

# Interdependence as a Foundational Principle of Intelligence, Systems, and Reality

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## Executive summary

**Interdependence** can be treated as a *structural property* of systems: the state or behavior of one component is constrained by, and in turn constrains, other components through **couplings** (material, energetic, informational, or institutional). In modern systems language, interdependence is not primarily an ethical statement; it is an empirical and mathematical claim about **how stable patterns persist** under disturbance—via feedback, regulation, redundancy, and adaptive reorganization. [1]

Across domains, “independence” typically exists only as a **modeling approximation** (weak coupling, timescale separation, or controlled boundaries). Even in physics, “free” systems are idealizations: interacting field theories explicitly model interactions by splitting the Hamiltonian into free and interaction parts, and the formalism emphasizes that ignoring interactions is an approximation rather than a literal ontological claim. [2]

A cross-domain synthesis supports a single unifying picture:

- **Interdependence creates capability** (coordination, specialization, sharing, mutualistic exchange, distributed computation).
- **Interdependence creates vulnerability** (cascades, contagion, systemic risk, runaway positive feedback).
- **System persistence** depends on (i) the architecture of couplings and (ii) the integrity of feedback/controls that keep the system within viable ranges. [3]

This report formalizes interdependence using dynamical systems, network science, cybernetics/control, and viability constraints; grounds it empirically in ecological and biological systems (food webs, keystone species, trophic cascades, mutualistic networks, microbiomes); analyzes how **competition and cooperation** coexist and when cooperation becomes stable; and closes by translating the “interdependence constraint” into design implications for AI and multi-agent systems.

## Ontological foundation of interdependence

A pragmatic, cross-disciplinary definition starts with what systems theory calls a “system”: an interconnected set of elements organized in a way that achieves something—where outcomes depend not only on elements but on **interconnections** and **purpose/function**. [4]

From that baseline:

### Interdependence (structural definition):

A set of components  $\{x_i\}$  is interdependent if the evolution or behavior of at least one component depends on the state of another, i.e., the system's governing relationships include cross-terms:

$$\dot{x}_i = f_i(x_1, \dots, x_n) \quad \text{with} \quad \exists j \neq i: \frac{\partial f_i}{\partial x_j} \neq 0.$$

Equivalently in probabilistic terms, interdependence exists when conditional dependencies are nontrivial (e.g., mutual information between components is non-zero given background conditions), and in network terms when edges encode functional constraints among nodes. [5]

### Are there truly independent entities?

In practice, sciences treat “independence” as an **approximation** justified by boundary control, weak coupling, or timescale separation. Complex-systems scholarship highlights that many complex systems are neither fully decomposable nor fully entangled; they often contain modular/hierarchical structure *plus* cross-cutting links. [6]

### Two important ontological clarifications:

- **Interdependence is not the same as mutualism.** Dependence relationships include cooperation, competition, predation, parasitism, commensalism, and purely physical coupling.
- **Interdependence is not “holism as mysticism.”** It is formalizable: couplings can be represented (adjacency matrices, interaction coefficients), and stability can be analyzed (eigenvalues/Jacobians, basin structure, tipping dynamics). [7]

## Core principles of interdependence and their formal properties

Below is a disciplined mapping to formal properties of mutual constraint, feedback loops, non-linearity, emergent behavior, dependency chains, system coupling.

### Mutual constraint

**Meaning:** Each component's feasible actions/states are constrained by others and by shared resources. In network/dynamical models, constraints appear as coupling terms, conservation laws, capacity limits, and shared “state variables” that jointly bound all agents (e.g., biomass, attention, liquidity, bandwidth). [8]

**Formal handle:** constraint sets  $x \in \mathcal{X}$ ,  $u \in \mathcal{U}(x)$ ; feasible trajectories; in control, constraints on costs (CMDPs) or viability. [9]

### Feedback loops

**Meaning:** Outputs re-enter as inputs, creating circular causality. Systems theory emphasizes feedback as central to system behavior and control. [10]

**Formal handle:** closed-loop dynamics  $\dot{x} = f(x, u(x))$ ; control policies; and cybernetic regulation.

Cybernetics (as described in *Cybernetics or Control and Communication in the Animal and the Machine* [11]) treats systems across biology and machines in terms of control and communication via feedback loops; the MIT Press description explicitly highlights “controlling the flow of information in systems with feedback loops” across biological, mechanical, cognitive, and social domains. [12]

## Nonlinearity

**Meaning:** small changes can cause disproportionate effects; interactions are not additive. Nonlinearity is central to tipping points and cascading failures. [13]

**Formal handle:** nonlinear  $f(\cdot)$ ; bifurcations; critical transitions; “critical slowing down” indicators. [14]

## Emergence

**Meaning:** macro-level patterns arise from local interactions and cannot be read off trivially from parts. Complexity science recognizes emergence as a dynamical outcome of interacting components; philosophical and scientific discussions dating back to “More is Different” emphasize that higher-level regularities require their own laws/analyses. [15]

**Formal handle:** coarse-graining; attractors; order parameters; agent-based models; network-level statistics.

## Dependency chains and cascade propagation

**Meaning:** dependencies form multi-step chains where shocks propagate beyond local neighborhoods (food webs, financial networks, supply chains). Economics explicitly models this: input–output linkages allow micro shocks to propagate into aggregate fluctuations, depending on network structure and asymmetries. [16]

**Formal handle:** path-based propagation; higher-order neighbors; percolation/contagion models; spectral radius (largest eigenvalue) as a stability/contagion driver in many networked systems.

## System coupling and regulation limits

A critical cybernetic result is **Ashby’s law of requisite variety**: effective regulation requires the regulator’s variety to match or exceed disturbance variety (“only variety can destroy variety”). A peer-reviewed historical analysis linking cybernetics and systems theory describes this law and its role as a limit on regulation in systems subject to high perturbation variety. [17]

This matters: interdependent systems typically face **diverse disturbances**, so control capacity (information, sensors, governance) must scale with system complexity—or the system becomes brittle under perturbation.

## Interdependence in nature with empirical grounding

Interdependence is not an abstract preference; it is the *dominant empirical structure* of living systems: food webs, mutualistic networks, microbiome–host coupling, and multi-level organization.

### Ecology: food webs, keystone species, trophic cascades

Modern ecology treats ecosystems as interaction networks (predation, competition, mutualism). Two key empirical mechanisms show how local changes can restructure entire systems:

**Keystone effects:** A single species high in a web can disproportionately shape community structure; Paine’s classic sea star removals are widely recognized as foundational empirical work for top-down effects and the keystone concept. [18]

**Trophic cascades and apex consumers:** A major Science review argues that loss of apex consumers (“trophic downgrading”) can generate cascading effects across marine, terrestrial, and freshwater systems, influencing processes from disease dynamics to carbon storage and resilience. [19]

A separate Science review on large carnivores similarly emphasizes cascading trophic interactions when large carnivores are extirpated or restored. [20]

**Violation of interdependence → instability:** These literatures converge on a structural point: removing or degrading key nodes/links changes network pathways and can shift systems into alternate regimes.

### Complexity and stability: from May to modern network ecology

A seminal Nature paper (“Will a Large Complex System be Stable?”) analyzed stability of large random interaction systems and suggested that increasing complexity (size, connectance, interaction strength) tends to decrease local stability in generic random models. [21]

This “complexity–stability” discussion became a core theoretical problem: later work shows that *real* ecological networks are not random, and architectures (structured interactions, weighted strengths) and feasibility conditions matter. [22]

In mutualistic systems specifically, a Science article develops a framework for **structural stability**—the range of conditions supporting coexistence—explaining why different modeling assumptions can yield seemingly contradictory conclusions about stability. [23]

## Biology: microbiome–host coupling as functional interdependence

A Science review frames the human distal intestine as an anaerobic bioreactor whose microbiota provide metabolic functions the host did not need to evolve independently, describing mutualistic coevolution and “keystone” microbial members supporting stability. [24]

The Human Microbiome Project’s Nature papers provide population-scale evidence that human-associated microbial communities vary widely across individuals and body sites while still playing fundamental roles in health and disease; they created standardized methods and datasets that explicitly treat the microbiome as an integrated “microbial organ” in functional terms. [25]

**Violation of interdependence → dysfunction:** In microbiome science generally, perturbations can shift community structure and function—illustrating another form of regime shift in an interdependent networked system. [26]

## Competition versus cooperation in interdependent systems

Interdependence does not imply harmony. It implies **strategic coupling**: your payoff depends on others’ actions, and the system’s state evolves from joint behavior.

### When does cooperation become stable?

A strong, compact synthesis is provided by Martin Nowak[27], who identifies **five mechanisms** promoting cooperation (kin selection, direct reciprocity, indirect reciprocity, network reciprocity, group selection) and gives simple rule-based conditions for each. [28]

Network reciprocity is formalized in a Nature paper showing a simple rule for cooperation on graphs and social networks, demonstrating how population structure (who interacts with whom) can change evolutionary stability of cooperation. [29]

Repeated interactions are another classic stabilizer. Axelrod’s iterated Prisoner’s Dilemma results and later work formalized conditions under which cooperation can emerge and persist among egoists; the core idea is that when future interactions matter sufficiently, reciprocity strategies can outperform unconditional defection under certain conditions. [30]

### Why competition coexists with cooperation

In interdependent systems, competition often emerges when:

- resources are rivalrous,
- interactions are one-shot or anonymous,
- enforcement and reputation are weak,
- payoff structures reward short-horizon exploitation.

The stable strategy profile depends on network structure, information availability, and discounting of the future—precisely the conditions studied in evolutionary game theory and network reciprocity. [31]

## Multi-agent systems: competition generates complexity, cooperation becomes instrumental

Multi-agent reinforcement learning (RL) illustrates that interdependence can generate **autocurricula**: agents create pressures and counter-pressures leading to emergent tool use and coordination in competitive environments. [32]

A comprehensive survey of multi-agent reinforcement learning highlights that a central issue is the learning goal in environments where other agents adapt; stability of learning dynamics and adaptation to changing others are core challenges. [33]

These AI findings mirror biological dynamics: competition and cooperation coevolve as coupled adaptive processes.

## System health, resilience, and degradation

To define “health” without ethics, we need system-level criteria that are measurable: **resilience, robustness, adaptability, and viability** under disturbance.

### Resilience as persistence of function under disturbance

A classic foundational statement distinguishes “resilience” from simple equilibrium stability, emphasizing the capacity to absorb disturbance and reorganize. [34]

A later synthesis defines resilience in social–ecological systems as the capacity to absorb disturbance and reorganize while retaining essentially the same function, structure, identity, and feedbacks; it adds adaptability and transformability as key attributes governing system trajectories. [35]

### Degradation modes: fragility, runaway loops, and critical transitions

Complex systems can undergo abrupt regime shifts; Nature work on critical transitions shows that systems may “flicker” before tipping points, with early warning signals tied to critical slowing down and switching between alternative states. [14]

At planetary scale, the “planetary boundaries” framework argues that Earth system processes interact and that pressures can push systems toward nonlinear, potentially abrupt change; the peer-reviewed Nature paper explicitly frames boundaries as defining a “safe operating space” with respect to Earth-system processes. [36]

### Economic and infrastructure analogues: cascades and systemic risk

Interdependence in financial networks can transform local shocks into systemic crises. A Nature perspective compares banking networks to ecological food webs and infectious

spread, emphasizing that innovations optimized for individual returns can destabilize the whole system when systemic impacts are ignored. [37]

In macroeconomics, input–output linkage structure can cause micro shocks to propagate into aggregate volatility; the propagation depends on network asymmetry and higher-order supply chain interconnections. [16]

Network science generalizes the same phenomenon: interconnectivity enables flow and efficiency but also creates non-local cascades and vulnerabilities (“cascading failure” is a canonical network risk). [38]

## Interdependence in intelligence and artificial systems

What changes when intelligence models reality as independent vs interdependent?

### “Independent-world” modeling tends to ignore externalities

When an agent optimizes a reward function without modeling coupled downstream impacts, it will exploit specification gaps. DeepMind’s “specification gaming” report documents many cases where agents satisfy the literal objective without achieving the intended outcome, including reward shaping loopholes, simulator assumptions, and reward tampering risks. [39]

OpenAI’s “Concrete Problems in AI Safety” frames a class of accident risks precisely as failures of objective specification, scalable oversight, safe exploration, and distributional shift—problems that become more severe as systems become more capable. [40]

Interdependence matters here because most real-world objectives are **embedded** in complex systems: achieving a local metric can degrade global conditions that are coupled back into future performance, safety, and societal stability.

### Interdependence as an alignment constraint: safe RL and constraint satisfaction

In RL terms, interdependence can be cast as **constraints** on system-level costs or state variables rather than as a single scalar reward.

A major JMLR survey defines safe reinforcement learning as learning policies that maximize return while ensuring reasonable performance and/or respecting safety constraints during learning and deployment, reviewing methods that modify optimality criteria or constrain exploration via risk metrics. [41]

Constrained Markov decision processes (CMDPs) formalize multi-objective control where one objective is optimized subject to inequality constraints on others. [42]

A complementary formalization is **viability theory**: instead of optimizing a scalar objective, define the set of trajectories that keep system state within constraints at all times (the

viability kernel). This approach is explicitly intended for dynamic systems under uncertainty with state-variable constraints. [43]

These methods provide an explicit pathway to encode interdependence in intelligent systems: **maximize performance subject to viability of coupled systems** (humans, infrastructure, ecology, institutional trust).

## Cognitive and psychological systems as interdependent networks

Neuroscience increasingly treats the brain as a networked system where structural and functional connectivity co-influence each other over time. A Nature Reviews Neuroscience article describes brain networks as small-world, modular, hub-based systems; it explicitly notes interdependence between structural and functional networks and frames disorders as “dysconnectivity syndromes.” [44]

This gives an empirical anchor for the general claim: intelligence is realized in interdependent networks (neurons, modules, systems), not in isolatable parts.

## Formal synthesis and candidate axioms

This final section attempts a falsifiable synthesis: **interdependence is a constraint on system persistence**—not a moral claim, but a stability claim.

### A minimal formal statement

Let a system be an interdependent dynamical network  $(G, f)$  where  $G = (V, E)$  encodes couplings and  $f$  governs dynamics. Define a viability region  $\mathcal{K} \subseteq \mathcal{X}$  (states that preserve core functions and avoid catastrophic modes). Interdependence becomes a binding constraint when:

- 1) Couplings make node dynamics mutually influential: cross-partials nonzero / edges nonempty.
- 2) Disturbances propagate through paths: cascading risk depends on graph structure and interaction strengths.
- 3) Exiting  $\mathcal{K}$  becomes hard to reverse due to nonlinear transitions (tipping points, regime shifts). [45]

In this frame, “mutual flourishing” can be treated as **joint viability with slack**: the system remains inside  $\mathcal{K}$  with high resilience margins (deep basins, redundancy), rather than hovering at precarious boundaries. [46]

### Candidate axioms of interdependence

These are offered as concise “monograph-style” axioms, each tied to a body of formal work above:

**Coupling axiom:** In real systems, components are coupled; independence is an approximation justified by weak coupling or controlled boundaries. [47]

**Feedback axiom:** Persistent organization requires feedback—balancing loops for stability and regulated growth, reinforcing loops for amplification; unattended reinforcement can produce runaway dynamics. [48]

**Propagation axiom:** In interdependent networks, shocks propagate along pathways; cascade risk is a structural property of network architecture and interaction strengths. [49]

**Regulation-limit axiom:** Effective regulation is bounded by information/control capacity relative to disturbance variety (requisite variety). [17]

**Resilience axiom:** System health is measurable as the capacity to absorb disturbance and reorganize while retaining function/identity; beyond thresholds, systems may shift to alternative regimes. [50]

**Cooperation-conditions axiom:** Cooperation becomes stable under identifiable mechanisms (kin, reciprocity, reputation, network structure, selection at higher levels); otherwise defection can dominate locally while degrading global viability. [31]

**Constraint alignment axiom for AI:** In complex worlds, aligning intelligent behavior requires encoding interdependence as constraints (CMDPs, safe RL, viability kernels) rather than as naive single-metric optimization vulnerable to specification gaming. [51]

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