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Unintended consequences of well-intended interventions

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Interventions in complex systems are notoriously unpredictable (1). Whether the system is ecological, technological, social, or economic, the interplay of nonlinear dynamics, feedback loops, adaptive behavior, and very different scales of time and space often amplifies the gap between intended and actual outcomes (2–5). Well-meaning interventions can easily trigger unintended side effects—sometimes minor, sometimes severe enough to undermine the very goals they were designed to achieve. This paradox is one of the defining properties of complex systems: small, targeted perturbations can cascade unpredictably (6); structural adjustments may be met with functional reorganization (7); and local optimization by social agents often generates global patterns that are counterintuitive or outright detrimental (8). Across these domains, and especially where human adaptation and strategic behavior shape collective outcomes, interventions that simply target visible structures often trigger behavioral adaptations that reconstitute the system in subtler, more resilient, and often more harmful forms. In the current issue of PNAS, by integrating an unusually rich empirical dataset from clandestine criminal networks with a sophisticated agent-based modeling framework, van Elteren et al. (9) shed new light on why interventions in complex systems often fail—and, even more importantly, how they can backfire.

Criminal networks are, in fact, excellent examples of such complex social systems (10–12). They are made up of individuals who make locally rational decisions under uncertainty, balancing risk, utility, and opportunity. Their structural organization coevolves with behavioral patterns, role specializations, and environmental pressures—including law enforcement interventions. The results of these processes are often large complex networks, as shown in Fig. 1. But despite their importance, direct empirical data on how such networks adapt are extremely rare, and systematic modeling of coevolving structure and function has only recently begun to develop (13, 14). Against this backdrop, the study by van Elteren et al. (9) makes a significant and timely contribution. And the central insight is as compelling as it is troubling: Interventions intended to weaken criminal networks often make them more resilient, more opaque, and more effectively coordinated. The authors demonstrate that criminal groups actively reconfigure their structure and role distributions in response to external pressure. Their model reveals a coevolutionary dynamic in which structural vulnerability and functional adaptation interact in complex ways, generating emergent phenomena that defy intuition and challenge many assumptions embedded in conventional enforcement strategies.

A core result is what van Elteren et al. (9) call "criminal opacity amplification." When a targeted intervention removes or isolates central individuals, the network's observable structure becomes more fragmented and sparse, reducing link density and weakening visible pathways. At first glance, this seems beneficial: a fragmented network is presumably easier to disrupt further, its operations more difficult to coordinate. Yet the functional response tells a different story. As individuals rewire their relationships to preserve or regain operational capacity, the network reorganizes into subtler, more decentralized structures that are much harder to detect. This can also be observed in Fig. 1, where beyond the largest connected component of each network, many smaller and disconnected clusters are visible. In essence, interventions prune the visible network but likely stimulate the growth of invisible connective tissue, thus creating a system that is lower in observable connectivity but higher in operational effectiveness. Criminal activity may therefore increase even as the network appears weaker on paper.

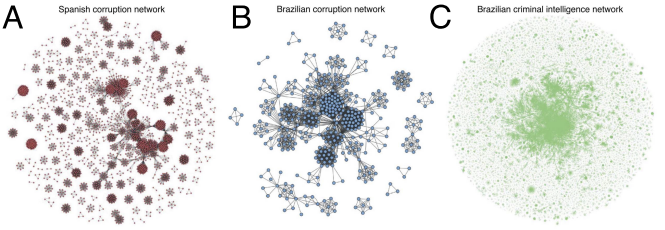

Fig. 1. Visualizations of large complex criminal networks. Shown is in (*A*) the network from Spanish corruption cases, in (*B*) the network from Brazilian corruption cases, and in (*C*) the Brazilian criminal intelligence network (11). Nodes in corruption networks (*A* and *B*) represent people that have been involved in corruption scandals, and links among them indicate pairs that have been involved in the same scandal(s). Nodes in the criminal intelligence network (*C*) represent people investigated by the Brazilian Federal Police, and a link between two individuals indicates that the investigations have revealed some form of coparticipation between them. For details about these datasets and networks please see ref. 11. Given the complexity and the scale of the displayed networks, it seems highly pertinent that the findings of van Elteren et al. (9) challenge common assumptions about how such complex systems respond to interventions, even if well-intended. While many interventions could be easily imagined based on node degree, edge strength, centrality, and indeed based on many other more advanced measures (15, 16), it seems hardly possible to envisage how these interventions would manifest over different scales of time and space, and ultimately how the networks would adapt to them.

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This paradox speaks to a deeper challenge: visibility and vulnerability in complex systems do not align as straightforwardly as structural metrics might suggest. A sparse network can be both harder to monitor and more resilient, because its reduced structural footprint leaves fewer observable traces while enabling flexible, role-based coordination that resists further disruption. And in ref. 9, the authors convincingly show that interventions can unintentionally drive networks toward these high-resilience, low-visibility regimes.

In PNAS, by integrating an unusually rich empirical dataset from clandestine criminal networks with a sophisticated agent-based modeling framework, van Elteren et al. (9) shed new light on why interventions in complex systems often fail—and, even more importantly, how they can backfire

The second important contribution of ref. 9 is the demonstration that interventions increase the variance of possible outcomes, thereby amplifying the system's sensitivity to small perturbations and stochastic fluctuations. Path dependency—a hallmark of complex adaptive systems—is vividly present: once the network has been perturbed, the trajectory it follows depends strongly on initial postintervention randomness. This means that two networks struck by identical interventions may diverge dramatically in their subsequent evolution, with one declining into inactivity while the other rebounds with surprising strength.

The analysis by van Elteren et al. (9) also reveals a surprising duality in the effect of connectivity-based interventions. Isolating nodes—simulating arrests, separations, or targeted suppression—does indeed fragment the network. However, it simultaneously strengthens the remaining active ties, consolidating criminal coordination within smaller groups and facilitating the emergence of tightly knit clusters. Conversely, interventions that increase a node's connectivity, analogous to reintegrating individuals into social or economic programs, can inadvertently boost criminal coordination by increasing opportunities and reducing structural friction. In some cases, stimulating connectivity destabilizes the network, not by weakening it, but by enabling rapid reorganization among opportunistic actors. These results underscore the nonmonotonic relationship between connectivity and systemic resilience: more links do not straightforwardly strengthen or weaken a network; what matters is how connectivity interacts with functional roles and cost–benefit incentives (7).

Underlying these empirical and computational findings is a broader theoretical insight, which is that resilience in multirole coordination networks emerges from a dynamic security–efficiency trade-off. Criminal networks must balance the advantages of coordination, such as information sharing, resource pooling, and task specialization, with the vulnerabilities introduced by visibility and exposure. Sparse, decentralized structures reduce risk but require flexible roles and high adaptability; dense structures enhance coordination but increase exposure. The coevolutionary model studied by van Elteren et al. (9) shows how networks dynamically navigate this trade-off, adjusting both their structure and functional states in response to pressures. As such, the work aligns with a large body of scholarship across ecology, sociology, and organizational science showing that complex systems must balance the benefits of dense, cohesive architectures for coordination and stability against the flexibility and robustness afforded by sparser, more decentralized structures (17–19).

These results pose a challenge to traditional intervention strategies. Law enforcement approaches that rely on node removal or structural disruption may inadvertently strengthen the adaptive mechanisms they seek to suppress. Interventions that are not calibrated to the functional roles of individuals, the nature of their connections, and the broader environmental context risk producing counterproductive outcomes, ranging from amplified criminal activity to heightened opacity. It is therefore important to emphasize that effective interventions must operate not merely on structure but on the decision environment that shapes individual incentives. Shifts in cost–benefit landscapes, combined with iterative, postintervention monitoring, may offer more promising paths than one-shot structural attacks (20).

From a methodological perspective, the work by van Elteren et al. (9) bridges a persistent gap in criminology: the lack of computational models that integrate empirical data with mechanistic behavioral dynamics. The authors' agent-based framework, grounded in actual role distributions and interaction types, demonstrates the value of such integrative approaches. While they rightly acknowledge limitations, such as simplified assumptions about symmetry, challenges in capturing higher-order structural measures, and imperfect data completeness, the model's ability to reproduce local structural features and emergent functional patterns attests to its robustness. It offers a blueprint for future work incorporating weighted, directional, multilayer, or higher-order interactions, as well as strategies for handling incomplete or uncertain network data.

The implications of these findings extend far beyond criminology. Many complex systems exhibit adaptive responses that undermine the effectiveness of interventions. Ecosystems reorganize under environmental stress, sometimes producing more resilient invasive species or destabilizing feedback loops. Organizations adapt to regulatory changes in ways that reintroduce inefficiencies or generate new risks. Technological networks such as the internet or power grids may route around damage in ways that temporarily stabilize the system but create new systemic vulnerabilities. In each case, interventions that focus on structural modification without accounting for functional adaptation often fall short.

Another important lesson is that intervening in complex systems requires anticipating—not just measuring—adaptive responses. Disrupting a system changes the incentive landscape for its components; those components then adjust their behavior, often in ways that reconstitute or even amplify the system's capabilities. This dynamic is especially potent in social systems, where

individual decision-making is strategic, temporally adaptive, and sensitive to local conditions (8). Criminal networks, with their blend of risk management, resource constraints, and role specialization, embody these properties acutely.

Last, we note that a broader reflection is required on how resilience is conceptualized. In most contexts, resilience is viewed as a desirable property—the capacity of a system to recover from shocks, maintain function, and resist collapse (7). Yet in criminal networks, resilience is precisely what interventions seek to undermine (9, 11, 12). The paradox is that actions aimed at weakening the system may, through decentralized adaptation, strengthen the very resilience they aim to reduce. This duality reinforces the importance of understanding resilience not as a static attribute but as a dynamic interplay between structure, function, and external pressure.

Taken together, "The paradox of intervention" (9) offers an important and timely contribution to the study of adaptive complex systems. By revealing how interventions can yield counterintuitive, even counterproductive outcomes, the authors deepen our understanding of complex social systems and highlight the need for more nuanced, adaptive, and anticipatory intervention strategies. Their work demonstrates that resilience can emerge not despite disruption but because of how systems respond to it and that well-intended actions can produce hidden reinforcing mechanisms that complicate efforts at control. As societies grapple with increasingly complex forms of organized crime, and as researchers confront similarly intricate systems across the natural and technological sciences, these insights are both sobering and essential.

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