livina, David A. Seekell, Egbert H. van Nes, and Marten Scheffer. "Methods for Detecting Early Warnings of Critical Transitions in Time Series Illustrated Using Simulated Ecological Data." *PLOS ONE*, 7(7):e41010, 2012. doi:10.1371/journal.pone.0041010.
- [6] Carl Boettiger and Alan Hastings. "Quantifying limits to detection of early warning for critical transitions." *Journal of the Royal Society Interface*, 9(75):2527–2539, 2012. doi:10.1098/rsif.2012.0125.
- [7] Rong Wang, John A. Dearing, Peter G. Langdon, Enlou Zhang, Xiangdong Yang, Vasilis Dakos, and Marten Scheffer. "Flickering gives early warning signals of a critical transition to a eutrophic lake state." *Nature*, 492:419–422, 2012. doi:10.1038/nature11655.
- [8] Vasilis Dakos, Stephen R. Carpenter, Egbert H. van Nes, and Marten Scheffer. "Resilience indicators: prospects and limitations for early warnings of regime shifts." *Philosophical Transactions of the Royal Society B: Biological Sciences*, 370(1659):20130263, 2015. doi:10.1098/rstb.2013.0263.
- [9] Marten Scheffer, Stephen R. Carpenter, Vasilis Dakos, and Egbert H. van Nes. "Generic Indicators of Ecological Resilience: Inferring the Chance of a Critical Transition." *Annual Review of Ecology, Evolution, and Systematics*, 46:145–167, 2015. doi:10.1146/annurev-ecolsys-112414-054242.
- [10] Xueming Liu, Daqing Li, Manqing Ma, Boleslaw K. Szymanski, H. Eugene Stanley, and Jianxi Gao. "Network resilience." *Physics Reports*, 971:1–108, 2022. doi:10.1016/j.physrep.2022.04.002.
- [11] Carl Folke, Thomas Hahn, Per Olsson, and Jon Norberg. "Adaptive Governance of Social-Ecological Systems." *Annual Review of Environment and Resources*, 30:441–473, 2005. doi:10.1146/annurev.energy.30.050504.144511.

- [12] Claudia Pahl-Wostl. “A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes.” *Global Environmental Change*, 19(3):354–365, 2009. doi:10.1016/j.gloenvcha.2009.06.001.
- [13] Elinor Ostrom. “Polycentric systems for coping with collective action and global environmental change.” *Global Environmental Change*, 20(4):550–557, 2010. doi:10.1016/j.gloenvcha.2010.07.004.

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