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Prototyping Interventions to Prevent Harmful Cascades

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Abstract

This article develops a conceptual account of prototyping as cascade modulation. Building on systemic mapping and on the companion method for detecting potential cascades, it examines how deliberate displacements might influence propagation, closure, and recoverability. The focus is harmful closure: the loss of viable alternatives for specified actors faster than those alternatives can be restored.

Eight proposed strategies organize the account: dispersion, selective amplification, dampening, redirection, buffering, threshold modulation, controlled release, and staged recovery. They are related to five candidate leverage sites: early alignment, fragility, routing nodes, boundary interfaces, and accumulated constraint. Prospective, computational, and situated prototypes supply different ways to investigate these relationships, without making simulated or anticipated effects equivalent to field evidence.

Constructed curbside and hospital-discharge scenarios illustrate the strategies; no new field or clinical study is reported. The paper distinguishes pathway-specific changes from competing attractors, and examines timing, interaction, and the possibility that a well-intended intervention displaces harm or creates a new dependency.

The contribution is a vocabulary and planning framework for trajectory stewardship. It does not supply validated intervention prescriptions. Practical use requires an explicit account of affected parties, permissible changes, comparison conditions, harms, and recovery or stopping arrangements. The strategies are proposals to investigate under those conditions, not guarantees that harmful cascades will be prevented.

Keywords: cascade modulation; systemic design; prototyping; intervention; leverage; closure; recoverability

SCOPE AND PLACE IN THE SERIES

This is the modulation paper in the four-part Cascades in Design series. Design in the Age of Cascades provides the conceptual foundation; Prototyping for Awareness of Potential Cascades develops detection; Prototyping Positive Cascades addresses cultivation. This paper can be read independently: its urban and clinical examples are analytical constructions, not evidence of interventions conducted by the authors.

INTRODUCTION: FROM DETECTION TO MODULATION

The companion paper Prototyping for Awareness of Potential Cascades proposes systemic prototyping as a means of examining propagation and closure. Its apparatus combines deliberate displacement with retained systemic maps, preserving the conditions under which a relationship is hypothesized, simulated, or observed. That proposal builds on systemic mapping and cascade research (de la Rosa & Ruecker, 2020; Watts, 2002; Meadows, 1999). The present article takes the next methodological question: how might an intervention alter a pathway whose dynamics have been sufficiently investigated?

The present article extends that framework by shifting from detection to modulation. Once cascade dynamics are rendered legible, design practice can engage them directly. Prototypes no longer function only as probes that expose system behavior. They become interventional instruments that shape the formation, direction, and intensity of cascades as they unfold.

This shift does not introduce a new apparatus. It reorients the existing one. The same structure of displacement, mapping, and overlay is retained. What changes is the intent with which displacements are constructed. Instead of asking what trajectories a system affords, the designer asks how those trajectories might be altered while they remain in formation. The concern moves from description to participation, from observing how closure emerges to influencing the conditions under which it accelerates or is delayed. This repositioning aligns with accounts of complex systems in which local interactions generate emergent and often nonlinear outcomes that cannot be fully specified in advance (Allen, 2014; Perrow, 1984).

The distinction can be articulated as a difference between two functions of prototyping. In the first, prototypes operate as cascade detectors. They are designed to reveal how local changes propagate and how those propagations interact with constraints. In the second, prototypes operate as cascade modulators. They are designed to alter

propagation pathways, redistribute alignment pressures, and preserve or redirect optionality within the system.

This reorientation builds on existing accounts of design as an intervention in ongoing situations rather than as the production of discrete artifacts (Schön, 1992; Nelson & Stolterman, 2003). It also extends participatory and infrastructuring approaches that treat design activity as embedded within evolving systems (Hillgren, Seravalli, & Emilson, 2011; Karasti, 2014). Work in policy prototyping further demonstrates how interventions can be introduced in live institutional contexts to explore and shape downstream effects under conditions of uncertainty (Bason, 2014; Kimbell & Bailey, 2017). The present contribution lies in specifying how such interventions can be directed toward cascade dynamics, using propagation, closure, and recoverability as operative parameters.

A system in which cascades are active can be understood as a field of trajectories in partial alignment. At early stages, multiple trajectories coexist, and alignment pressures are distributed. As cascades develop, certain pathways become reinforced while others diminish. Closure accelerates when alignment outpaces the system's capacity to generate or sustain alternatives (Granovetter, 1978; Vaughan, 1996). Modulation operates within this process. It does not halt cascades. It alters their configuration by redistributing how alignment occurs and where effects are directed.

This perspective introduces a different criterion for intervention. The question is not whether a design produces a desired outcome in isolation. It is how that design participates in the ongoing dynamics of the system. An intervention may be evaluated in terms of whether it amplifies particular trajectories, dampens emerging instabilities, redirects propagation into more manageable pathways, or preserves recoverability by maintaining alternative options (Meadows, 1999; Verbeek, 2011).

The sections that follow articulate a set of prototyping strategies that operate within this framework. These strategies are not abstract categories but operational patterns that can be enacted through prospective, computational, and situated prototyping. Each strategy engages cascade dynamics at a different point in their development, from early-stage dispersion to late-stage recovery. Together, they provide a vocabulary and a set of practices for treating design as a form of trajectory stewardship, in which the aim is not to eliminate complexity but to shape how it unfolds over time.

LITERATURE REVIEW

This article extends a line of work that treats prototypes as instruments for investigating complex systems, repositioning them as interventional devices that can modulate cascade dynamics. While the companion detection paper proposed a framework for detecting cascades through systemic prototyping, the present review expands the scope to include traditions in which prototypes participate directly in shaping social, institutional, and infrastructural conditions. The result is a composite view in which prototyping operates not only as a mode of inquiry, but as a form of situated intervention with downstream consequences.

A first strand provides continuity with systemic design and prototyping as inquiry. Design research has examined the interdependence of problem framing and possible responses, alongside the distinctive character of designerly inquiry (Rittel & Webber, 1973; Cross, 2001), and more recent work has extended this orientation to complex social systems (Irwin, 2015; Jones, 2014). Within this trajectory, systemic mapping and participatory design approaches have demonstrated how prototypes can be used to generate high-resolution representations of evolving systems (de la Rosa & Ruecker, 2020; de la Rosa, Ruecker, & Giraldo Nohora, 2021; Ruecker et al., 2020). Parallel work in human–computer interaction and co-design has positioned prototypes as epistemic artifacts that support exploration, communication, and mutual learning (Bødker, 1987; Sanders & Stappers, 2014; Galey & Ruecker, 2010). This body of work establishes prototyping as a means of revealing system behavior through iterative displacement.

A second strand expands the role of prototypes beyond inquiry toward intervention. Participatory and infrastructuring approaches describe how prototypes can reorganize relations among actors, resources, and practices within ongoing systems (Hillgren, Seravalli, & Emilson, 2011; Karasti, 2014; Kimbell & Bailey, 2017). Rather than representing future states, prototypes become embedded within present conditions, shaping how systems evolve over time. Related work on research prototypes emphasizes their role in constructing and testing alternative configurations within real or simulated environments (Koskinen & Frens, 2017). These perspectives align with the present framework's treatment of prototypes as deliberate displacements that participate in the dynamics they expose.

A third strand introduces explicitly critical and political dimensions of prototyping. Work in adversarial and critical design demonstrates how artifacts can be used to contest dominant configurations and reveal underlying assumptions (DiSalvo, 2015). Provocative prototypes, often referred to as provotypes, are designed to elicit responses that make latent tensions visible, particularly in contexts of public deliberation and policy formation. These approaches establish that prototypes can intervene in social and institutional dynamics by redistributing attention, altering participation, and surfacing conflict. Within the present

framework, such interventions can be understood as intentional perturbations of cascade pathways, designed to redirect or destabilize alignment under specific conditions.

A fourth strand comes from science and technology studies and related work on infrastructure and the politics of artifacts. Research in this area has shown how technical systems shape and stabilize patterns of action, often in ways that extend beyond their immediate function (Latour, 1992; Akrich, 1992; Star & Ruhleder, 1996; Winner, 1980; Verbeek, 2011). These accounts emphasize that interventions introduced into socio-technical systems participate in ongoing processes of mediation, redistribution, and constraint. Prototyping, when understood as an interventional practice, operates within this field, influencing how trajectories form and how responsibilities and risks are distributed across actors.

A fifth strand addresses systemic failure and the dynamics of tightly coupled systems. Perrow (1984) examines failures arising from interactions rather than isolated breakdowns, while Vaughan (1996) traces organizational processes through which apparently acceptable decisions can accumulate into dangerous conditions. The high-reliability debate, including La Porte and Rochlin (1994), cautions against treating the organizational consequences as settled by a single account. For this paper, recoverability is a design question prompted by those differences and by systems-oriented analyses of leverage and adaptation (Meadows, 1999; Allen, 2014), not a result already established for the proposed prototypes.

Sixth, a related body of work in policy design and public sector innovation further extends the role of prototyping as an instrument of intervention. Policy prototyping practices, including those developed in governmental innovation labs, use small-scale, time-bounded interventions to explore how policy changes unfold under real conditions (Bason, 2014; Kimbell & Bailey, 2017). These approaches acknowledge that policy actions propagate through complex institutional environments and therefore require iterative testing rather than upfront specification. Similarly, provocative prototypes, or provotypes, are designed to elicit responses that reveal latent tensions and alternative pathways within a system, particularly in contexts of public deliberation. Work on design friction and interventionist design further demonstrates how deliberate disruptions can redistribute attention and alter system behavior. Across these traditions, prototypes are not neutral representations but active participants in shaping trajectories. The present framework builds on this orientation by specifying how such interventions engage cascade dynamics directly, influencing propagation, closure, and recoverability across systems.

Across these strands, a common theme emerges: interventions introduced into complex systems do not remain localized. They participate in processes of propagation, alignment, and constraint that shape the system's future behavior. A growing body of work has demonstrated that prototypes can reveal system dynamics, reorganize relationships, and intervene in social and political contexts. At the same time, these contributions can be brought into closer relation by articulating more explicitly how such interventions participate in cascade formation, closure, and recoverability over time.

The present article builds on these traditions by integrating them into a cascade-oriented framework for design practice. By treating prototypes as instruments for modulating propagation pathways, redistributing alignment pressures, and preserving or restoring optionality, the framework foregrounds cascade-oriented intervention within traditions that already connect prototyping and inquiry. It situates design within a broader field of practices concerned with system dynamics, while maintaining a focus on the operational construction and deployment of prototypes as tools for shaping how change unfolds.

In doing so, the article contributes to an emerging understanding of design as a form of trajectory stewardship. Rather than resolving complexity through reduction, it engages complexity by influencing how it develops, providing a basis for interventions that are responsive to the conditional and distributed nature of cascade dynamics.

WHAT CASCADES ARE AND WHY THEY MATTER

The term cascade refers to a pattern of change in which an initial displacement produces effects that propagate through a system, interacting with existing structures and constraints as they move. These effects do not travel along a single path. They branch, overlap, and sometimes reinforce one another, producing trajectories that extend beyond the original point of intervention. Work in sociology and network science has shown how such processes can arise from local interactions and spread across populations or infrastructures (Bikhchandani, Hirshleifer, & Welch, 1992; Granovetter, 1978; Watts, 2002). In complex systems research, cascades are understood as nonlinear phenomena in which small inputs can generate large and sometimes unexpected outcomes (Meadows, 1999; Allen, 2014; Perrow, 1984).

Within the present framework, cascades are characterized not only by propagation but by their effects on the space of possible trajectories available to the system. As changes align with existing constraints, certain pathways become more likely while others diminish or disappear. This process can lead to accelerated closure, where alternatives are

reduced faster than they can be generated or restored. The concern is not that change occurs, but that the system's capacity to adapt is diminished as a result. Studies of organizational drift and normalization processes further demonstrate how such alignment can proceed under conditions of apparent correctness, gradually narrowing the space of viable action (Vaughan, 1996).

Cascades are not inherently undesirable. Many systems depend on forms of propagation to function effectively. The spread of beneficial practices, the coordination of activities across distributed actors, and the stabilization of shared standards all rely on aligned trajectories. The challenge arises when cascades reduce optionality in ways that limit the system's ability to respond to changing conditions. In such cases, outcomes that appear locally coherent may contribute to broader patterns of rigidity or vulnerability. Work on socio-technical systems has shown how such dynamics can become embedded in infrastructures that shape behavior over time (Star & Ruhleder, 1996; Winner, 1980).

The difficulty of working with cascades lies in their conditional and distributed nature. Their progression depends on interactions among multiple elements, each of which may change as the cascade unfolds. Effects that are negligible in one configuration may become significant in another. Feedback loops can amplify or dampen propagation, and pathways may only become visible once they are activated. As a result, cascades are often difficult to predict in advance. Models can identify possible patterns, but the specific trajectory that develops depends on conditions that are only partially observable (Allen, 2014; Watts, 2002).

These characteristics make cascades a central concern for design practice in complex systems. Interventions introduced into such systems do not remain localized. They participate in ongoing processes of propagation and alignment, influencing the range of futures available to the system. Recognizing cascades as both necessary and potentially constraining provides a basis for engaging them deliberately. The task is not to eliminate cascades, but to understand how they form, how they evolve, and how their effects on optionality can be shaped over time.

The sections that follow develop this approach by identifying sites within systems where cascade dynamics are particularly responsive to intervention, and by articulating prototyping strategies that can be used to modulate propagation, closure, and recoverability in practice.

SITES OF CASCADE LEVERAGE

The transition from detection to modulation requires an account of where an intervention might influence propagation. The companion paper's constructed scenarios suggest that some locations could be more consequential than others, but do not establish those locations empirically. The following leverage categories are therefore analytic candidates to guide investigation, drawing on Meadows (1999) and Jones (2014), rather than a tested classification of effective intervention points. Five candidate types of leverage site organize the discussion. Their usefulness and boundaries require evaluation in a particular setting.

Points of early alignment are locations where trajectories begin to cohere. At these sites, multiple potential pathways remain available, but signals, incentives, or constraints begin to favor particular directions. Because closure has not yet accelerated, interventions introduced here can redistribute alignment pressures before alternatives are eliminated. In the constructed curbside scenario, the timing and allocation of delivery windows function as such points, shaping how activity patterns begin to stabilize. In hospital discharge, the framing and sequencing of instructions influence how patients interpret their responsibilities as they transition out of care. Work on participatory and infrastructuring design highlights how early-stage interventions can shape emerging configurations before they stabilize (Hillgren, Seravalli, & Emilson, 2011).

Points of fragility are locations where small disturbances can trigger amplified effects. These sites often sit at the intersection of tightly coupled dependencies, where the failure of one element propagates rapidly through others (Perrow, 1984). In the hospital scenario, information or access gaps are candidate points of fragility; an actual connection to readmission would require clinical evidence. In urban systems, bottlenecks near loading zones or intersections can transform minor disruptions into broader congestion patterns. Interventions at these sites operate by absorbing, slowing, or redistributing propagation.

Routing nodes are locations through which multiple pathways pass and are redistributed. These nodes do not necessarily initiate cascades, but they influence their direction and composition. A delivery micro-hub reorganizes flows by concentrating and redistributing activity. A follow-up contact might alter the route through which a patient obtains appropriate care, but emergency escalation must not be treated as an undesirable outcome in itself. Because routing nodes connect multiple pathways, interventions introduced here can channel cascades without requiring control over the entire system. Actor-network approaches have emphasized how such nodes mediate and transform action as it moves through a system (Latour, 1992).

Boundary interfaces mark transitions between domains, actors, or regimes. These are sites where information, responsibility, or resources move from one context to another. Discharge from hospital to home care is a boundary interface, as is the transfer of goods from freight vehicles to curbside delivery. Cascades often intensify at these interfaces because coordination must be re-established across differing conditions. Interventions at boundaries can stabilize or reshape propagation by clarifying responsibilities, aligning representations, or introducing intermediary structures (Star & Ruhleder, 1996).

Zones of accumulated constraint are regions where prior alignments have already narrowed available trajectories. These zones are characterized by reduced flexibility and increased path dependence. Interventions introduced here encounter resistance, as existing configurations reinforce themselves. However, such zones are also critical for recovery-oriented strategies, where buffering or staged reintroduction of variation can reopen portions of the trajectory space. Studies of organizational drift illustrate how such constrained states emerge gradually through aligned local decisions (Vaughan, 1996).

These categories are not mutually exclusive. A single location may function simultaneously as a point of alignment, a routing node, and a boundary interface. The distinctions are analytic, providing a vocabulary for recognizing where cascade dynamics are likely to be most responsive to intervention. The search for leverage can begin with partial maps rather than an exhaustive account of the system. Repeated observations of a possible amplification or routing point may justify a focused test; repetition alone does not prove leverage. A useful record would specify the proposed mechanism, a comparison or counterfactual, and what finding would defeat the interpretation before a more consequential intervention is attempted.

Once such sites are identified, prototyping can shift from observation to modulation. Interventions can be designed with specific leverage points in view, targeting the conditions under which cascades form and evolve. The following section develops a set of prototyping strategies that operate on these sites, specifying how design can engage cascade dynamics through deliberate, situated action.

PROTOTYPING STRATEGIES FOR CASCADE MODULATION

Once sites of cascade leverage have been identified, prototyping can be directed toward the modulation of propagation, closure, and recoverability. The strategies that follow are not categories of design outcomes. They are operational patterns that specify how displacements can be constructed to influence cascade dynamics under particular conditions. Each operates on alignment pressures, thresholds, routing conditions, or reserves of optionality within the system, redistributing how trajectories form and evolve over time (Meadows, 1999; Allen, 2014).

All examples in this section are proposed uses of the strategies. Their names describe intended functions, not effects that can be inferred from an intervention's label. A real application would specify the target pathway, affected actors, resources and risks, comparison conditions, and a stopping or recovery arrangement. Table 1 provides a compact planning guide derived from the argument; it is not a validated classification or scoring instrument.

Table 1. Eight modulation strategies and questions for testing them

Strategy	Proposed action	Question or failure to examine
Dispersion	Maintain several early pathways.	Does variation reveal alternatives or obstruct needed coordination?
Selective amplification	Support a promising pathway locally.	Are benefits supported, and are other viable pathways being displaced?
Dampening	Reduce or absorb a disturbance's propagation.	Is the disturbance reduced or merely moved beyond the study boundary?
Redirection	Change a pathway or introduce an alternative focal point.	Can the receiving pathway safely and fairly absorb the change?
Buffering	Retain reserve capacity, representations, or alternative processes.	Will the buffer remain usable, maintained, and sufficiently independent?
Threshold modulation	Alter conditions or timing of uptake.	Does the change pace demand or create new access barriers and surges?
Controlled release	Pace a bounded accumulation within agreed limits.	Are limits, monitoring, and stop conditions explicit, without inducing harm?
Staged recovery	Reopen possibilities through intermediate changes.	Do the stages restore usable alternatives without creating new lock-in?

Early-stage dispersion prototypes are introduced at points of initial alignment, where multiple trajectories remain available but pressures toward coherence are beginning to emerge. Their purpose is to delay premature closure by sustaining variation. Rather than allowing a single pathway to dominate, these prototypes redistribute activity across alternatives, extending the period during which different configurations can be observed. In an urban setting, this may involve deliberately varying curb allocations across adjacent segments rather than standardizing them. In clinical contexts, it may take the form of parallel discharge pathways tailored to different patient conditions. The intended effect is not to prevent alignment, but to slow its consolidation, preserving the system's capacity to reveal how different trajectories perform.

Selective amplification prototypes operate in the opposite direction. They strengthen specific trajectories without collapsing the broader field. The challenge is to increase the viability or visibility of a pathway while maintaining alternative options. This requires localized amplification that does not propagate indiscriminately. For example, a pedestrian-priority zone may intensify foot traffic within a defined area while leaving surrounding circulation patterns intact. In healthcare, enhanced follow-up for a specific patient group may improve outcomes without imposing uniform procedures across all cases. Amplification, in this sense, is constrained by its scope, supporting particular trajectories without accelerating global closure.

Dampening prototypes target candidate points of fragility. Their intended role is to absorb or slow propagation so that a local disturbance does not escalate. In a proposed discharge study, a communication change might reveal unmet needs; whether it would reduce harmful escalation or instead add workload requires evidence. In a curbside model or authorized pilot, a buffer zone could be tested for its effects on fluctuations in demand and congestion outside the immediate site. Perrow (1984) and Vaughan (1996) motivate attention to interacting failures, but do not validate these particular interventions.

Redirection prototypes engage cascades by altering their pathways rather than suppressing them. These interventions recognize that certain forms of propagation are unavoidable or even desirable, but that their trajectories can be guided toward regions of the system that can absorb or transform their effects. A delivery micro-hub, for instance, reorganizes freight flows, channeling activity into a controlled node rather than allowing it to disperse unpredictably along the curb. In a clinical setting, a proposed referral change would be judged by access to appropriate care, including timely emergency treatment where needed, rather than by reduced emergency-department use alone. Redirection changes where and how cascades unfold, influencing their impact without requiring their elimination. A related form of redirection operates through competing attractors. Rather than modifying a specific pathway, the intervention introduces a more compelling focal point that draws activity away from harmful trajectories. A safer transit option that becomes more convenient than private curbside drop-off can reduce congestion without directly restricting vehicle use. A more accessible community service might change how some people seek care, but suitability, capacity, and safe escalation would have to be assessed rather than assumed. In such cases, the cascade is modulated through field

reorganization, as participation flows toward a stronger attractor.

Buffering prototypes introduce or maintain structures that preserve optionality even as closure progresses elsewhere in the system. These structures are not fully aligned with dominant trajectories. They remain partially external, retaining the capacity to support alternative pathways when needed. In design practice, buffering may take the form of parallel workflows, alternative representations, reserve capacity, or contingency protocols that can be activated when existing configurations become too constrained. Their value lies in sustaining recoverability, aiming to retain the ability to shift trajectories under changing conditions (Meadows, 1999).

Threshold modulation prototypes alter the conditions under which a cascade might begin or accelerate. The intended changes include raising barriers to harmful propagation, lowering barriers to beneficial participation, or staggering access to avoid simultaneous demand. A curbside reservation model could test whether timed windows spread arrivals or merely move the queue elsewhere. A service-access prototype could examine administrative barriers without assuming a health benefit. Threshold models motivate these questions (Granovetter, 1978; Watts, 2002); they do not establish that any particular change in scheduling will improve a real system.

Controlled release prototypes seek to pace accumulated demand through small, bounded changes rather than allow simultaneous release. The intended object is manageable administrative or material pressure, such as a queued load within a capacity-tested curbside model, not the deliberate creation of clinical deterioration or other harm. A field application would require explicit limits, monitoring, and a means to stop or reverse the change. In the hospital scenario, eliciting unresolved questions is better understood as information gathering, not as permission to trigger adverse events. The strategy's proposed stabilizing effect must be tested rather than presumed.

Staged recovery prototypes operate in situations where closure has already advanced and trajectories have narrowed significantly. Rather than attempting immediate reversal, these prototypes introduce intermediate configurations that gradually reintroduce variation. In institutional systems, abrupt change may be infeasible due to established dependencies. A staged approach allows new pathways to emerge incrementally, reducing resistance while restoring flexibility over time. In healthcare, this might involve phased adjustments to discharge protocols. In urban systems, it may involve temporary reallocations that evolve into more permanent configurations as patterns stabilize.

These strategies are not mutually exclusive. They can be combined and sequenced in response to the evolving state of the system. Early-stage dispersion may be followed by selective amplification as promising trajectories emerge. Dampening and redirection may operate concurrently at different leverage sites. Threshold modulation may be used to slow harmful synchronization while controlled release dissipates accumulated pressure. Buffering structures may be established in advance and activated when closure accelerates. Staged recovery may follow periods of consolidation, reopening the space of possibilities.

The same three prototyping modalities introduced earlier remain operative across these strategies. Prospective prototyping can be used to anticipate where dispersion, threshold modulation, or dampening may be effective. Computational prototyping allows controlled exploration of amplification thresholds, timing effects, and redirection pathways. Situated prototyping enacts these strategies within the system, revealing how they perform under real conditions. Coordination can connect anticipation with observation only when the assumptions, provenance, and limitations of each modality remain explicit; agreement does not automatically establish validity.

Taken together, these strategies organize a cascade-oriented form of intervention within systemic prototyping. They provide a vocabulary for engaging cascade dynamics deliberately, specifying how design can influence the formation, direction, timing, and intensity of propagation. The emphasis remains on trajectory stewardship. Interventions are evaluated not in isolation, but in terms of how they participate in the ongoing configuration of the system and the futures it makes available.

COMPOSING INTERVENTIONS ACROSS CASCADE PHASES

The preceding strategies describe distinct ways of engaging cascade dynamics at particular leverage sites. In practice, however, cascades rarely present as isolated events that can be addressed through a single intervention. They unfold over time, shifting in structure as alignment pressures accumulate, dissipate, synchronize, or are redirected. Effective design practice therefore involves composing multiple prototyping strategies across the phases of cascade development, attending to how interventions interact as conditions change (Meadows, 1999; Allen, 2014).

In a proposed early-phase composition, dispersion, threshold modulation, and selective amplification would be tested as complementary strategies. Dispersion aims to preserve variation; threshold modulation changes conditions of uptake; selective amplification supports a candidate pathway. In the curbside scenario, varying delivery windows, reservations, and pedestrian-priority arrangements could be investigated separately and together.

A comparison would need to establish whether they interact as intended, displace pressure to neighboring sites, or make coordination more difficult. The combination is a research proposition, not an established recipe.

As a candidate cascade consolidates, dampening, redirection, and bounded release may become relevant hypotheses. Their combination could change both the intensity and timing of propagation, but might also create new dependencies. In a clinically governed discharge study, follow-up contact, routing, and information exchange would need separate measures before their effects could be combined. The scenario does not establish that calls prevent readmission or that reduced emergency use signals better care. General accounts of interaction and coupling (Perrow, 1984) justify examining these relationships, not assuming their outcomes.

Where closure accelerates, buffering is a candidate response, not a guaranteed source of resilience. Retained alternative circulation patterns, reserve loading areas, or flexible curb allocations could provide options in the constructed urban scenario. Their usefulness would depend on maintenance, access, capacity, and sufficient independence from the dominant pathway. In a clinical setting, any proposed contingency pathway would additionally require evidence of appropriateness and safety. Infrastructure theory motivates attention to these relations (Star & Ruhleder, 1996); it does not establish the clinical effectiveness of a parallel care pathway.

In later phases, where paths have stabilized and dependencies make abrupt change difficult, staged recovery is another candidate strategy. Intermediate configurations would be intended to restore usable alternatives without requiring an immediate reversal. Whether those stages reduce resistance or instead reproduce existing exclusions must be investigated. Vaughan's (1996) analysis motivates attention to organizational histories and normalization; it does not validate staged recovery as a general treatment for lock-in.

The composition of these strategies is not linear. Cascades may develop unevenly across different parts of a system, requiring simultaneous engagement at multiple phases. A single intervention may perform different functions depending on where it is introduced. A follow-up call in a hospital setting may act as a dampener for some patients while serving as a redirector for others. A curbside reallocation may amplify pedestrian activity in one context while buffering traffic variability in another. A timed access rule may function as threshold modulation in one district and controlled release in another. The role of an intervention is therefore relational, determined by its position within the evolving configuration of the system.

This relational character places emphasis on timing and coordination. Interventions must be aligned not only with leverage sites but with the temporal state of cascade development. Introducing amplification too early may accelerate closure before sufficient variation has been explored. Delaying dampening may allow instabilities to propagate beyond manageable limits. Applying controlled release too late may fail to prevent synchronization that has already formed. Effective modulation requires attention to when interventions are introduced, how long they remain active, and how they interact with other ongoing displacements.

A further temporal consideration concerns churn, in which new disturbances, signals, or demands are introduced at a rate that exceeds the system's capacity to interpret and respond coherently. Under such conditions, even beneficial interventions may fail to stabilize. Composition therefore includes pacing. In some cases the appropriate intervention is not an additional displacement, but the slowing, bundling, sequencing, or temporary suspension of incoming changes so that uptake, reinforcement, and recovery remain possible.

The layered prototyping apparatus supports this compositional approach. Prospective prototyping can be used to anticipate how different strategies might interact across phases, identifying potential sequences of intervention. Computational prototyping allows controlled exploration of timing, threshold, and interaction effects, testing how variations in sequence or intensity influence cascade behavior. Situated prototyping enacts these compositions within the system, which could provide empirical traces if an appropriately governed field study were conducted.

Across these modalities, the accumulation of maps remains central. Each intervention, whether oriented toward dispersion, amplification, dampening, redirection, buffering, threshold modulation, controlled release, or recovery, produces a record of how the system responds under specific conditions. When these records are overlaid, they reveal not only individual cascade pathways but the interactions among them. Patterns emerge that indicate which combinations of strategies sustain desirable trajectories and which lead to unintended closure.

This compositional perspective reinforces the role of design as trajectory stewardship. The task is not to select a single intervention that resolves a problem, but to orchestrate a sequence of displacements that guide how the system evolves over time. By attending to the phases of cascade development, the pacing of change, and the interactions among strategies, design practice can engage complexity in

a way that preserves adaptability while shaping the conditions under which change occurs.

CONDITIONS FOR RESPONSIBLE INTERVENTION

A cascade-modulation plan needs an account of who authorizes the intervention, who bears its risks, and who may contest or stop it. The affected field extends beyond the design team and can include people who do not participate directly. Before situated deployment, the plan should name the changes that are permissible, baseline and comparison conditions, anticipated and unanticipated harms to monitor, and arrangements for withdrawal, escalation, and restoration. Safety-critical settings require their applicable professional and ethical oversight; the present taxonomy does not substitute for it. Success would require more than preventing one visible failure. It should include the distribution of benefits and burdens, the preservation of necessary alternatives, and the costs of sustaining buffers or parallel pathways. An intervention that protects one group by exporting fragility to another cannot be classified as successful solely from the first group's map. These judgments are to be made explicitly with affected parties, rather than hidden inside a claim about the system as a whole.

IMPLICATIONS FOR DESIGN PRACTICE

The articulation of cascade modulation as a design practice introduces a shift in how design work is organized, evaluated, and sustained over time. Rather than treating interventions as discrete solutions to bounded problems, this approach positions design as an ongoing engagement with system dynamics, where the effects of any action extend beyond its immediate context. The practical implication is not an increase in complexity for its own sake, but a reorientation toward managing how complexity unfolds.

One immediate implication concerns the structure of design workflows. Conventional processes often move from problem definition to solution development and evaluation, with success measured against predefined criteria. Within a cascade-aware framework, these stages remain, but their function changes. Problem framing becomes the identification of leverage sites and the conditions under which cascades form. Prototyping becomes the introduction of displacements designed to reveal and shape propagation pathways. Evaluation extends beyond immediate outcomes to include the trajectories that interventions initiate and the ways in which they alter system flexibility over time. This reframing aligns with accounts of design as reflective and situated practice (Schön, 1992; Nelson & Stolterman, 2003).

A second implication concerns documentation and representation. The accumulation of systemic maps is not an auxiliary activity but a central component of the method. Each prototype produces a record of how the system responds under particular conditions, including the pathways through which effects propagate. Over time, these records form an archive that supports comparison across interventions and conditions, functioning as a working memory for the design process. This emphasis extends systemic mapping practices by incorporating temporal and trajectory-based dimensions (de la Rosa & Ruecker, 2020; Ruecker et al., 2020).

A third implication involves the distribution of responsibility within design teams and across stakeholders. Because cascades extend beyond the immediate scope of an intervention, their effects are often experienced by actors not directly involved in the design process. Engaging cascade dynamics therefore requires coordination across organizational boundaries and inclusion of diverse perspectives. Participatory approaches are critical in this regard, both for legitimacy and for their capacity to reveal otherwise unobserved pathways (Bødker, 1987; Hillgren, Seravalli, & Emilson, 2011).

A fourth implication concerns evaluative criteria. Traditional measures such as efficiency or usability remain relevant but insufficient. A cascade-aware approach introduces criteria related to propagation and recoverability. Interventions may be judged by their ability to stabilize desirable trajectories, reduce cascading failure, or preserve adaptability under changing conditions. This expanded frame shifts attention toward long-term system behavior rather than short-term performance.

A fifth implication relates to temporality. Cascade modulation requires attention to when interventions are introduced and how they evolve. Early-stage actions may sustain variation, while later interventions address consolidation or recovery. Design processes therefore extend beyond initial implementation, incorporating ongoing monitoring and adjustment as cascades develop.

Finally, the framework reframes the role of the designer. Rather than acting solely as a creator of solutions, the designer becomes a steward of trajectories, balancing alignment, variation, and intervention across evolving system conditions. The work focuses less on achieving a fixed end state and more on maintaining conditions under which desirable patterns can persist and adapt.

These implications extend existing design methods rather than replacing them. By integrating attention to propagation, closure, and recoverability into everyday practice, designers can engage more deliberately with the dynamics that shape complex systems.

CONCLUSION

This article has advanced a cascade-aware account of design practice in which prototyping functions as a means of engaging directly with the dynamics of change in complex systems. Extending a prior framework for cascade detection, it has articulated a complementary set of strategies for cascade modulation, positioning design as an activity that shapes how propagation, closure, and recoverability unfold over time.

The framework foregrounds prototypes as instruments that can represent, test, or enact a proposed change. Its eight strategies are dispersion, selective amplification, dampening, redirection, buffering, threshold modulation, controlled release, and staged recovery. Their coordination across prospective, computational, and situated work provides a planning structure, while leaving the effectiveness and safety of any application to be established through appropriate evidence.

The identification of sites of cascade leverage further refines this approach by locating where interventions might influence propagation pathways. By attending to early alignment, fragility, routing nodes, boundary interfaces, and accumulated constraint, design practice can move toward more targeted engagement with system dynamics. The compositional perspective emphasizes that effective intervention involves sequencing and combining strategies in response to evolving conditions. Situating this framework within a broader body of work on participatory design, infrastructuring, policy experimentation, and systemic failure highlights the expanding role of design in shaping social and institutional processes. Prototyping emerges as a means of intervening in systems where outcomes are distributed, conditional, and difficult to predict.

The contribution of this work lies in proposing a coherent methodological articulation of prototyping as cascade modulation. By integrating detection and intervention within a single apparatus, it offers a basis for design practice that engages complexity while preserving adaptability. Future work may extend this framework by developing more detailed protocols for evaluating intervention effects over time and by exploring how cascade-aware design can be integrated into institutional decision-making processes at larger scales.

An initial evaluation could test whether the categories help different teams identify comparable pathways, document disagreement, and notice harms or closures omitted by conventional project criteria. No such evaluation is reported here. The paper's present contribution is therefore conceptual organization and a basis for study, not evidence that the strategies prevent harmful cascades in practice.

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