

H H E U R I S T I C S

RESEARCH REPORT · OCTOBER 2026

A Unified Architecture of Reality

Constraints, Flows, Emergence and Transformation
Across the Scales of Existence

Universe · Life · Earth · Intelligence · Civilisation · Synthesis

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H Heuristics · Architecture of Creation series · Culminating synthesis

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About This Report

This report asks whether one analytical framework can describe how reality generates, organises, sustains and transforms complex systems at every scale from the cosmic web to the global economy. It is the culminating synthesis of the H Heuristics [Architecture of Creation](#) series. The foundational report asked why the same forms recur across unrelated systems and answered with a layered model of constraints, generators and filters. Four applications followed. [The Architecture of Creation in the Universe](#) took the model to cosmology. [The Architecture of Life](#) took it to biology. [The Architecture of Earth](#) took it to a planet whose rock, air, water and life are coupled by feedback. [The Architecture of Creation and Development](#) took it to economies, technology and convergence. The companion report [The Architecture of Entropy](#) supplied the thermodynamic background on which all of them rely.

Each of those reports looked at one scale. This one looks across them. It asks what the series has found to be common, what it has found to be specific, and whether the common part is strong enough to be called an architecture. It is deliberately the most sceptical report in the series. A synthesis invites grand claims, and the history of attempts to unify the sciences of organisation is a history of claims that were either too vague to test or too specific to survive. The report therefore states its framework in a form that can fail, tests it with original calculations, and ends with a verdict rather than a celebration.

The report is written for researchers, students and policy readers interested in complex systems, and for anyone who has noticed that a river delta, a lung and a road network look alike and wondered whether that means anything. It integrates established science with the H Heuristics framework but keeps them apart. Every major claim is graded for strength of evidence, analogies are labelled as analogies, and the framework's own propositions are marked as such.

How to read this report

Each section starts on a new page and can be read on its own. The report has four parts (Figure 1). Sections 1 to 4 set out the question, review earlier attempts at unification, state the six-layer framework and separate four quantities that are often confused: energy, entropy, information and complexity. Sections 5 to 9 apply the framework to five domains: the physical universe, life, planetary systems, intelligence and civilisation. Sections 10 to 12 compare recurring structures across domains, test cross-domain claims with quantitative models and state eight hypotheses. Sections 13 to 15 examine the limits of unification, draw out implications and give the verdict.

FOUNDATIONS

**1. Introduction**

The question, the thesis and what would count as an answer

Section 1

**2. Literature Review**

A century of attempts to unify the sciences of organisation

Section 2

**3. The Theoretical Framework**

Six interacting layers and how they are formalised

Section 3

**4. Energy, Entropy, Information, Complexity**

Four quantities that must not be conflated

Section 4

DOMAINS

**5. The Physical Universe**

Gravity, the cosmic web, stars and planets

Section 5

**6. Life and Biological Complexity**

Metabolism, heredity, scaling and major transitions

Section 6

**7. Planetary Systems**

Coupled cycles, regulation and habitability

Section 7

**8. Intelligence**

Brains, learning, collective cognition and machines

Section 8

**9. Civilisation and Human Systems**

Cities, economies, diffusion and resilience

Section 9

SYNTHESIS

**10. Recurring Structures**

Branching, hierarchy, modularity, feedback, thresholds

Section 10

**11. Quantitative Tests**

Scaling, networks, cascades and heavy tails

Section 11

**12. Research Hypotheses**

Eight testable propositions

Section 12

EVALUATION

**13. The Limits of Unification**

Teleology, reduction and irreducible particulars

Section 13

**14. Implications**

For science, policy and the series

Section 14

**15. Conclusion**

Is a unified architecture scientifically defensible?

Section 15

Figure 1. The structure of the report. Four foundational sections establish the framework, five domain sections apply it, three synthesis sections test it, and three evaluation sections judge it.

Source: *H Heuristics*. Illustrative.

Blue underlined text is a hyperlink. Links to the primary literature go to a DOI record where a specific result is cited, and to a reference article where a concept is introduced. Every DOI was checked against its registered title before publication. A full reference list follows Section 15.

Evidence grades

Claims are graded on the same four-level scale used throughout the series.

Table 1. Evidence grades used in this report

Grade	Meaning	Cross-domain example
A: Established	Derived from physical law, or confirmed repeatedly by independent observation or experiment.	Every persistent organised structure is sustained by a throughput of free energy
B: Well supported	Strong evidence from several lines of work, with unresolved detail or some dissent.	Rising autocorrelation precedes many fold-type transitions in models and in some data
C: Plausible or contested	A credible mechanism and partial evidence; the field is actively debating it.	Quarter-power metabolic scaling arises from the geometry of supply networks
D: Speculative	A hypothesis offered for testing, labelled as such wherever it appears.	Living, cognitive and social systems are all poised near critical points

The grade describes the state of knowledge about a claim, not its importance. Several of the claims most often made for unified theories of complexity are graded C or D in this report.

A note on the figures and calculations

The report contains 28 figures and 14 tables. Many of the figures are original calculations made for this report: the cosmic web in the Zel'dovich approximation; a mass–radius map of structures from protons to the observable universe with the limits that bound them; entropy and statistical complexity along the logistic map; recomputed energy rate densities with counterexamples; the exponent of a West–Brown–Enquist supply network as a function of its depth; Daisyworld; the memory capacity of a Hopfield network; simple and complex contagion on small-world networks; three branching networks grown by different mechanisms and compared by fractal dimension and Strahler ratios; heavy tails from four different generators; network robustness to failure and attack; shock containment in modular networks; Simon's watchmaker parable; critical slowing down before a fold; feedback with gain and delay; and a model of structures that exist only above a minimum flow. Each caption says what was computed. The remaining figures are explanatory diagrams drawn for this report or charts of published estimates, credited in their source lines.

How to cite

Hughes, H. (2026). *A Unified Architecture of Reality: Constraints, Flows, Emergence and Transformation Across the Scales of Existence*. H Heuristics Research Report, Architecture of Creation series. The report synthesises published research and presents original calculations and propositions, which are labelled as such.

Executive Summary

Abstract

Reality contains systems organised across radically different scales: filaments of dark matter hundreds of millions of light-years long, stars, planets, cells, ecosystems, brains, cities and a global economy. They obey different rules and operate through different mechanisms. Yet they show recurring features: branching networks, nested hierarchies, modules, feedback loops, thresholds, heavy-tailed size distributions and cycles of growth, rigidity, release and reorganisation. This report asks whether a common architecture can explain how reality generates, organises, sustains and transforms complex systems, without assuming that every phenomenon reduces to one mechanism or that the universe has a purpose. It proposes a six-layer framework: fundamental constraints; flows and interactions; emergence and organisation; persistence and adaptation; evolution and transformation; and dissolution and reorganisation. It reviews a century of earlier attempts at unification, separates energy, entropy, information and complexity, applies the framework to five domains, and tests cross-domain claims with sixteen original models. It concludes that a unified architecture is defensible as a comparative and methodological framework but not as a single theory. Three principles generalise as physical law or shared mathematics: organised structure requires a throughput of free energy; constraints bound the space of possible forms; and systems near certain thresholds share universal dynamics. Others, including quarter-power scaling, self-organised criticality and Gaia-like regulation, remain domain-specific or contested. The report states eight testable hypotheses and the research programme needed to establish stronger claims.

The question

The defining question of the report is whether a common architecture can explain how reality generates, organises, sustains and transforms complex systems across different scales of existence. The question has an obvious appeal and an obvious danger. The appeal is that recurring forms are real: a lightning strike, a river basin and a blood vessel network do branch in similar ways, and the same equation describes a lake turning murky, a climate flipping state and a market crashing. The danger is that resemblance is cheap. Any two complex systems can be made to look alike at a sufficient level of abstraction, and a framework that fits everything explains nothing.

The defining question. Can a common architecture explain how reality generates, organises, sustains and transforms complex systems across different scales of existence?

The thesis

The report's thesis is that reality's complex systems share an architecture of *problems* rather than an architecture of *mechanisms*. Every persistent structure, from a star to a city, must solve the same small set of problems: it must exist within physical constraints, draw on a flow of energy and matter, hold itself together against degradation, respond to disturbance, change over time and eventually come apart. Different domains solve these problems with different machinery. Where the machinery is genuinely shared, usually because the same mathematics applies near the same kind of instability, cross-domain prediction works. Where only the problem is shared, comparison is still useful, because it tells researchers what to look for, but it does not license borrowing explanations.

Principal findings

1. **Three principles generalise as law or shared mathematics (Grade A or B).** Every persistent organised structure examined in the report is sustained by a throughput of free energy and exports entropy to its surroundings. Every domain operates within hard constraints that bound the space of possible forms: the mass–radius map of Figure 9 shows that all known structures lie between a quantum limit, a black-hole limit and the density of matter. And systems approaching a fold-type threshold share universal dynamics, including critical slowing down, regardless of what they are made of (Figure 22).
2. **Similar structures routinely arise from different mechanisms (Grade A).** Three branching networks grown here by random aggregation, resource-seeking growth and length minimisation look alike and two of them share river-like Strahler bifurcation ratios of 4.5 and 4.9, yet their causes have nothing in common (Figure 18). Four different generators produce heavy-tailed distributions that cannot be told apart by shape alone (Figure 23). Resemblance is weak evidence of shared mechanism.
3. **Connectivity shapes outcomes, but not in one direction (Grade A in models, B in data).** Rewiring 1 per cent of the ties in a clustered network cut the time for a simple contagion to spread from 150 steps to 23, while rewiring 30 per cent stopped a complex contagion that needs two contacts from spreading at all (Figure 16). Removing the best-connected 20 per cent of nodes destroyed a scale-free network but left two-thirds of a random network of the same size connected (Figure 17). Modularity contained shocks to under 6 per cent of a network but slowed beneficial diffusion by an order of magnitude (Figure 20).
4. **Persistence requires maintenance, and maintenance creates thresholds (Grade B).** A simple model in which structure captures the flow that sustains it produces a minimum flow below which organisation cannot exist and collapse is abrupt and delayed (Figure 24). Structures with higher maintenance costs collapsed earlier under the same decline in supply. The same logic appears in stars, cells, ecosystems and institutions, though the variables differ.
5. **Hierarchy is favoured because stable intermediates make assembly feasible (Grade B).** In Simon's watchmaker parable, computed here, a three-level hierarchy of ten-part modules finished about 1,400 times faster than a flat sequence of 1,000 parts when the chance of interruption was 1 per cent per step (Figure 19).
6. **The same mathematics can have opposite consequences.** Organisms and cities both obey power-law scaling with size, but in organisms the metabolic rate per kilogram falls by 44 per cent for every tenfold increase in mass while in cities socio-economic output per person rises by about 41 per cent for every tenfold increase in population (Figure 15). A shared equation is not a shared explanation.
7. **Energy, entropy, information and complexity must be kept apart.** Statistical complexity peaks between order and randomness, so maximum entropy is minimum complexity (Figure 7). Energy rate density rises from stars to societies, as Eric Chaisson showed, but a candle flame scores ten million times higher than a human brain (Figure 8). No single number captures how organised a system is.
8. **Some popular unifying claims do not survive (Grade C or D).** Self-organised criticality, strong Gaia-type regulation, a universal three-quarter scaling law and a directional law of increasing complexity are each supported in particular cases but fail as general principles. The apparent acceleration of novelty through cosmic history is partly an artefact of logarithmic time axes (Figure 26).

9. **The framework's main value is diagnostic.** Asking the same six questions of any system, about its constraints, flows, organisation, maintenance, change and dissolution, reliably exposes what is known, what is missing and where an analogy from another domain might help or mislead (Figure 5).

The verdict

A unified architecture of reality is scientifically defensible as a comparative framework, with three conditions. It must be pluralist about mechanism, treating shared structure as a hypothesis about shared cause rather than evidence for it. It must be graded, distinguishing the few principles that are physical law from the larger number that are shared mathematics and the larger still that are analogies. And it must be falsifiable, which the report makes it by stating eight hypotheses with tests that could fail. On that basis the architecture is real but modest. It is a map of the problems that all complex systems must solve and of the small set of mathematical forms their solutions tend to take. It is not a theory of everything, and the report argues that the search for one is likely to mislead.

In one sentence. Reality's complex systems are not built by one mechanism, but they are built under one set of constraints and must solve one set of problems, and that shared architecture of problems is real, measurable and useful.

01

INTRODUCTION

1. Introduction

1.1 One question across many scales

Within a few minutes' walk of most cities it is possible to see a river branching into tributaries, a tree branching into twigs and a road network branching into streets. Inside the walker, arteries branch into capillaries and airways into alveoli. Far overhead, invisible to the eye but mapped by galaxy surveys, matter is organised into a web of filaments that meet at dense nodes around enormous voids. Patterns like these recur across scales that differ by more than forty orders of magnitude in size and sixty in time (Figure 2). The question this report asks is whether that recurrence reflects something deep about how reality builds things, or whether it is a coincidence of description.

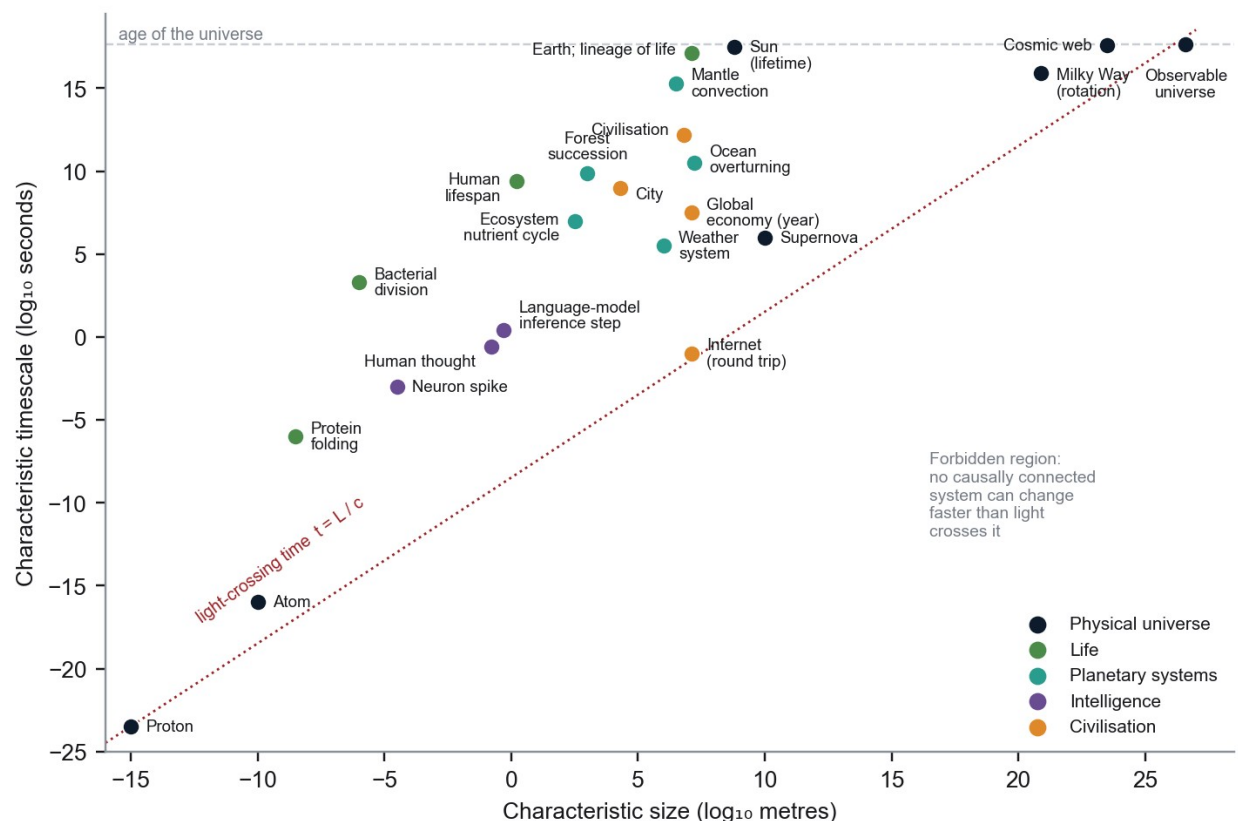


Figure 2. One framework, many scales. Characteristic sizes and timescales of systems studied in this report, coloured by domain. No causally connected system can change faster than light can cross it, which rules out the region below the dotted line. Everything else spans more than forty orders of magnitude in size and forty in time. Source: H Heuristics. Order-of-magnitude values from standard references; positions are indicative.

The [Architecture of Creation](#) series has examined the question one scale at a time. The universe report followed gravity from a nearly smooth early cosmos to galaxies, stars and planets. The life report followed chemistry into self-copying cells, multicellular bodies and ecosystems. The Earth report treated a planet as a set of coupled subsystems held within habitable limits by feedback. The development report treated economies as structures that emerge when capabilities diffuse through networks. Each found the same recurring vocabulary: constraint, flow, network, hierarchy, feedback, threshold, selection, diffusion, collapse. This report asks whether that vocabulary names a real common architecture.

1.2 The central thesis

Central thesis. Reality contains systems organised across radically different scales, from fundamental physical processes and cosmic structures to living organisms, ecosystems, intelligence and civilisation. Although these systems obey different rules and operate through different mechanisms, they may exhibit recurring principles of organisation, emergence, interaction, adaptation and transformation.

The thesis is phrased cautiously on purpose. It claims recurrence of *principles*, not identity of *mechanisms*. Gravity organises stars; natural selection shapes populations; institutions coordinate people. These mechanisms are not interchangeable and nothing in this report suggests otherwise. The claim is that each can be studied in terms of constraints, interactions, emergent structure and system change, and that doing so systematically reveals regularities that single-domain study misses.

The thesis also makes two refusals. It refuses reductionism of the strong kind, in which every phenomenon is said to follow from one master mechanism such as entropy production or information processing. And it refuses teleology, the idea that the universe is heading somewhere or that complexity is its goal. Both refusals are argued for in Section 13; here it is enough to say that the framework must work without them or not at all.

1.3 What would count as an answer

A framework that aims to unify must say in advance what would count as success. The report uses four criteria, borrowed in spirit from the philosophy of [explanatory unification](#).

1. **Coverage.** The framework should apply to systems in every domain without special pleading. A framework that works for organisms and cities but not for stars is a theory of something narrower than reality.
2. **Discrimination.** It should distinguish systems that genuinely share a mechanism from those that merely look alike. A framework that cannot tell a river network from a lung from a road network is a description, not an explanation.
3. **Prediction.** At least some cross-domain claims should allow a quantitative prediction in one domain from knowledge of another. Where the framework predicts nothing, it is at best a filing system.
4. **Falsifiability.** It should be possible to state observations that would show the framework to be wrong or empty.

Most earlier unification programmes, reviewed in Section 2, satisfied the first criterion and failed the others. They were broad enough to cover everything and therefore unable to discriminate or predict. The report's strategy is to accept narrower coverage for each specific claim in exchange for discrimination and prediction, and to state its hypotheses (Section 12) in a form that could fail.

1.4 Method

The report combines four methods. First, it synthesises published findings from physics, cosmology, chemistry, evolutionary biology, Earth system science, neuroscience, network science, economics and complexity research, grading each for strength of evidence. Second, it applies a single six-layer framework, set out in Section 3, to five domains in turn, so that comparison is structured rather than anecdotal. Third, it builds sixteen simple quantitative models, each designed to test a specific cross-domain claim: whether different mechanisms produce the same pattern, whether connectivity shapes outcomes in a consistent direction, whether thresholds share universal warning signs, and whether maintenance requirements create minimum flows. Fourth, it uses a *unification ladder* (Figure 3) to classify every cross-domain claim by its strength, from metaphor to shared law.

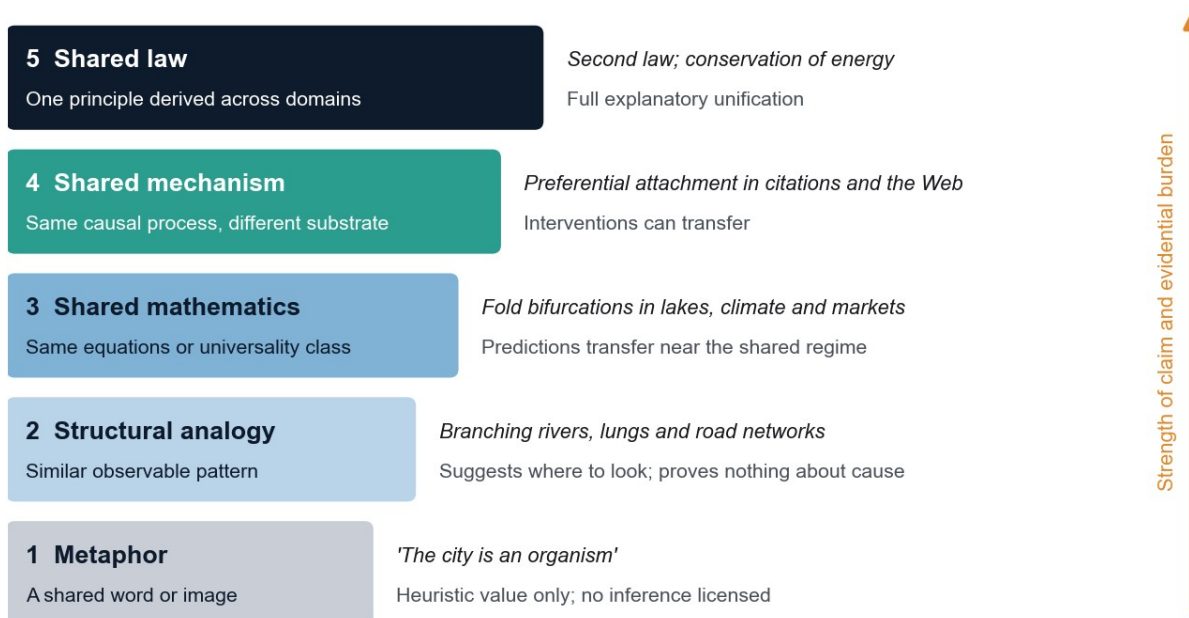


Figure 3. The unification ladder. Cross-domain claims range from metaphor, which licenses no inference, through structural analogy and shared mathematics to shared mechanism and shared law. Each rung requires more evidence and licenses stronger inferences. The report classifies every major cross-domain claim by the highest rung it reaches. Source: H Heuristics. Original framework contribution.

The ladder is an original H Heuristics contribution and does much of the work in later sections. Its point is that the word *unified* covers claims of very different strength. To say that a city is like an organism is a metaphor. To say that both cities and organisms obey power-law scaling with size is a structural analogy backed by data. To say that lakes, climates and markets all pass through the same fold bifurcation is a claim of shared mathematics, which licenses transferring predictions about warning signals. To say that citation networks and the World Wide Web both grow by preferential attachment is a claim of shared mechanism. And to say that both obey the second law of thermodynamics is a claim of shared law. Most confusion about unified theories comes from treating a lower rung as if it were a higher one.

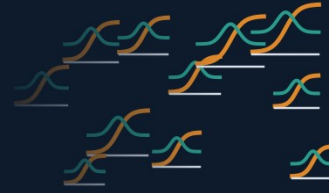
1.5 Scope and limits

The report covers five domains. The physical universe includes cosmic structure, stars and planetary formation. Life includes chemical organisation, metabolism, heredity, evolution and ecosystems. Planetary systems include geology, climate, water and nutrient cycles. Intelligence includes nervous systems, learning, collective cognition and machine learning. Civilisation includes technology, cities, economies, institutions, information networks and systemic risk. Quantum foundations, consciousness as a philosophical problem and the origin of physical law are outside its scope, although Section 13 notes where they bear on the question.

The report does not offer a new theory of physics, biology or economics. Its contribution is comparative. It asks what the specialised sciences already know when their findings are placed side by side, and whether the arrangement reveals anything that none of them can see alone.

02

LITERATURE REVIEW



2. Literature Review: A Century of Unification

2.1 Why unification keeps being attempted

The ambition to find common principles across the sciences is old, but the modern form of it dates from the 1920s, when it became possible to describe biological and social systems in the language of physics. Since then, at least a dozen major programmes have tried to identify principles of organisation that hold across domains (Figure 4). They can be grouped into three overlapping eras: systems, cybernetics and information (roughly 1920 to 1960); self-organisation and non-equilibrium physics (1960 to 1990); and networks, scaling and quantitative complexity science (1990 to the present). Each era added real tools and each overreached in a characteristic way.

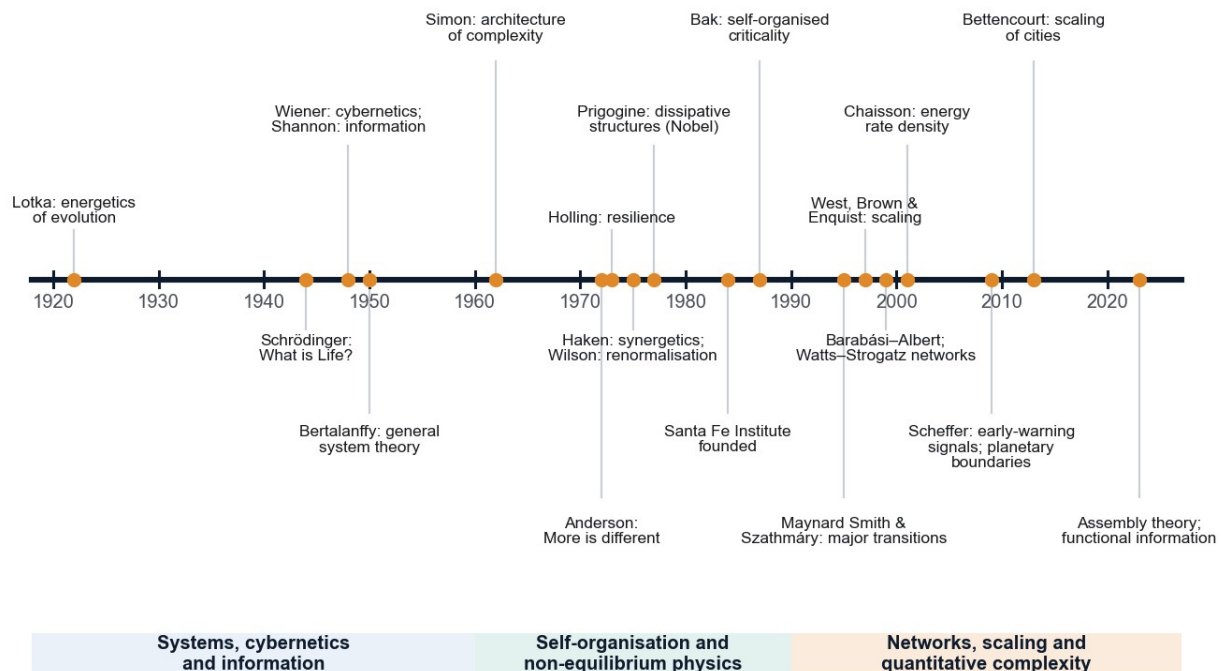


Figure 4. A century of attempts to find cross-domain principles of organisation. Each programme added tools that remain in use; most also made general claims that later work narrowed.

Source: H Heuristics, from the works cited in Section 2. Dates are of the principal publication or event.

2.2 Systems, cybernetics and information

Alfred Lotka's 1922 paper on the [energetics of evolution](#) proposed that natural selection favours organisms that increase the total flux of energy through the biosphere. It was the first serious attempt to link a biological process to a physical quantity, and versions of it recur in every later era. Erwin Schrödinger's *What is Life?* (1944) argued that organisms maintain their order by feeding on what he called negative entropy, an idea that is still the starting point for the thermodynamics of life discussed in Section 4.

After the Second World War, three developments gave unification a mathematical language. Norbert Wiener's [cybernetics](#) showed that feedback control could be described identically in machines, organisms and societies. Claude Shannon's [mathematical theory of communication](#) defined information as a measurable quantity independent of its physical carrier. And Ludwig von Bertalanffy's [general system theory](#) proposed that open systems in every domain share formal properties, including the capacity to maintain steady states far from equilibrium.

These programmes established three enduring ideas: that feedback is a general mechanism of regulation, that information can be quantified, and that open systems behave differently from closed ones. Their overreach was to assume that formal similarity implied deep identity. General system theory in particular promised laws of organisation that would hold in every science and produced instead a vocabulary that applied everywhere and predicted little. Herbert Simon's 1962 essay [The Architecture of Complexity](#) was a turning point. Simon made a specific, testable argument: complex systems are usually hierarchical and nearly decomposable because hierarchies of stable sub-assemblies evolve much faster than flat structures. Section 10 computes his argument directly.

2.3 Self-organisation and non-equilibrium physics

The second era moved from describing organisation to explaining how it arises. Ilya Prigogine's work on [dissipative structures](#), recognised by the 1977 Nobel Prize in Chemistry, showed that systems driven far from equilibrium can spontaneously form ordered patterns, such as convection cells and chemical oscillations, that are sustained by a continuous flow of energy and matter. Hermann Haken's [synergetics](#) described the same phenomenon in terms of a few slow *order parameters* that enslave the many fast variables of a system. Alan Turing's [chemical basis of morphogenesis](#), published in 1952 but widely appreciated only later, showed how two diffusing chemicals could generate spots and stripes from uniformity.

In physics, Kenneth Wilson's [renormalisation group](#) explained why systems as different as magnets and fluids behave identically near critical points. This is the strongest result in the history of cross-domain unification, because it explains *why* microscopic details do not matter: near a critical point, many different microscopic models flow to the same large-scale description. The concept of [universality classes](#) that emerged from this work is the model for what genuine unification looks like, and it is discussed in Section 11.

Philip Anderson's essay [More Is Different](#) (1972) supplied the philosophical counterweight. Anderson argued that while everything obeys the same fundamental laws, each level of organisation has its own laws that cannot in practice be derived from those below. The ability to reduce does not imply the ability to reconstruct. This principle, sometimes called *emergence*, is built into the framework of Section 3.

Ecology contributed C. S. Holling's distinction between stability and [resilience](#), and later his [adaptive cycle](#) of growth, conservation, release and reorganisation. Holling's ideas were adopted widely in social science

and are among the most influential cross-domain proposals ever made. They are also among the hardest to test, a tension examined in Section 9.

The late 1980s brought two further claims of great generality. Per Bak, Chao Tang and Kurt Wiesenfeld's [self-organised criticality](#) proposed that many natural systems drive themselves to a critical state in which disturbances of all sizes occur, explaining the ubiquity of power laws. And the founding of the Santa Fe Institute in 1984 created an institutional home for the idea of [complex adaptive systems](#) as a single field. Both programmes produced lasting results. Both also produced claims, about the universality of criticality and of power laws in particular, that later work has substantially narrowed (Figure 23).

2.4 Networks, scaling and quantitative complexity

The third era has been the most quantitative. In 1997 Geoffrey West, James Brown and Brian Enquist derived [quarter-power allometric scaling](#) in biology from the geometry of branching supply networks. Their model predicted that metabolic rate should scale with body mass to the three-quarters power, a relationship first measured by [Max Kleiber in 1932](#), and became the basis of a proposed [metabolic theory of ecology](#). Luís Bettencourt, West and colleagues later found systematic [scaling laws for cities](#), with infrastructure scaling sublinearly and socio-economic output superlinearly with population, and proposed a [theory of their origin](#) in social interaction networks.

Network science arrived at almost the same moment. Duncan Watts and Steven Strogatz showed that [small-world networks](#), highly clustered but with short path lengths, arise from a small amount of random rewiring of a regular lattice. Albert-László Barabási and Réka Albert showed that [preferential attachment](#) produces scale-free degree distributions and that such networks are [robust to random failure but fragile under targeted attack](#). Mark Newman's [review of network structure and function](#) consolidated the field. Network science gave unification a concrete object: a graph can represent a food web, a power grid, a brain or a trade system, and its properties can be measured in the same way in each.

In parallel, Eric Chaisson proposed [energy rate density](#), the power flowing through a system per unit mass, as a single metric of complexity that rises from galaxies through stars, planets, plants, animals and brains to modern society. John Maynard Smith and Eörs Szathmáry identified a sequence of [major evolutionary transitions](#) in which formerly independent units became parts of new individuals and new ways of storing and transmitting information appeared, an idea since [extended](#) toward a general theory. Marten Scheffer and colleagues showed that [catastrophic shifts](#) occur in ecosystems, climates and other systems with alternative stable states, and that [early-warning signals](#) of such shifts are generic. Johan Rockström and colleagues used related ideas to propose [planetary boundaries](#) for the Earth system.

Most recently, two programmes have proposed new general quantities. [Assembly theory](#) measures the minimum number of steps needed to construct an object from basic building blocks and argues that objects with high assembly index found in abundance are signatures of selection. A related proposal frames [functional information and selection](#) as a law-like tendency of evolving systems in general, including minerals and stars. Both are currently contested and are graded C or D in this report. [Constructor theory](#) reformulates physics in terms of which transformations are possible and which are not, an approach with clear affinities to the constraint layer of the present framework.

2.5 What the literature establishes

Table 2. Major unification programmes: their contributions and their limits

Programme	Lasting contribution	Where it overreached	Rung reached
Cybernetics and general system theory	Feedback as a general mechanism; the open-system concept	Formal similarity treated as identity; few testable predictions	Shared mathematics (feedback)
Information theory	Information as a measurable quantity	Shannon information applied to meaning and value	Shared law (communication limits)
Dissipative structures, synergetics	Order from flows far from equilibrium; order parameters	Proposed extremal principles of entropy production remain unproven	Shared mathematics
Renormalisation and universality	Why microscopic details do not matter near critical points	Rarely overreached; limited to systems near criticality	Shared law within its domain
Self-organised criticality	A mechanism for scale-free events	Claimed for systems later shown to be non-critical	Shared mechanism in some cases only
Resilience and adaptive cycle	Resilience distinct from stability; release and reorganisation	Hard to operationalise; often used as metaphor	Structural analogy, sometimes mathematics
Metabolic and urban scaling	Systematic size dependence; network origins	Universality of exponents disputed	Shared mathematics; mechanism contested
Network science	Common measures for any interaction structure	Scale-free networks claimed to be ubiquitous	Shared mathematics and some mechanisms
Energy rate density	A quantitative history of rising energy throughput	Treated as a measure of complexity itself	Structural analogy
Major transitions	Recurrent creation of new levels of individuality	Generalisation beyond biology is preliminary	Shared mechanism within biology
Assembly theory, functional information	Attempts to quantify selection in general	Strong claims ahead of evidence	Not yet established

Rung refers to the unification ladder of Figure 3. Assessments are H Heuristics judgements based on the literature cited in Section 2.

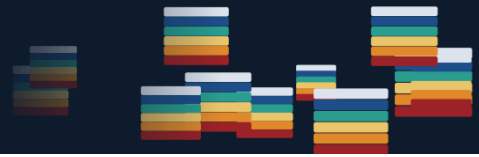
Three lessons emerge from the review. First, the most successful unifications have been mathematical rather than substantive: they show that different systems obey the same equations near the same kind of instability, not that they are the same kind of thing. The renormalisation group and the theory of [critical transitions](#) are the clearest examples. Second, claims of universal mechanisms have repeatedly been narrowed by careful data analysis. Power laws turned out to be [harder to establish](#) and [less common](#) than early work suggested; metabolic exponents turned out to [vary and curve](#). Third, the deepest unifying principles are thermodynamic and informational constraints, not generative mechanisms: they say what cannot happen and what every process must pay, not what will happen.

Steven Frank put the third lesson precisely in his analysis of [the common patterns of nature](#). Many recurring distributions, he showed, arise because aggregation of many small processes erases almost all information about them, leaving only a few constraints such as a fixed mean or a fixed scale. The pattern is common precisely because it is uninformative about mechanism. The framework of Section 3 is built around this insight: what recurs across domains is often the residue of constraint, and recurrence is therefore weak evidence of shared cause.

Gap addressed by this report. No previous programme has combined a cross-domain framework with explicit evidence grades, a classification of claims by strength, and original tests designed to discriminate shared mechanism from shared appearance. The report attempts all three.

03

THE THEORETICAL FRAMEWORK



3. The Theoretical Framework

3.1 Six interacting layers

The synthesis organises the theory around six interacting layers (Figure 5). They are proposed analytical categories, not six established laws of nature. Each layer corresponds to a question that can be asked of any system, and the answers differ from domain to domain. The layers are ordered from the most general to the most historical, but real systems can skip layers, occupy several at once and feed back between them.

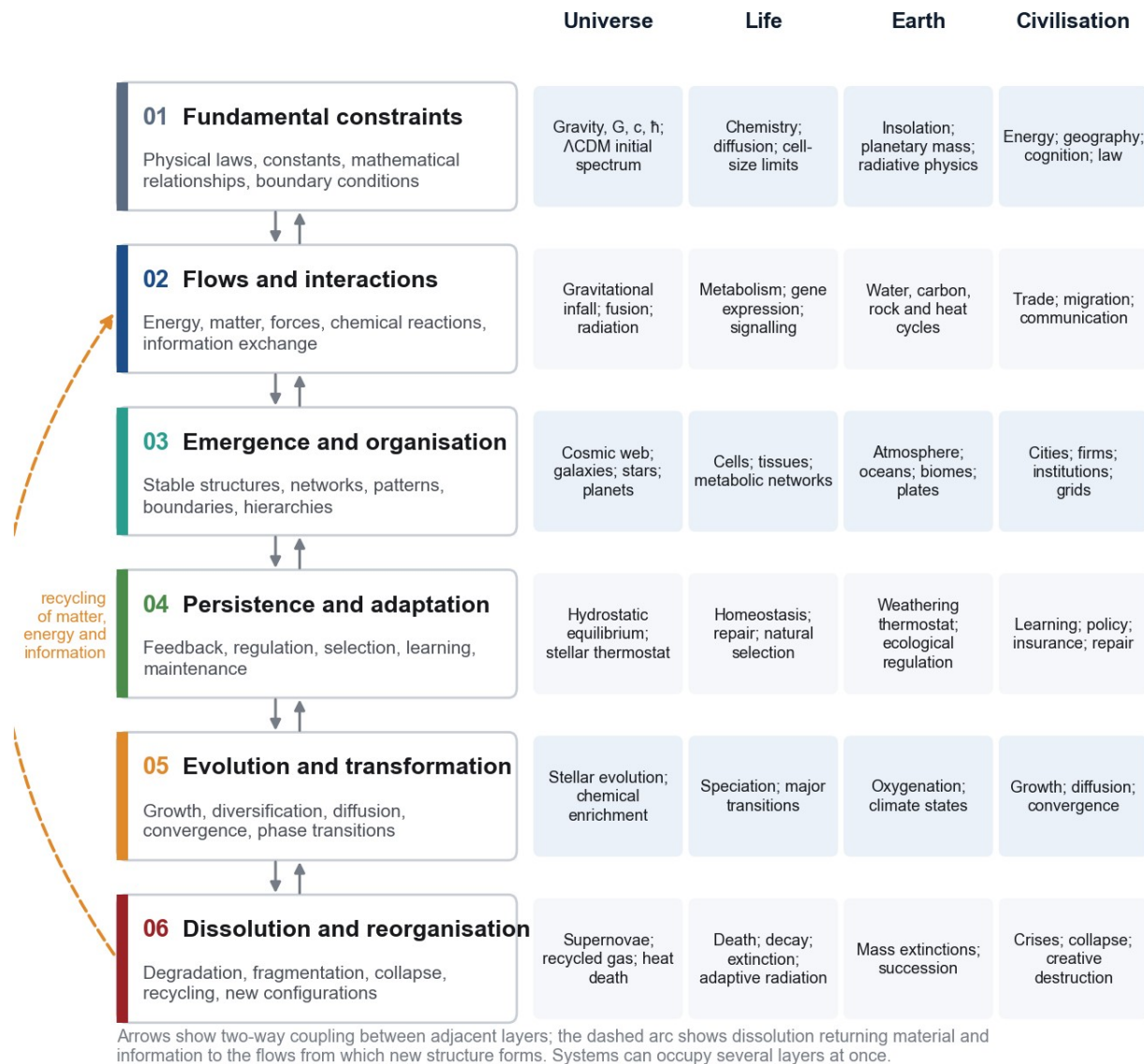


Figure 5. The six-layer architecture with examples from four domains. Fundamental constraints bound what is possible; flows and interactions drive change; emergence produces organised structure; persistence and adaptation keep it in being; evolution and transformation change it over time; dissolution and reorganisation return its material and information to the flows from which new structure forms.

Source: H Heuristics. Conceptual architecture: real systems can skip layers, contain multiple layers simultaneously and undergo feedback between them.

- 1. Fundamental constraints.** Physical laws, constants, mathematical relationships and boundary conditions. They determine what is possible, not what happens. The speed of light, conservation of energy, the second law of thermodynamics, the geometry of space and the combinatorics of possible arrangements belong here, as do domain-level constraints such as the genetic code or the legal framework of an economy.
- 2. Flows and interactions.** Energy, matter, forces, chemical reactions and information exchange. These are the drivers. Nothing organises without them, and the direction of every flow is ultimately set by a gradient: of temperature, concentration, gravitational potential, price or knowledge.

3. **Emergence and organisation.** Stable structures, networks, patterns, boundaries and hierarchies that arise from flows acting under constraints. This is the layer at which new entities appear: stars, cells, organs, cities, firms. Their behaviour can often be described with fewer variables than their parts require.
4. **Persistence and adaptation.** Feedback, regulation, selection, learning and maintenance. These are the processes that keep a structure in being against degradation and disturbance, and that adjust it to changing conditions.
5. **Evolution and transformation.** Growth, diversification, diffusion, convergence and phase transitions. These are the processes by which structures change their kind, not just their state: stars evolve through stages, species diverge, technologies spread, economies restructure.
6. **Dissolution and reorganisation.** Degradation, fragmentation, collapse, recycling and new configurations. Every structure examined in the series eventually comes apart, and the material, energy gradients and information it held become available for new structures.

The framework would investigate how these layers interact in different domains. For example, gravity helps organise matter into stars, while natural selection shapes biological populations and institutions coordinate human activity. These mechanisms are not interchangeable, but each can be studied in terms of constraints, interactions, emergent structure and system change.

3.2 Each layer as a question

The layers become useful when each is turned into a question with a defined set of tools and observable variables (Table 3). This is what allows the framework to be applied in the same way to a galaxy and a firm, and what allows the comparison to be checked.

Table 3. The six layers as questions, with the tools and observables used to answer them

Layer	Question	Formal tools	Observable variables
1 Constraints	What is possible, and what is forbidden?	Conservation laws; dimensional analysis; combinatorics; feasibility bounds	Limits, invariants, maximum efficiencies, forbidden regions
2 Flows	What drives the system, and how much?	Thermodynamics; transport equations; input–output accounts	Power, throughput, gradients, fluxes, residence times
3 Emergence	What structures form, and can they be described with fewer variables?	Coarse-graining; network analysis; pattern formation; order parameters	Topology, modularity, hierarchy depth, scaling exponents
4 Persistence	What keeps it in being, and against what?	Control theory; stability analysis; selection and learning dynamics	Return time, loop gain, maintenance cost, error rates
5 Transformation	How does it change its kind?	Bifurcation theory; diffusion models; evolutionary dynamics	Growth rates, adoption curves, thresholds, novelty rates
6 Dissolution	How does it come apart, and what is recycled?	Percolation; cascade models; decay kinetics	Failure sizes, recovery times, recycling fractions

The tools are standard in their fields; the contribution of the framework is to apply all six questions to every system.

3.3 A formal statement

The framework can be written compactly. Let a system be described by a microscopic state x that evolves under dynamics driven by external flows J and parameters θ , subject to constraints:

$$dx/dt = f(x, J; \theta), \quad g(x) \leq 0 \quad (1)$$

The constraint set g is layer 1; the flows J and the interactions encoded in f are layer 2. Emergence (layer 3) occurs when there is a coarse-graining $X = \Phi(x)$, mapping many microscopic variables to a few macroscopic ones, such that the macroscopic variables obey their own closed dynamics to good approximation:

$$dX/dt \approx F(X, J; \Theta) \quad (2)$$

This is a precise version of Anderson's claim that more is different. It holds when the microscopic details compress into a small number of effective parameters Θ , as studies of [parameter-space compression](#) have shown for models in physics and biology, and it can sometimes be detected directly by information-theoretic measures of [causal emergence](#), which ask whether a macroscopic description is more predictive than a microscopic one, an approach since [refined and debated](#).

Persistence (layer 4) has a thermodynamic statement. The entropy of an open system changes through internal production, which by the second law is never negative, and exchange with its surroundings:

$$dS/dt = d_i S/dt + d_e S/dt, \quad d_i S/dt \geq 0 \quad (3)$$

An organised structure can persist only if it exports entropy at least as fast as it produces it, so that $d_e S/dt \leq -d_i S/dt$. That export requires a throughput of free energy, which is why every persistent structure in the report depends on a flow. Persistence also has a dynamical statement: an organised state X^* persists if it is an attractor of Equation 2 whose basin is wider than typical disturbances.

Transformation (layer 5) is change in Θ or in the attractor structure of Equation 2, including the bifurcations at which attractors appear or disappear. Dissolution (layer 6) is the loss of closure: the macroscopic description stops working because the flows that sustained it fall below a threshold or a disturbance carries the system out of its basin. The six layers are therefore not arbitrary. They correspond to the six things that must be specified to describe any open dynamical system that organises, persists and changes.

3.4 How the layers interact

The layers are coupled in both directions. Upward, constraints shape flows, flows generate structure and structure enables persistence. Downward, organised structures change the flows that pass through them and even the effective constraints on their parts. A forest changes the rainfall that sustains it. A cell membrane changes which chemical reactions can occur inside it. A legal system constrains what its citizens can do. This downward influence is sometimes called downward causation; in the framework it requires no new physics, only the observation that macroscopic variables appear as parameters in the dynamics of microscopic ones.

Three generative motifs recur across domains and connect the layers in characteristic sequences.

- **Constraint, flow, structure.** A gradient is imposed across a constrained medium and structure appears to dissipate it: convection cells in a heated fluid, the cosmic web in an expanding universe, river networks on a landscape, trade routes between regions of different prices.

- **Structure, feedback, persistence.** An organised structure regulates the flows that sustain it, keeping itself within a viable range: hydrostatic equilibrium in a star, homeostasis in a body, the silicate-weathering thermostat on Earth, monetary policy in an economy.
- **Variation, selection, transformation.** Variants are generated, some persist longer or copy themselves more, and the population of structures changes: natural selection, learning in brains and machines, market competition, cultural evolution.

The third motif deserves care because it is the one most often generalised beyond its evidence. Variation and selection require heredity, some way for successful variants to be copied with modification. Biology, cognition and culture have heredity. Stars and planets do not. Claims that selection operates on non-replicating physical systems, including recent proposals discussed in Section 5, must therefore establish what plays the role of heredity, and so far none has done so convincingly.

3.5 Relation to the series framework

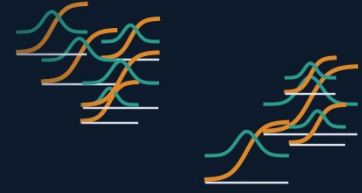
The foundational report described recurring forms as the product of a three-part *creation structure*: constraints that define a space of viable forms, generators that explore it, and filters that decide what persists. The six-layer architecture extends that structure in time. Constraints are layer 1. Generators are layers 2 and 3, the flows and the organisation they produce. Filters are layer 4. Layers 5 and 6 add what the creation structure left implicit: that the space of viable forms itself changes, and that every structure eventually ends and returns its components to the pool from which new forms are drawn.

3.6 What the framework claims and does not claim

- **It claims that the six questions can be asked of any organised system and that the answers are informative.** This is a methodological claim and is tested by the domain sections that follow.
- **It claims that some answers recur across domains for identifiable reasons.** Section 11 tests which recurrences reflect shared law or shared mathematics and which reflect only shared appearance.
- **It does not claim that the layers are fundamental entities.** They are a way of organising inquiry, as the levels of a map are a way of organising geography.
- **It does not claim that every system passes through every layer in order,** or that later layers are more advanced or more valuable than earlier ones.
- **It does not claim that the universe has a direction or purpose.** Increases in local organisation are compatible with, and paid for by, increases in total entropy.

04

ENERGY · ENTROPY · INFORMATION · COMPLEXITY



4. Energy, Entropy, Information and Complexity

4.1 Why the distinctions matter

Unified theories of complexity often rest on one of four quantities, and frequently slide between them. Energy, entropy, information and complexity are related but not interchangeable, and treating them as synonyms is the single most common error in the literature reviewed in Section 2. Two further concepts, adaptation and resilience, are often added to the list and are equally prone to confusion. Figure 6 sets out what each means, how it is measured and what it is not.

Energy The capacity to do work. Conserved; flows down gradients and is degraded, never destroyed. Measured in joule (J); power in watts It is not Not order, not information, not complexity	Entropy The number of microstates compatible with a macrostate (thermodynamic), or uncertainty of a distribution (statistical). Measured in J K^{-1} ; or bits It is not Not 'disorder' in the everyday sense; local decreases are allowed	Information Reduction in uncertainty; in biology and cognition, correlation that is used to act. Measured in bits It is not Not meaning; Shannon information is blind to semantics
Complexity Structure that is neither fully ordered nor random; hard to compress yet not noise. Measured in No single unit; many rival measures It is not Not size, not energy use, not entropy	Adaptation A change in a system that improves its fit to its environment through selection or learning. Measured in Fitness, loss, performance It is not Not any change; not progress or purpose	Resilience Capacity to absorb disturbance and keep function, or to reorganise without losing identity. Measured in Return time; basin width; recovery It is not Not stability alone; not resistance to all change

Figure 6. Six concepts that unified theories often conflate. Each has a distinct definition and measure. Most errors in cross-domain reasoning come from treating one as a proxy for another.

Source: H Heuristics, from the standard definitions in thermodynamics, information theory and complex systems research cited in Section 4.

4.2 Energy and entropy

Energy is conserved. What changes in every process is its quality: concentrated, low-entropy energy such as sunlight or chemical bonds is degraded into dispersed, high-entropy heat. The [second law of thermodynamics](#) states that the total entropy of an isolated system never decreases. It does not forbid local decreases. A refrigerator, a cell or a city can become more ordered as long as it exports at least as much entropy as its internal order removes, as Equation 3 requires. [Schneider and Kay](#) argued that living systems can be understood as structures that arise to degrade imposed gradients, and [Kleidon](#) has developed the same view for the whole Earth system.

Earth illustrates the principle at planetary scale. It absorbs about 122,000 terawatts of sunlight radiated from the Sun's surface at about 5,800 K and returns the same power to space as infrared radiation at an effective temperature of about 255 K. Because the entropy carried by radiation is proportional to its power divided by its temperature, Earth exports entropy at a rate of roughly

$$\dot{S} \approx (4/3) Q (1/T_E - 1/T_\odot) \approx (4/3) \times 1.22 \times 10^{17} \text{ W} \times (1/255 - 1/5,772) \text{ K}^{-1} \approx 6 \times 10^{14} \text{ W K}^{-1} \quad (4)$$

That export budget is what pays for every weather system, ocean current, organism and city on the planet. It is a constraint, not a cause: it says how much order can be maintained, not which order will appear. The [entropy of the universe](#) as a whole is dominated by supermassive black holes and dwarfs everything on Earth by many orders of magnitude, so local structure is a negligible eddy in a cosmic entropy budget that is rising steadily, as [Lineweaver and Egan](#) have emphasised. Gravity is what makes the eddies possible: by clumping matter into stars it creates the temperature differences that drive everything else.

A further step is often taken and should be resisted. Several authors have proposed that systems organise so as to [maximise the rate of entropy production](#). The principle reproduces some features of atmospheric circulation, but it has no general derivation and counterexamples are known. [Jeremy England's](#) statistical physics of self-replication provides a more rigorous link between dissipation and replication but makes no claim that dissipation is maximised. The report grades maximum entropy production as a general principle C.

4.3 Information

Shannon defined the information content of a source as the average reduction in uncertainty when a message is received:

$$H = -\sum_i p_i \log_2 p_i \text{ bits} \quad (5)$$

Shannon entropy has the same mathematical form as thermodynamic entropy, and [Jaynes](#) showed that statistical mechanics can be derived as inference under constraints, so the link is not an accident. The physical link is [Landauer's principle](#): erasing one bit of information dissipates at least $kT \ln 2$ of heat, about 3×10^{-21} joules at body temperature. The principle was [verified experimentally](#) in 2012 and is now part of a broader [thermodynamics of information](#) built on [stochastic thermodynamics](#).

Shannon information is blind to meaning. A random string has maximal Shannon entropy and no use. Biology, cognition and civilisation trade in what might be called functional or semantic information: correlations between a system and its environment that the system uses to persist. [Kolchinsky and Wolpert](#) have proposed a formal definition: semantic information is the information a system holds about its environment that is causally necessary for it to maintain itself. The definition links information to

persistence (layer 4) and is one of the more promising bridges in the literature, graded C as a general principle.

4.4 Complexity

Complexity has no single accepted measure, and that is itself informative. Proposed measures include algorithmic complexity, the length of the shortest program that generates an object; [statistical complexity](#), the amount of information a model needs to store to predict a process optimally; logical depth; effective complexity; and the [disequilibrium-based measure](#) of López-Ruiz, Mancini and Calbet (LMC). Most share one property: they are low for both perfect order and perfect randomness and high in between, as [Crutchfield](#) has argued in detail.

The report illustrates this with the [logistic map](#), the simplest system that passes from order to chaos as one parameter r is increased (Figure 7). For each value of r from 2.9 to 4.0 a long trajectory was converted to a binary sequence and the Shannon entropy and LMC complexity of its eight-symbol words were computed. When the map settles to a fixed point, entropy and complexity are both zero. In periodic windows, entropy is low and complexity is high. In fully developed chaos at $r = 4$ the binary sequence is indistinguishable from coin tosses: entropy reaches 1.00 and complexity falls to zero. Complexity in this calculation peaked at $r \approx 3.83$, at the edge of the period-three window, where the normalised entropy was only about 0.2.

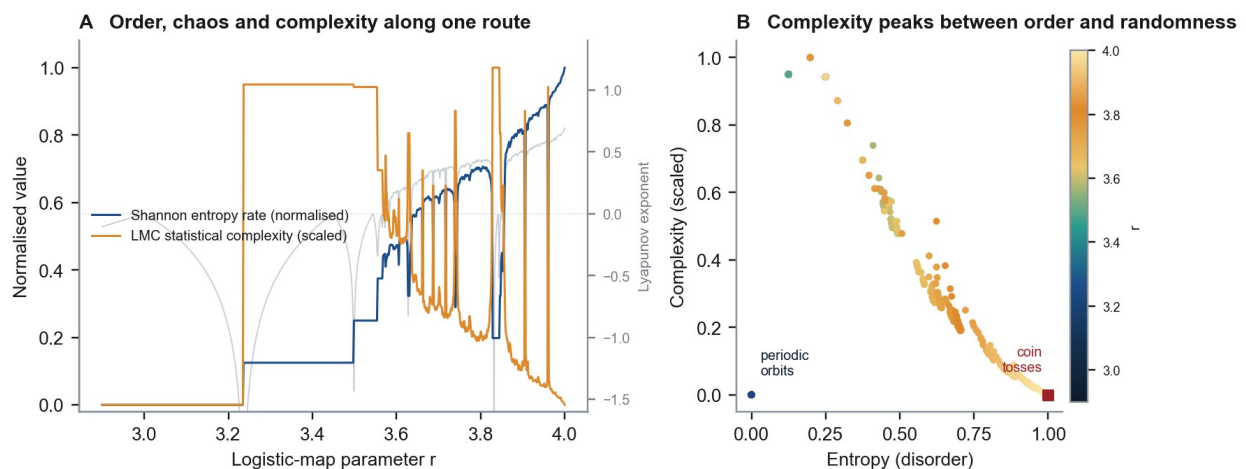


Figure 7. Entropy is not complexity. Panel A: normalised Shannon entropy and LMC statistical complexity of eight-symbol words along the logistic map, with the Lyapunov exponent (grey) marking chaos where it is positive. Panel B: complexity against entropy for every value of r ; complexity is zero for perfect order and for randomness and peaks at low-to-intermediate entropy.

Source: *H* Heuristics calculation. Sixty thousand iterations per value of r after a transient of 2,000; binary partition at $x = 0.5$; words of length eight.

$$C_{\text{LMC}} = H \times D, \quad D = \sum_i (p_i - 1/N)^2 \quad (6)$$

The lesson for a unified theory is direct. Entropy measures disorder; complexity measures structure that is neither ordered nor random. A process that increases entropy can increase or decrease complexity depending on where it starts. Claims that the universe grows more complex because entropy increases, or that complexity is a form of negative entropy, conflate two different quantities.

4.5 Energy rate density

Eric Chaisson's energy rate density, Φ_m , the power flowing through a system per unit of its mass, is the most ambitious attempt to give cross-domain complexity a single number. His published values rise from about 0.5 erg per second per gram for the Milky Way and 2 for the Sun through 900 for photosynthesising plants and about 20,000 for animal bodies to 150,000 for the human brain and 500,000 for modern society (Figure 8, Panel A). The sequence is real and the report reproduces it from first principles: the Sun's luminosity divided by its mass gives 1.9; a resting human body of 70 kilograms at 100 watts gives 14,000; a 1.4-kilogram brain at 20 watts gives 143,000; and global primary energy use of about 19.6 terawatts divided by the mass of humanity gives about 400,000.

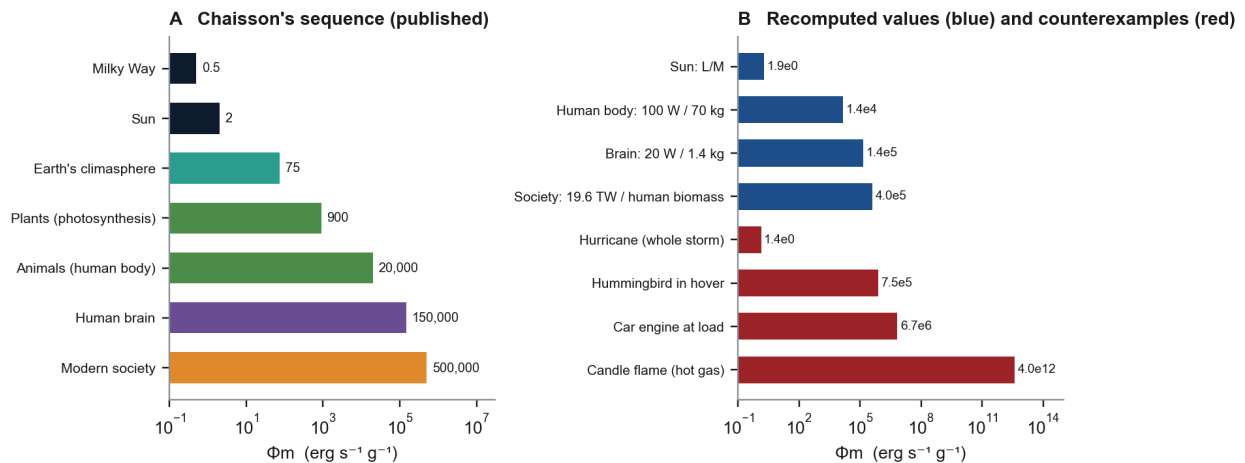


Figure 8. Energy rate density rises from stars to societies but is not a measure of complexity. Panel A: values published by Chaisson. Panel B: the same quantity recomputed for this report (blue) and for four counterexamples (red). A hurricane, one of the most organised structures in the atmosphere, scores lower than the Sun; a candle flame scores higher than any brain.

Source: Panel A, Chaisson (2011). Panel B, H Heuristics order-of-magnitude calculation: hurricane dissipation 1.5×10^{12} W over 1.1×10^{16} kg of air; hummingbird 0.3 W at 4 g; car engine 100 kW at 150 kg; candle flame 80 W in about 0.2 mg of hot gas. $1 \text{ W kg}^{-1} = 10^4 \text{ erg s}^{-1} \text{ g}^{-1}$.

The counterexamples show what the metric does and does not capture. A mature hurricane dissipates about 1.5 terawatts across some 10^{16} kilograms of air, giving an energy rate density of about 1.4, lower than the Sun's. A hummingbird in hovering flight reaches about 750,000, above modern society. A car engine at load reaches about 7 million. A candle flame, a simple chemical reaction with a few square centimetres of structure, reaches about 4×10^{12} because its tiny mass of hot gas carries 80 watts. Energy rate density therefore measures how intensely a system processes energy, which is a necessary condition for maintaining complex structure. It is not a measure of the structure itself. The report grades the trend in Panel A as B and the use of Φ_m as a general complexity metric as C.

4.6 Adaptation and resilience

Adaptation is change that improves fit to an environment through selection or learning. Its mathematics is surprisingly shared. The [replicator equation](#) of evolutionary dynamics,

$$dx_i/dt = x_i (f_i(x) - \bar{f}(x)) \quad (7)$$

in which the share x_i of type i grows when its fitness exceeds the average, has the same form as [Bayesian updating](#) of beliefs in light of evidence, and closely related forms describe learning by reinforcement and market share dynamics under competition. This is a genuine shared mathematics

(rung 3 of the ladder). It does not mean that markets, brains and gene pools are the same kind of thing; it means that any system in which variants are amplified in proportion to relative success will show certain common behaviours, including the loss of diversity under constant conditions and the dependence of long-run outcomes on rare early events.

Resilience has two meanings that must be kept apart. *Engineering resilience* is the speed of return to equilibrium after a small disturbance. *Ecological resilience*, in Holling's sense, is the size of disturbance a system can absorb before it moves to a different state. The two can move in opposite directions: a system can return quickly from small shocks while its basin of attraction shrinks, which is exactly what happens on the approach to a tipping point (Section 10). Resilience is not resistance to all change, and a system that cannot change is often less resilient over the long run.

4.7 How the quantities relate

Table 4. Relations between the core quantities and the errors that come from conflating them

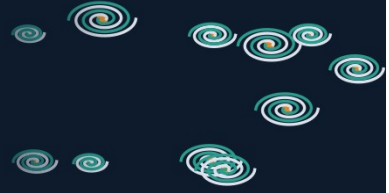
Pair	Genuine relation	Common conflation error
Energy and entropy	Degrading free energy produces entropy; organised structures need free-energy throughput	Treating energy use as a measure of order
Entropy and information	Same mathematical form; Landauer links erasure to heat	Treating any decrease in entropy as an increase in useful information
Information and complexity	Complexity measures stored predictive information	Treating maximum information (randomness) as maximum complexity
Energy and complexity	Complex structures generally need high energy rate density	Treating energy rate density as complexity (Figure 8)
Complexity and adaptation	Adaptation can build complexity when it pays	Assuming selection always increases complexity; parasites and cave fish lose it
Adaptation and resilience	Adaptive capacity can widen a basin of attraction	Assuming an optimised system is resilient; efficiency often removes redundancy

Source: H Heuristics synthesis of the literature cited in Section 4.

Principle. No single scalar measures how organised a system is. A unified architecture must track flows (energy), costs (entropy), correlations (information) and structure (complexity) as separate quantities, and must say which one a given claim is about.

05

DOMAIN I · THE PHYSICAL UNIVERSE



5. Domain I: The Physical Universe

5.1 Constraints: what the universe allows

The physical universe is the domain in which the constraint layer is most visible, because the constraints are written in physical law. The [Planck satellite](#) measured the initial conditions with extraordinary precision: a spatially flat universe about 13.8 billion years old, made of roughly 5 per cent ordinary matter, 27 per cent dark matter and 68 per cent dark energy, which began with density fluctuations of about one part in 100,000 that were nearly the same amplitude on every scale. Everything that follows is the working-out of gravity, the other forces and these initial conditions.

The constraints can be drawn. Figure 9 places twenty structures, from the proton to the observable universe, on a map of mass against radius. Three limits bound the populated region. No object can be smaller than its own [Compton wavelength](#), $\hbar/Mc$, below which quantum uncertainty dominates. No object can be smaller than its [Schwarzschild radius](#), $2GM/c^2$, without becoming a black hole. And ordinary matter cannot be compressed beyond atomic density without enormous pressure, or beyond nuclear density at all. Everything from proteins to planets lies close to the line of constant atomic density, because chemistry and electromagnetism set their size. Stars and galaxies lie above it, held together by gravity at lower mean density. Neutron stars sit on the nuclear-density line; black holes sit on the Schwarzschild line.

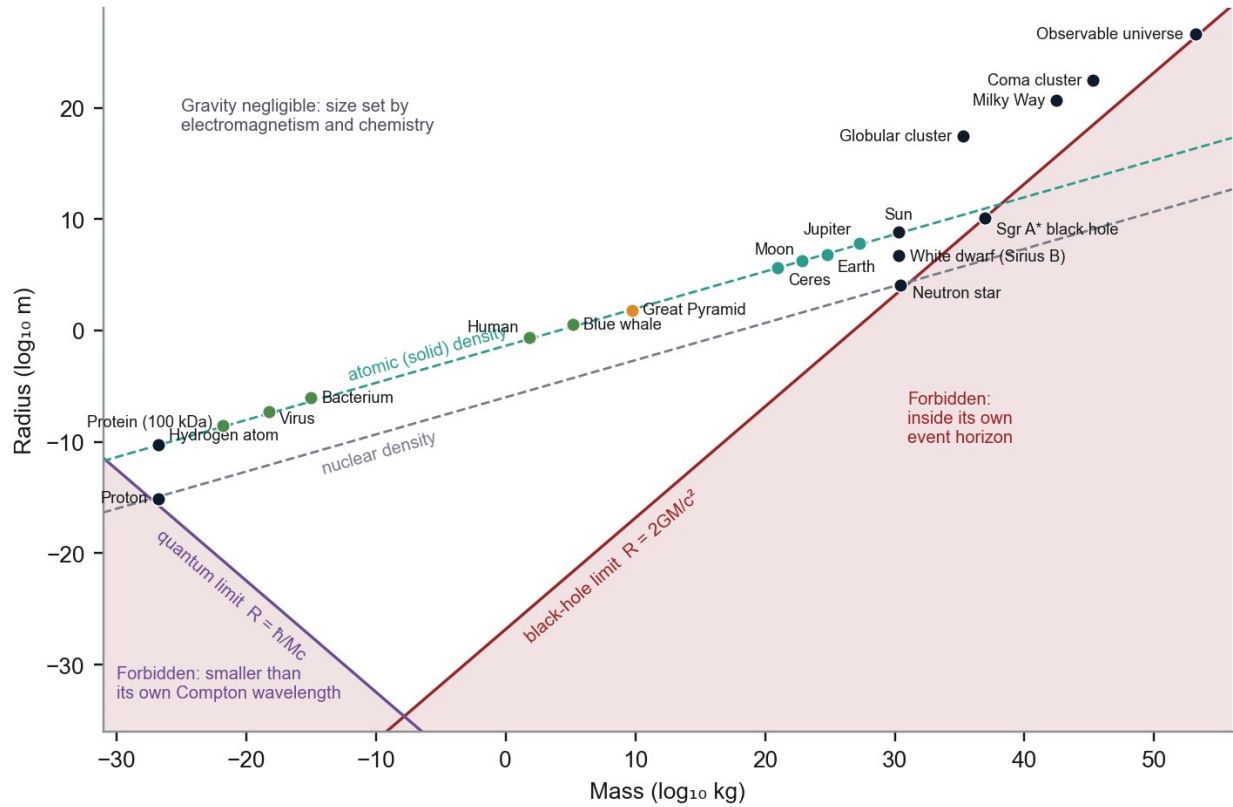


Figure 9. The constraint space of the physical universe. Every known structure lies in the band bounded by the quantum limit (purple), the black-hole limit (red) and the densities of atomic and nuclear matter (dashed). Objects from proteins to planets lie near constant atomic density; stars, clusters and galaxies are gravitationally bound at lower density; compact objects approach the limits.

Source: H Heuristics calculation from standard masses and radii. Radii of organisms and buildings are equivalent-sphere radii. The observable universe uses ordinary-matter mass within the particle horizon.

The map yields a quantitative curiosity that illustrates how constraints interlock. The line of atomic density crosses the black-hole line at a mass of about 1.6×10^{38} kilograms, some 80 million times the mass of the Sun. A black hole of that mass has the mean density of rock. Supermassive black holes at the centres of galaxies lie in this range, which is why their event horizons are not regions of extreme density on average, only of extreme curvature at their centres. Constraint maps of this kind are the most general tool in the framework: they apply in every domain and say what cannot happen before any mechanism is considered.

5.2 Flows: gravity as the engine

In the universe, the dominant flow is the conversion of gravitational potential energy into kinetic energy and heat as matter falls together. A cloud of gas becomes unstable to collapse when its size exceeds the [Jeans length](#):

$$\lambda_J = (\pi c_s^2 / G \rho)^{1/2} \quad (8)$$

where c_s is the sound speed and ρ the density. Regions larger than λ_J cannot be supported by pressure and collapse; smaller ones oscillate. The Jeans criterion is the archetype of a threshold in the framework: a competition between a destabilising flow (gravity) and a stabilising one (pressure), whose balance switches at a critical scale. Gravity is unusual among forces in that self-gravitating systems have *negative*

heat capacity: when they lose energy they contract and heat up. This property, which has no counterpart in the everyday thermodynamics of gases in boxes, is what allows gravity to create the temperature differences that drive every later flow.

5.3 Emergence: the cosmic web

The first large structure to emerge is the [cosmic web](#), a network of sheets, filaments and nodes surrounding enormous voids. Its basic geometry can be reproduced with a remarkably simple model, the Zel'dovich approximation, in which each particle moves in a straight line along the gradient of the initial gravitational potential. Figure 10 shows a two-dimensional version computed for this report. Starting from nearly uniform conditions, matter streams out of underdense regions and piles up where flows converge, first in sheets, then in filaments that meet at nodes. In the calculation the fraction of empty cells rose from 4 per cent to 43 per cent as structure grew, and the densest 1 per cent of cells came to hold about 15 per cent of the mass.

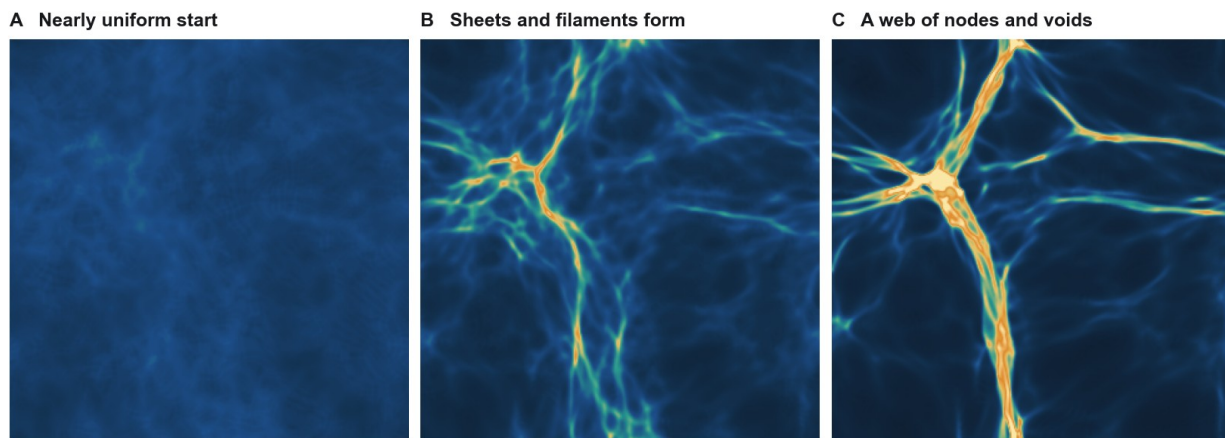


Figure 10. The cosmic web emerging in the Zel'dovich approximation. A Gaussian random density field with a power-law spectrum is evolved by moving particles along the initial potential gradient. Panel A: nearly uniform. Panel B: sheets and filaments. Panel C: a web of dense nodes connected by filaments around empty voids.

Source: H Heuristics calculation. Two-dimensional Zel'dovich approximation on a 960×960 particle grid binned to 320×320 cells; spectral slope -2.4 with a Gaussian cut-off. Illustrative of the geometry, not a cosmological simulation.

Full N-body simulations such as the [Millennium Simulation](#) confirm and refine this picture with billions of particles and show that galaxies form at the nodes and along the filaments. The cosmic web is the largest example in nature of the first generative motif of Section 3.4: constraint, flow, structure. It also shows why visual resemblance is a poor guide to mechanism. The web looks strikingly like a neural network or a fungal mycelium, and popular accounts often say so. Its mechanism, gravitational instability in an expanding space, has nothing in common with either.

5.4 Persistence: the stellar thermostat

Stars are the universe's most important persistent structures, and they persist by negative feedback. A star is in [hydrostatic equilibrium](#): the inward pull of gravity is balanced at every radius by the outward push of pressure. If the core produces slightly too much energy from fusion, the star expands, the core cools, and the fusion rate, which is extremely sensitive to temperature, falls. If it produces too little, the star contracts, heats and burns faster. The Sun has been held near a stable output by this thermostat for 4.6 billion years while its luminosity drifted upward by about 30 per cent. The mechanism is a pure example

of the second generative motif, structure, feedback, persistence, and it needs no selection, foresight or information processing.

5.5 Transformation: stellar evolution and chemical enrichment

Stars change their kind as they exhaust their fuel, and the changes transform their surroundings. Massive stars burn faster and die sooner; a star of ten solar masses lives tens of millions of years, the Sun about ten billion. In their cores and in the explosions that end the lives of the most massive, stars forge the elements heavier than helium. Each generation of stars enriches the gas from which the next forms, so the chemistry available for planets and life is the product of earlier stellar evolution. The cosmic rate of star formation peaked roughly ten billion years ago and has been falling since, a reminder that the universe's capacity to generate new structure is not constant.

5.6 Dissolution and reorganisation: recycling and heat death

Supernovae destroy stars and scatter their products, but they also compress neighbouring gas and trigger new star formation. The interstellar medium is a recycling system in which matter passes through many cycles of stellar birth and death. On the longest timescales the recycling ends. Star formation will dwindle as gas is locked into stellar remnants, and the [eventual state](#) of an ever-expanding universe is one of maximum entropy in which no gradients remain to drive structure. Dissolution in the physical universe is therefore both local and creative, as in a supernova, and global and terminal, as in heat death.

5.7 Does selection operate on non-living systems?

Recent proposals argue that something like selection operates in the physical universe. Hazen and colleagues documented [mineral evolution](#), the increase in the number of mineral species over Earth history from about a dozen in the presolar nebula to more than 5,000 today. Wong and colleagues proposed that systems of many interacting components that generate configurations which persist preferentially obey a [law of increasing functional information](#). The documentation of mineral diversification is solid (Grade A). The interpretation of it as selection in the biological sense is contested (Grade C to D), because minerals do not reproduce and there is no heredity to carry successful variants forward. What increases is the number of accessible configurations as new environments and new chemistry appear, which is better described as the expansion of a possibility space than as selection within it.

5.8 The universe through the six layers

Table 5. The physical universe through the six-layer framework

Layer	Main mechanism	Governing relation	Grade
1 Constraints	Physical constants; initial fluctuations; quantum and gravitational limits	c, G, $\hbar$; Planck-measured spectrum	A
2 Flows	Gravitational collapse; fusion; radiation	Jeans criterion; virial theorem	A
3 Emergence	Cosmic web; galaxies; stars; planetary systems	Gravitational instability; N-body dynamics	A
4 Persistence	Hydrostatic equilibrium; stellar thermostat	Negative feedback via temperature-sensitive fusion	A
5 Transformation	Stellar evolution; chemical enrichment	Nuclear reaction networks; stellar structure	A
6 Dissolution	Supernovae; recycling; ultimate heat death	Core collapse; second law	A to B
Selection?	Mineral diversification; functional information	Proposed law of increasing functional information	C to D

Source: H Heuristics synthesis. The universe is the domain in which the framework's layers are best understood and least contested; selection-like claims are the exception.

06

DOMAIN II · LIFE



6. Domain II: Life and Biological Complexity

6.1 Constraints: chemistry, diffusion and geometry

Life works within constraints that are partly physical and partly historical. The physical ones are chemistry, which fixes the available reactions and their energies, and transport. Molecules move by diffusion, and the time to diffuse a distance L grows with its square:

$$t \approx L^2 / 2D \quad (9)$$

For a small molecule in water, with a diffusion coefficient D of about 10^{-9} square metres per second, crossing a bacterium of one micrometre takes about half a millisecond; crossing one millimetre takes about eight minutes; crossing ten centimetres would take two months. This single relation explains why cells are small, why large organisms need circulatory systems and why those systems branch. Geometry adds a second constraint: volume grows with the cube of size and surface with the square, so larger bodies have less surface per unit of metabolism through which to exchange heat and materials. The historical constraints are the genetic code, the body plans inherited from ancestors and the [developmental machinery](#) that biases which variants can arise.

6.2 Flows: metabolism and its energetics

Every living system is a flow of matter and energy maintained far from equilibrium. A human body turns over roughly its own weight in ATP each day. The availability of energy also constrains what complexity can evolve. [Lane and Martin](#) argued that the acquisition of mitochondria, which multiplied the energy available per gene, was the precondition for the large genomes and complex cells of eukaryotes. Across the [major transitions](#), metabolic scaling shifts in ways that suggest each new level of organisation relaxed an energetic constraint of the level below.

6.3 Emergence: cells, networks and modules

Life's emergent structures are nested: molecules form pathways, pathways form cells, cells form tissues and organisms, organisms form populations and ecosystems. Within cells, biochemical networks are organised into [functional modules](#) and recurring circuit patterns called [network motifs](#), which [occur far more often than chance](#) and perform specific tasks such as filtering noise or generating pulses. Modularity appears to evolve because it pays when environments change: simulations show it arises [spontaneously under varying goals](#) and when connections are [costly](#). Modularity also underlies [evolvability](#), because a change in one module need not disrupt the others.

6.4 Persistence: homeostasis, repair and selection

Living systems persist by three mechanisms that operate on different timescales. Homeostasis holds internal variables within limits over seconds to days through negative feedback, as the stellar thermostat does for stars. Repair replaces damaged components over hours to years. And natural selection, over generations, removes variants that fail to persist and amplifies those that succeed. Only the third is unique to life and its descendants, cognition and culture. It requires heredity, and it is what allows living structures to accumulate adaptations rather than simply maintain a state.

6.5 Scaling: a test case for unification

Biological scaling is the most celebrated case of a proposed cross-domain law, and therefore the most instructive. Metabolic rate B rises with body mass M as a power law:

$$B = B_0 M^\beta, \quad \beta \approx 3/4 \quad (10)$$

The West–Brown–Enquist (WBE) model derived $\beta = 3/4$ by assuming that organisms are supplied by space-filling, fractal-like branching networks whose terminal units, capillaries, are the same size in all species and whose energy losses are minimised. The report recomputes the model's central result (Figure 11). In a binary network in which vessel cross-sectional area is preserved at every branching, the exponent approaches $3/4$ quickly: it is 0.734 for a network with ten levels and 0.749 with twenty. But if the smallest vessels follow the different rule appropriate to slow viscous flow, as WBE themselves proposed, small networks scale with an exponent of about 0.88 that relaxes toward $3/4$ only once the large, pulsatile vessels dominate, at about forty levels.

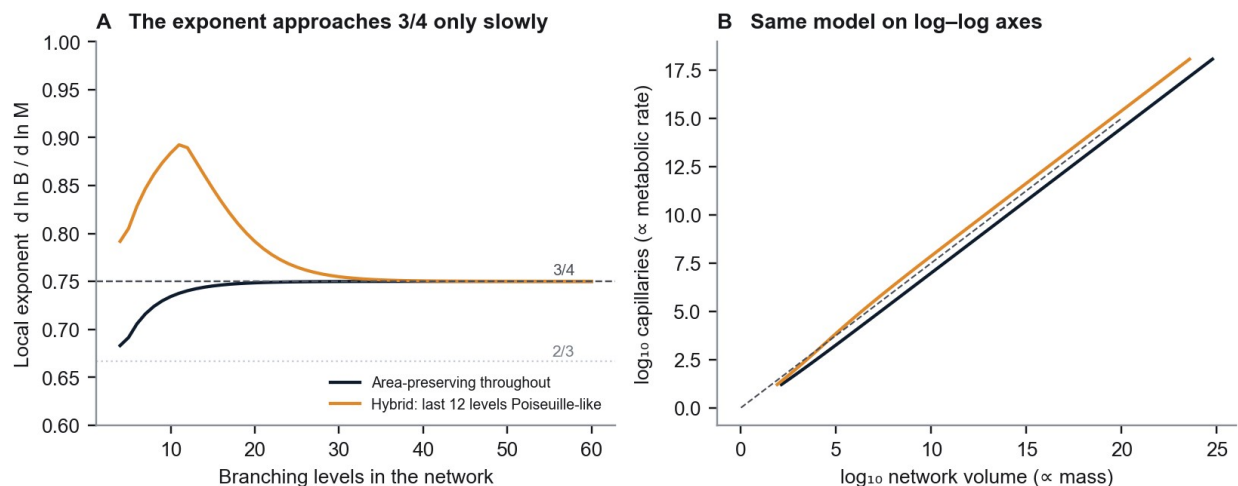


Figure 11. Where the three-quarter exponent comes from, and how fragile it is. Panel A: local scaling exponent of metabolic rate with mass for a West–Brown–Enquist branching network as the number of levels grows. With area-preserving branching throughout (navy) the exponent reaches $3/4$ within twenty levels; with Poiseuille-like scaling in the last twelve levels (orange) it starts near 0.88 and approaches $3/4$ slowly from above. Panel B: the same networks on log–log axes with a $3/4$ reference line.

Source: H Heuristics calculation of the WBE model with branching ratio 2, area-preserving radius ratio $2^{-1/2}$, Poiseuille radius ratio $2^{-1/3}$ and space-filling length ratio $2^{-1/3}$.

The calculation shows why the debate over the three-quarter law has lasted twenty-five years. The exponent is a robust consequence of the model's assumptions in the limit of large networks, but finite networks and different flow regimes produce different values. Empirically, [Dodds, Rothman and Weitz](#)

found that $2/3$ could not be rejected for mammals; [Kolokotronis and colleagues](#) found that the log–log relationship is curved, with the exponent *increasing* with mass, the opposite direction to the hybrid model's prediction; and [Savage and colleagues](#) defended the predominance of quarter powers across many traits. [Hatton and colleagues](#) found an exponent near $3/4$ linking growth, production and size across eukaryotes. The report's grade is B for systematic power-law scaling of metabolism with size, and C for the claim that a single network geometry explains it in all organisms.

6.6 Transformation: major transitions and the role of history

Life's history is punctuated by transitions in which formerly independent units became parts of a new whole: replicating molecules into chromosomes, prokaryotes into eukaryotes, single cells into multicellular organisms, solitary animals into colonies, and individuals into societies with language. Each transition created a new level of individuality and a new way of storing and transmitting information. The [theory of major transitions](#) is the closest thing biology has to a general account of how new levels of organisation arise, and its logic, cooperation stabilised by mechanisms that suppress conflict among the parts, may extend to societies (Section 9).

History matters in a way it does not for stars. In Richard Lenski's long-term evolution experiment, one of twelve replicate populations of *E. coli* evolved the ability to use citrate after more than 30,000 generations, and [replay experiments](#) showed that the innovation depended on earlier, apparently neutral mutations. Reviews of [contingency and determinism](#) conclude that evolution is repeatable when the selective problem is simple and the path short, and contingent when it requires several steps. This is a direct test of the framework's layer 5: transformation is partly predictable from constraints and partly a record of particular events.

6.7 Ecosystems: complexity and stability

Ecosystems raise the oldest question about complexity and stability. In 1972 Robert May showed that a large random community of S species with connectance C and interaction strengths of typical size σ is [stable only if](#)

$$\sigma (S C)^{1/2} < 1 \quad (11)$$

so that, all else equal, more diverse and more connected communities should be less stable. Real ecosystems are diverse and persistent, and the resolution of this paradox has driven fifty years of work. [McCann](#) and [Ives and Carpenter](#) showed that real communities are far from random: weak interactions, particular patterns of predation and asynchrony among species stabilise them. [Allesina and Tang](#) extended May's criterion to predator–prey, competitive and mutualistic structures and showed that predator–prey structure is stabilising. Empirical food webs share [structural regularities](#) that depend on connectance and size. The lesson for the framework is that complexity alone neither stabilises nor destabilises; what matters is the *structure* of interactions, which is a layer-3 property.

Ecosystems also show directional change within limits. Eugene Odum described [ecosystem development](#) as a sequence in which biomass, nutrient retention and the complexity of food webs increase until a mature state is reached. Holling's adaptive cycle added that mature, tightly connected states become brittle and are periodically reset by fire, pests or storms (Section 7).

6.8 Dissolution: death, extinction and radiation

Death and decomposition return the matter of organisms to nutrient cycles, and the same logic operates at larger scales. Mass extinctions removed most species several times in the last 500 million years. Each was followed by an adaptive radiation in which survivors diversified into vacated niches; the end-Cretaceous extinction 66 million years ago opened the way for mammals. Dissolution in biology is therefore not only loss. It is the release phase of a cycle that frees resources and opportunities for reorganisation, although the recovery of diversity has typically taken millions of years.

6.9 Life through the six layers

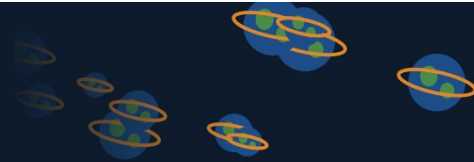
Table 6. Life through the six-layer framework

Layer	Main mechanism	Governing relation	Grade
1 Constraints	Chemistry; diffusion; surface-to-volume; inherited body plans	$t \approx L^2/2D$; developmental bias	A
2 Flows	Metabolism; ATP turnover; nutrient uptake	Free-energy budgets; mitochondrial energetics	A
3 Emergence	Cells; modules; motifs; organisms; food webs	Network structure; modularity	A
4 Persistence	Homeostasis; repair; natural selection	Feedback control; replicator dynamics	A
5 Transformation	Speciation; major transitions; contingent innovation	Population genetics; cooperation theory	A to B
6 Dissolution	Death; decomposition; extinction; adaptive radiation	Mortality; extinction–recovery dynamics	A
Scaling	Size dependence of rates	$B \propto M^\beta$ with β near 3/4; mechanism contested	B (C for mechanism)

Source: H Heuristics synthesis of the studies cited in Section 6.

07

DOMAIN III · PLANETARY SYSTEMS



7. Domain III: Planetary Systems

7.1 Constraints: a planet's parameters

A planet's possible states are bounded by a handful of parameters: the brightness of its star and its distance from it, its mass, its composition and its rate of rotation. Mass determines whether it can hold an atmosphere and how long its interior stays hot. Distance and stellar brightness set the energy it receives. Radiative physics then fixes its effective temperature from the balance of absorbed sunlight and emitted infrared radiation. For Earth, with a solar constant of 1,361 watts per square metre and an albedo of 0.3, the effective radiating temperature is about 255 K, or -18°C . Everything that makes Earth's surface warmer than that, and keeps it in the narrow range that allows liquid water, is the work of the coupled systems described in [The Architecture of Earth](#).

7.2 Flows: two engines and coupled cycles

Earth runs on two energy sources that act on different parts of the planet. Absorbed sunlight, about 122,000 terawatts, drives the fluids: weather, ocean currents, the water cycle and photosynthesis. Heat escaping from the interior, about [46 terawatts](#), drives the solid Earth: plate tectonics, volcanism and the magnetic field. Humanity's primary energy use, about 19.6 terawatts, is now of the same order as the interior flow. The two natural engines meet in the long-term carbon cycle. Volcanoes, powered by internal heat, supply carbon dioxide; the [weathering of silicate rock](#), powered by the water cycle and therefore by sunlight, removes it. Because weathering speeds up when the climate is warmer and wetter, the coupling forms a thermostat that has kept Earth's surface temperature within habitable limits over hundreds of millions of years while the Sun brightened.

7.3 Emergence: a planet of organised structures

The flows generate a hierarchy of structures: Hadley cells, jet streams and storm tracks in the atmosphere; gyres and an overturning circulation in the ocean; plates, mountain belts and ocean basins in the solid Earth; biomes, soils and food webs in the biosphere. Life is now a dominant layer of this structure. Living biomass contains about [550 billion tonnes of carbon](#), 80 per cent of it in plants. In 2020 the mass of [human-made objects](#), concrete, metal, asphalt, brick and plastic, overtook the mass of all living things. Earth's surface has acquired a new structural layer, sometimes called the [technosphere](#), within a single human lifetime.

7.4 Persistence: regulation without foresight

Planetary persistence depends on negative feedback, and the most debated question in Earth system science is whether life contributes to it. The [Gaia hypothesis](#) proposed that the biosphere regulates the

planet in its own favour. The difficulty is mechanism: organisms are selected for their own reproduction, not for planetary stability, so how could regulation evolve?

Andrew Watson and James Lovelock's [Daisyworld](#) was designed to show that regulation does not require foresight. A planet is populated by two kinds of daisy, black and white, each growing best at the same temperature. Black daisies absorb more sunlight and warm their surroundings; white daisies reflect more and cool them. Figure 12 reproduces the model. As the star brightens, black daisies dominate first, warming the cold young planet; as it grows hotter, white daisies take over and cool it. In the calculation, life persisted across a range of stellar luminosity from 0.71 to 1.53 times the reference value, and over that range held the planet's temperature between 19 and 29 °C, while a bare planet would have warmed from 2 to 60 °C. When the star finally becomes too bright, the white daisies can no longer cope and the system collapses abruptly to the lifeless state.

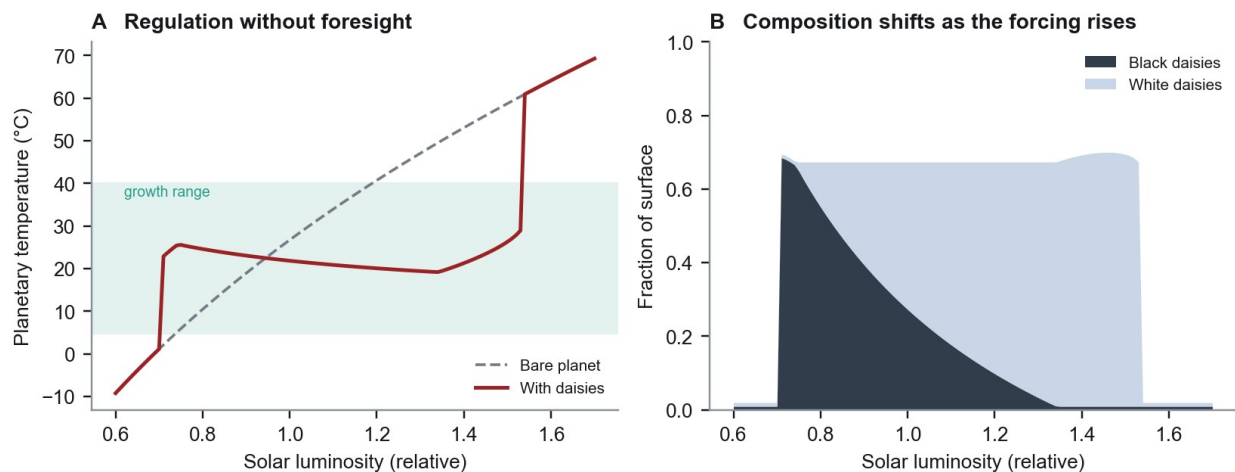


Figure 12. Daisyworld: planetary regulation without foresight. Panel A: temperature of a planet with black and white daisies (red) and of a bare planet (grey) as the star brightens. Panel B: the daisy populations. Regulation emerges from differential growth and fails abruptly at the end of the habitable range.

Source: H Heuristics reimplementation of Watson and Lovelock (1983): solar flux 917 W m^{-2} , albedos 0.5 (ground), 0.75 (white), 0.25 (black), parabolic growth optimum 22.5°C , death rate 0.3, heat-transfer coefficient $2.06 \times 10^9 \text{ K}^{-1}$.

Daisyworld is a proof of principle, not a description of Earth. It shows that regulation can be an emergent property of a coupled system in which organisms alter their environment and are in turn selected by it, with no need for planetary-scale selection or purpose. Whether Earth's biosphere actually regulates in this way is a separate question. [Kirchner](#) distinguished weak forms of Gaia, which are well supported, from strong forms, which are not. Lenton and colleagues have proposed mechanisms of [selection for Gaia across scales](#) and an updated [Gaia 2.0](#) framing in which humans may consciously add regulation. The report grades the claim that life strongly influences planetary conditions A, the claim that the biosphere's net effect is stabilising C.

7.5 Transformation: a planet remade

Earth has been transformed several times by its own processes. The most dramatic was the [rise of oxygen](#), produced by photosynthetic bacteria, which changed the atmosphere's chemistry about 2.4 billion years ago and again around 600 million years ago, made complex animal life possible and created the ozone layer. Hazen's [mineral evolution](#) roughly doubled the number of mineral species as oxygen reacted with the crust. These transformations show that the planetary architecture is not fixed: its constraints, flows and structures are rewritten by what emerges within it.

7.6 Thresholds: tipping elements

Coupled feedbacks create thresholds. Lenton and colleagues identified [tipping elements](#) in the climate system, including the Greenland and West Antarctic ice sheets, the Atlantic overturning circulation and the Amazon rainforest, each of which could shift to a different state if pushed past a critical point. Some ecosystems show [self-organised patchiness](#) in which the pattern of vegetation itself changes as a threshold approaches; in Mediterranean drylands the [size distribution of vegetation patches](#) departs from a power law near desertification. [Dakos and colleagues](#) found rising autocorrelation before eight past abrupt climate shifts, and [Boers](#) reported early-warning signals in indicators of the Atlantic overturning circulation. Section 10 shows why the same warning signals should appear in any system approaching this kind of threshold.

7.7 Dissolution and reorganisation

The geological record contains five mass extinctions and many smaller crises, each followed by reorganisation. Forests burn and regrow through successional stages; ice sheets advance and retreat; ocean basins open and close over hundreds of millions of years in the Wilson cycle. Planetary dissolution is rarely total, because the processes that destroy structure also release the nutrients, space and energy gradients from which new structure forms. Holling's adaptive cycle (Figure 13) was developed to describe exactly this alternation in forests and fisheries.

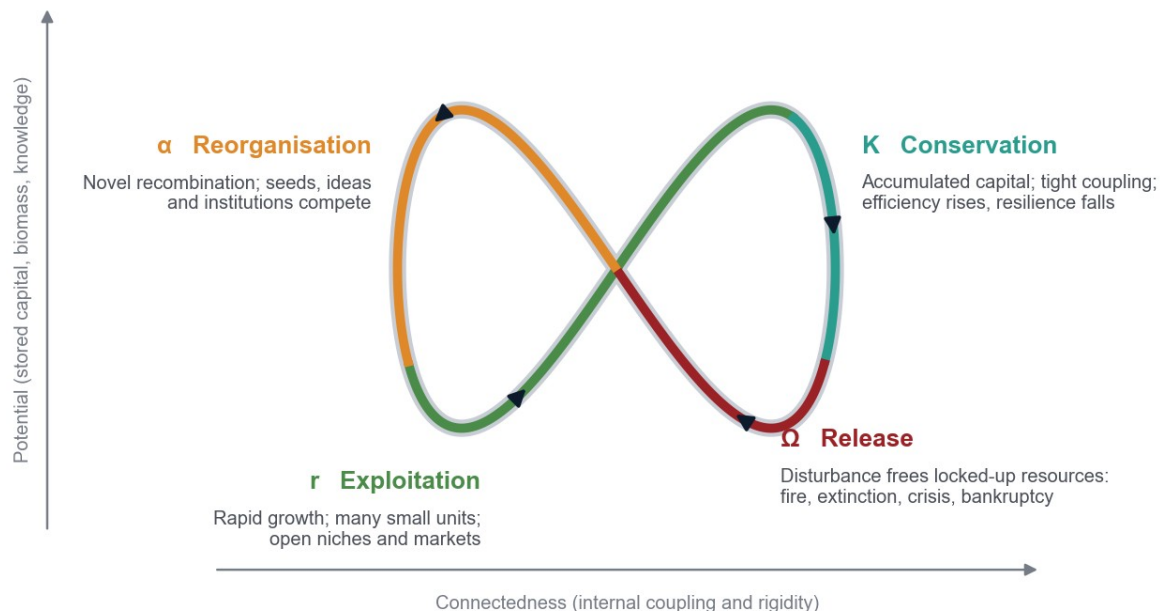


Figure 13. The adaptive cycle. Systems grow (r), accumulate capital and connectedness (K), are released by disturbance (Ω) and reorganise (α). The model was developed for ecosystems and has been applied to economies and institutions; it is an influential structural analogy whose mathematical content varies by application.

Source: H Heuristics, after Holling (2001) and Gunderson and Holling (2002). Schematic.

7.8 Humanity as a planetary process

The newest feature of the planetary domain is that one species now acts at planetary scale. The post-1950 [Great Acceleration](#) in population, energy use, fertiliser, dams, plastics and greenhouse gases

has no precedent in the record. The [planetary boundaries](#) framework identifies nine Earth-system processes with thresholds that define a safe operating space; the most recent assessment found that [six of nine](#) had been transgressed. For the unified architecture, this marks a point at which civilisation (Section 9) stops being a separate domain and becomes a component of the planetary one. The coupling is two-way: the planet's thresholds now constrain civilisation, and civilisation's choices determine whether those thresholds are crossed.

7.9 Planetary systems through the six layers

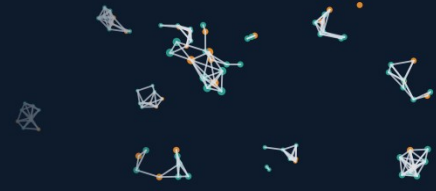
Table 7. Planetary systems through the six-layer framework

Layer	Main mechanism	Governing relation	Grade
1 Constraints	Insolation; planetary mass; radiative physics	$T_e = [S(1-\alpha)/4\sigma]^{1/4} \approx 255 \text{ K}$	A
2 Flows	Sunlight; interior heat; water, carbon and rock cycles	Energy budgets; reservoir–flux accounting	A
3 Emergence	Circulation cells; plates; biomes; technosphere	Fluid dynamics; mantle convection	A
4 Persistence	Radiative damping; weathering thermostat; biotic feedbacks	Negative feedback; Daisyworld-type regulation	A to C
5 Transformation	Oxygenation; climate states; mineral evolution	Biogeochemical coupling; bifurcations	A to B
6 Dissolution	Mass extinctions; glaciations; succession	Tipping and recovery dynamics	A to B

Source: H Heuristics synthesis of the studies cited in Section 7 and *The Architecture of Earth* (2026).

08

DOMAIN IV · INTELLIGENCE



8. Domain IV: Intelligence

8.1 Intelligence in the framework

Intelligence is the domain in which information becomes the dominant flow. For the purposes of this report, an intelligent system is one that builds internal models of its environment and uses them to select actions that help it persist or achieve goals. The definition covers nervous systems, collective systems such as ant colonies and human groups, and machine learning systems. It does not require consciousness, which is outside the report's scope. Intelligence is placed between life and civilisation not because it is a stage that follows life, but because it is the capacity on which civilisation is built and the one through which civilisation now acts on every other domain.

8.2 Constraints: energy, wiring and physics

Brains are expensive. The human brain is about 2 per cent of body mass and uses about 20 watts, roughly 20 per cent of resting metabolism. [Attwell and Laughlin](#) estimated that most of this energy goes to restoring the ion gradients used in signalling, so that the cost of a thought is set by the number of spikes and synapses involved. [Laughlin and Sejnowski](#) argued that this cost explains why neural codes are sparse and neural networks are wired to minimise long connections. The human brain's 86 billion neurons follow [primate scaling rules](#) that pack neurons more densely than in rodents of similar brain size. At the lowest level the constraint is physical: Landauer's principle sets a floor of $kT \ln 2$ on the energy of erasing a bit, and both brains and computers operate many orders of magnitude above it.

8.3 Emergence: networks and attractors

Brain networks share a recognisable architecture. They are [small-world, modular and organised around hubs](#), a combination that [balances wiring cost against efficient communication](#). Memory emerges from the dynamics of these networks. In John Hopfield's [model of associative memory](#), memories are stored as stable patterns of activity, attractors, in a network whose connections are set by a simple learning rule; presenting part of a pattern lets the network complete the rest. Figure 14 shows the model's most important property, computed for a network of 400 neurons. Recall is essentially perfect while the number of stored patterns is below about 14 per cent of the number of neurons. Past that point, interference between memories destroys the attractors and recall collapses: at a load of 0.20 the network recovered only 57 per cent of a stored pattern.

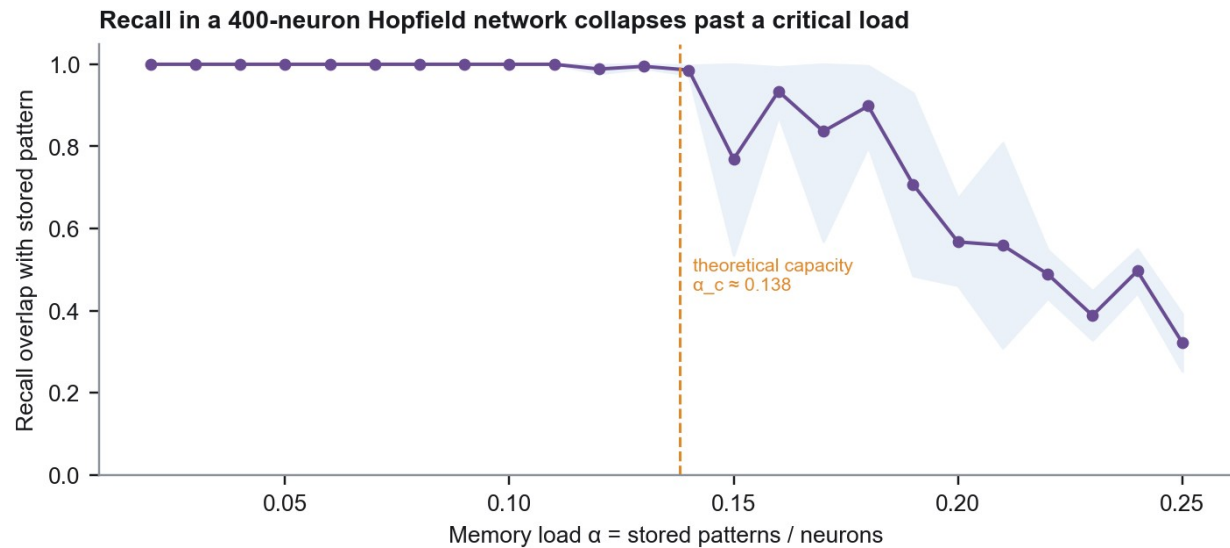


Figure 14. A threshold in a learning system. Recall overlap in a 400-neuron Hopfield network as the number of stored patterns grows, starting each trial from a stored pattern with 5 per cent of its bits flipped. Recall collapses near the critical load predicted by statistical physics.

Source: H Heuristics calculation. Hebbian weights; asynchronous updates; six trials per load; shading shows one standard deviation. Theoretical capacity from Amit, Gutfreund and Sompolinsky (1985).

The critical load, about 0.138 for large networks, was derived by [Amit, Gutfreund and Sompolinsky](#) using the statistical physics of spin glasses. This is an example of genuine cross-domain transfer at the level of shared mathematics: the same methods that describe disordered magnets predict the capacity of a model memory. It does not mean that brains are magnets. It means that any system storing information in the attractors of a network of interacting units faces a capacity threshold of this kind.

8.4 Persistence: learning and prediction

Learning is the intelligence-domain counterpart of selection: it changes internal structure in response to the success or failure of actions. Many neuroscientists now describe the brain as a prediction machine that minimises the mismatch between expected and actual input. Karl Friston's [free-energy principle](#) generalises this into a proposed unified theory of brain function, and in its broadest form of any self-organising system that persists. It is one of the most ambitious unification attempts of recent decades. Its mathematics is rigorous; its status as an empirical theory is contested because, in its most general form, it is difficult to state an observation that would contradict it. The report grades predictive processing as an account of perception B and the free-energy principle as a theory of all self-organisation C.

8.5 Is the brain critical?

In 2003 [Beggs and Plenz](#) reported that cascades of activity in cortical tissue, which they called neuronal avalanches, have power-law size distributions like those of Bak's sandpile. The finding launched a programme arguing that brains, and perhaps [biological systems generally](#), operate near critical points where information transmission and dynamic range are maximised; simulations suggest that [selection for information processing](#) can drive systems toward criticality. The evidence is suggestive but not decisive, because power laws can arise from non-critical mechanisms (Section 11). The report grades the criticality hypothesis for the brain C.

8.6 Collective intelligence

Intelligence also emerges in groups. Tamás Vicsek showed that particles that simply align with their neighbours undergo a [phase transition to collective motion](#) as noise falls, reproducing the onset of flocking. Iain Couzin and colleagues showed that a [small informed minority](#) can steer a group without signalling and without the others knowing who is informed. In humans, collective intelligence extends across generations through cumulative culture. Robert Boyd, Peter Richerson and Joseph Henrich argue that humans occupy a [cultural niche](#) in which socially learned knowledge, accumulated over generations, is essential for survival: no individual could reinvent the tools and techniques a hunter-gatherer group depends on. Culture is the bridge from intelligence to civilisation.

8.7 Machine intelligence

Machine learning has produced the first non-biological systems that learn general capabilities from data. [Deep learning](#) uses many-layered networks trained by gradient descent and has achieved human-level or better performance on tasks from image recognition to [protein structure prediction](#). Large language models show smooth [power-law scaling](#) of performance with model size, data and computation over many orders of magnitude, a regularity that resembles the scaling laws of organisms and cities. The resemblance is at rung 2 of the ladder: the exponents and mechanisms differ, and it is not yet known whether the machine scaling laws share an origin with any natural one.

Machine intelligence differs from biological intelligence in its energetics. A brain runs on 20 watts; training a large model consumes energy measured in gigawatt-hours. It also differs in its relation to persistence: current models do not maintain themselves, and their learning is mostly separated from their operation. These differences matter for the framework, because they mean that machine intelligence sits in the intelligence domain on layers 2, 3 and 5, flows, structure and transformation, but depends on civilisation for layers 4 and 6, maintenance and replacement.

8.8 Dissolution: forgetting and loss

Intelligent systems lose structure as well as build it. Memories decay or are overwritten; artificial networks trained on a new task can suffer [catastrophic forgetting](#) of the old one, a direct analogue of the capacity threshold in Figure 14. Brains lose neurons and connections with age and disease. Cultures can lose knowledge when populations shrink or transmission is interrupted. In every case, dissolution in the intelligence domain is the loss of correlations between internal structure and the world, and reorganisation is the formation of new ones.

8.9 Intelligence through the six layers

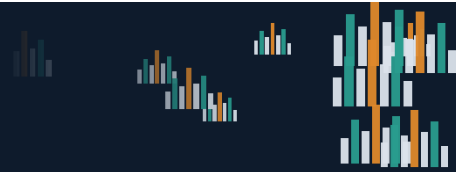
Table 8. Intelligence through the six-layer framework

Layer	Main mechanism	Governing relation	Grade
1 Constraints	Energy cost of signalling; wiring cost; Landauer limit	$kT \ln 2$ per erased bit; metabolic budgets	A
2 Flows	Spikes; synaptic transmission; data and gradients in machines	Information rates; energy per operation	A
3 Emergence	Small-world modular networks; attractor memories; representations	Network theory; spin-glass capacity $\alpha_c \approx 0.138$	A to B
4 Persistence	Learning; prediction; homeostatic plasticity	Prediction-error minimisation; gradient descent	B (C for free-energy principle)
5 Transformation	Development; cumulative culture; scaling of machine capabilities	Cultural evolution; empirical scaling laws	B
6 Dissolution	Forgetting; interference; neurodegeneration; cultural loss	Capacity thresholds; decay	A to B
Criticality	Neuronal avalanches	Power-law cascades; mechanism unresolved	C

Source: H Heuristics synthesis of the studies cited in Section 8.

09

DOMAIN V · CIVILISATION



9. Domain V: Civilisation and Human Systems

9.1 Civilisation as an organised system

Civilisation is the youngest and fastest-changing domain in the report, and the one in which the framework is most at risk of becoming metaphor. Human societies are made of agents with intentions, language, institutions and histories, and the specialised social sciences have good reasons to resist analogies with stars or cells. The test for the framework is whether it adds anything to what economics, sociology and political science already know. The report argues that it adds three things: a common accounting of the flows that sustain human systems, a quantitative description of how their structure depends on size and connectivity, and a way of thinking about thresholds and systemic risk that is shared with planetary and ecological systems.

9.2 Constraints: energy, geography and rules

Human systems operate within physical constraints that the other domains share and within institutional constraints that are their own. Physically, every economic activity requires energy and materials. Global primary energy use is about 19.6 terawatts, roughly 2,400 watts per person on average and far more in rich countries. [Garrett](#) showed that civilisation's energy consumption is closely tied to its accumulated wealth, a relation that treats the global economy as a single thermodynamic system. Geographically, rivers, coasts, mountains and climate shaped where cities could grow and which regions could trade. Institutionally, laws, property rights, norms and organisations constrain what individuals can do. Elinor Ostrom's [framework for social-ecological systems](#) is the most developed attempt to describe these institutional constraints in a form comparable across cases.

9.3 Flows: trade, migration and information

Civilisation is sustained by flows of energy, materials, people, money and information through networks. Trade networks move goods, and with them embodied resources: the [global virtual water trade network](#) more than doubled in connections and volume between 1986 and 2007 as food trade grew. Migration moves people and skills. Communication networks move information at the speed of light. Like flows in other domains, human flows follow gradients, of prices, wages, safety and opportunity, and like them they build the structures that channel them: ports, roads, cables and institutions.

9.4 Emergence: cities and economic complexity

Cities are civilisation's most visible emergent structures, and they show striking quantitative regularities. Across urban systems in many countries, Bettencourt and colleagues found that urban indicators scale with population N as power laws, $Y \propto N^\beta$, with exponents that fall into three groups (Figure 15, Panel A). Infrastructure, such as road surface and the length of electrical cables, scales sublinearly with $\beta \approx 0.85$: larger cities need less per person. Individual needs, such as housing, employment and household water use, scale linearly. Socio-economic outputs, including wages, GDP, patents and also serious crime and new infections, scale superlinearly with $\beta \approx 1.15$. Each doubling of city size brings about 15 per cent more output per person, and with it more of the problems that come from interaction.

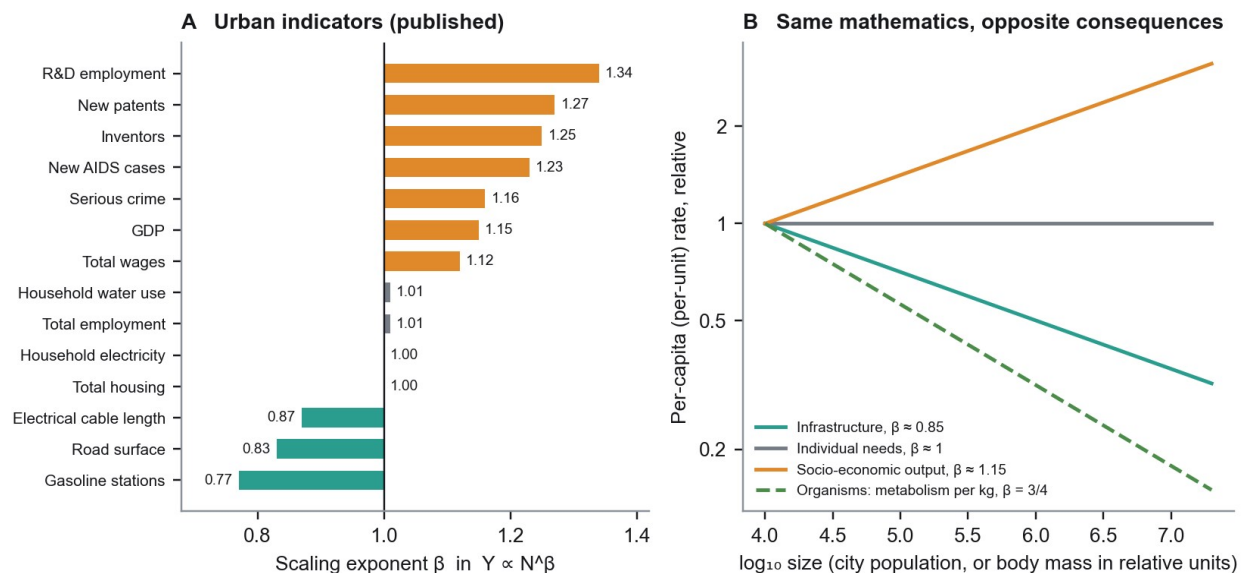


Figure 15. Same mathematics, opposite consequences. Panel A: published scaling exponents for urban indicators in United States metropolitan areas; infrastructure scales sublinearly, individual needs linearly and socio-economic outputs superlinearly. Panel B: per-capita rates implied by the three urban regimes, compared with the per-kilogram metabolic rate implied by quarter-power scaling in organisms.

Source: Panel A, Bettencourt et al. (2007), Table 1. Panel B, H Heuristics calculation from the stated exponents.

Panel B makes a cross-domain comparison explicit. Organisms and cities both follow power laws in size, and the proposed explanations of both invoke networks. But the consequences are opposite. A tenfold increase in body mass reduces metabolic rate per kilogram by 44 per cent: larger organisms live slower. A tenfold increase in city population raises socio-economic output per person by about 41 per cent: larger cities live faster. Bettencourt's [theory of urban scaling](#) attributes this to social interactions, whose number grows faster than population, and the [scaling of human interactions with city size](#) has been measured directly in telephone data. Organisms have no counterpart to this mechanism. The two scaling laws share mathematics, rung 3 of the ladder, but not mechanism.

Other urban regularities have still other origins. The size distribution of cities follows [Zipf's law](#) approximately, and Gabaix showed that this [follows from proportional growth](#) with a lower barrier, a mechanism that has nothing to do with networks and that the report reproduces in Section 11. The [size, scale and shape of cities](#) have been described by Michael Batty as the outcome of many overlapping processes rather than one.

Economies show emergent structure beyond cities. César Hidalgo and Ricardo Hausmann showed that the products a country exports reveal its productive capabilities, and that countries move into new

products that require capabilities similar to those they already have, along the network of the [product space](#). Their measure of [economic complexity](#) predicts future growth better than many standard indicators. The idea that development is the accumulation and recombination of capabilities through networks is the subject of [The Architecture of Creation and Development](#).

9.5 Persistence: institutions and the cost of complexity

Human systems persist through institutions that regulate behaviour, insurance and savings that buffer shocks, and maintenance that repairs infrastructure. These are civilisation's counterparts of homeostasis and repair, and like them they require a continuing flow of resources. Joseph Tainter argued that societies solve problems by adding complexity, in the form of new institutions, specialists and infrastructure, and that the [returns to complexity eventually diminish](#). When the cost of maintaining a society's complexity exceeds the benefits it delivers, the society becomes vulnerable to collapse. Tainter's argument is a social-science version of the framework's hypothesis that persistence requires maintenance (H3), and Section 11 models it.

Large comparative datasets now allow some of these ideas to be tested. Analysis of the [Seshat global history databank](#) found that nine different measures of social complexity, from population and territory to writing, money and bureaucracy, are strongly correlated across 414 polities over 10,000 years, so that a single dimension captures about three-quarters of the variation. This is evidence that social complexity has a common structure, Grade B, though not that it follows a single law.

9.6 Transformation: diffusion, learning and lock-in

Technologies, practices and ideas spread through populations along S-shaped curves. Zvi Griliches's study of [hybrid corn](#) established the pattern in 1957; Fisher and Pry showed that technological [substitution](#) follows a logistic curve; and Diego Comin and Bart Hobijn's [cross-country data](#) on 15 major technologies in 166 countries over two centuries found that countries adopted new technologies on average about 45 years after their invention, and that differences in adoption lags account for a large share of income differences. The [Bass model](#) describes adoption as the sum of independent innovation and imitation:

$$dF/dt = (p + qF)(1 - F) \quad (12)$$

where F is the adopted fraction, p the rate of independent adoption and q the strength of imitation. The same equation, with different interpretations of its terms, describes the spread of an epidemic in its early phase and the invasion of a new species. This is shared mathematics, and it is useful, but the mechanism of adoption matters for how network structure affects it.

Figure 16 tests that dependence. Contagion was simulated on networks of 1,000 nodes that begin as clustered rings and are progressively rewired at random, following Watts and Strogatz. A *simple* contagion, which spreads from any single contact, like a rumour or a virus, accelerates dramatically as random shortcuts are added: the time to reach 90 per cent of the network fell from 150 steps with no rewiring to 23 steps with 1 per cent of ties rewired and 4 steps with full randomisation. A *complex* contagion, which requires reinforcement from two contacts, like a costly behaviour or a risky technology, behaves in the opposite way. It spread fully on clustered networks, reached 84 per cent of nodes when 10 per cent of ties were rewired, and failed almost completely, reaching 2 per cent, when 30 per cent were rewired.

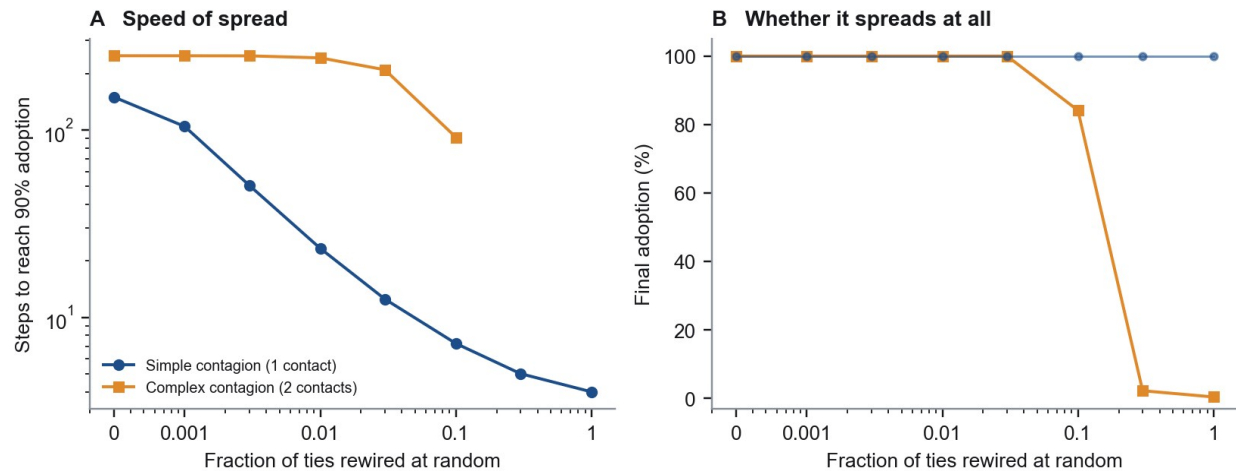


Figure 16. Connectivity shapes outcomes, in opposite directions for different mechanisms. Simple contagion (one contact suffices) and complex contagion (two contacts required) on Watts–Strogatz networks of 1,000 nodes with six neighbours each. Panel A: steps to 90 per cent adoption. Panel B: final adoption.

Source: H Heuristics calculation. Twelve networks per rewiring level; seeds are four adjacent nodes; deterministic threshold dynamics. After Centola and Macy (2007).

The result reproduces the central finding of [Centola and Macy](#) and it matters for unification. Network topology clearly shapes outcomes, which supports hypothesis H2. But the direction of the effect depends on the mechanism of spread. Random long-range ties, which make a network a small world, help simple contagions and hinder complex ones, because they bring a node one new contact at a time and complex contagions need reinforcement. A framework that said only that connectivity matters would be true and useless; one that specifies how it matters for each mechanism is a theory.

Two further regularities shape technological transformation. Costs fall predictably with cumulative production, as first noted by [Theodore Wright](#) for aircraft; [Nagy and colleagues](#) found that Wright's law predicts cost declines across dozens of technologies, and [Way and colleagues](#) used it to show that a rapid clean-energy transition would be cheaper than a slow one. And increasing returns create path dependence: Brian Arthur showed that when adoption makes a technology better, small early events can [lock in](#) an inferior option. Lock-in is civilisation's counterpart of evolutionary contingency.

9.7 Systemic risk and civilisational resilience

The interconnection that makes modern civilisation productive also makes it fragile. Dirk Helbing described [globally networked risks](#) in which failures propagate across tightly coupled systems. Andrew Haldane and Robert May applied ecological stability theory to [banking networks](#) and argued that the pre-2008 financial system had become homogeneous and over-connected in ways that ecology would have recognised as unstable; [Ecology for bankers](#) made the case for importing ecological thinking into financial regulation. [Buldyrev and colleagues](#) showed that networks which depend on each other, such as a power grid and the communications network that controls it, can fail far more abruptly than either alone. Thomas Homer-Dixon and colleagues described [synchronous failure](#) across multiple global systems, and Luke Kemp and colleagues called for systematic study of [catastrophic climate scenarios](#) in which such cascades combine. These are the civilisational counterparts of the tipping elements of Section 7.

Network structure again decides which disturbances a system survives. Figure 17 computes the classic result of [Albert, Jeong and Barabási](#) for networks of 4,000 nodes with the same mean degree. Under random failure of 20 per cent of nodes, a random network kept 76 per cent of its nodes in one connected

piece and a scale-free network 77 per cent: there was no practical difference. Under targeted removal of the best-connected 20 per cent, the random network kept 68 per cent connected while the scale-free network disintegrated, keeping less than 1 per cent. Heterogeneous, hub-dominated networks are robust to accidents and fragile to attacks on their hubs, which is why the concentration of global trade, finance and communication through a few hubs is a systemic risk.

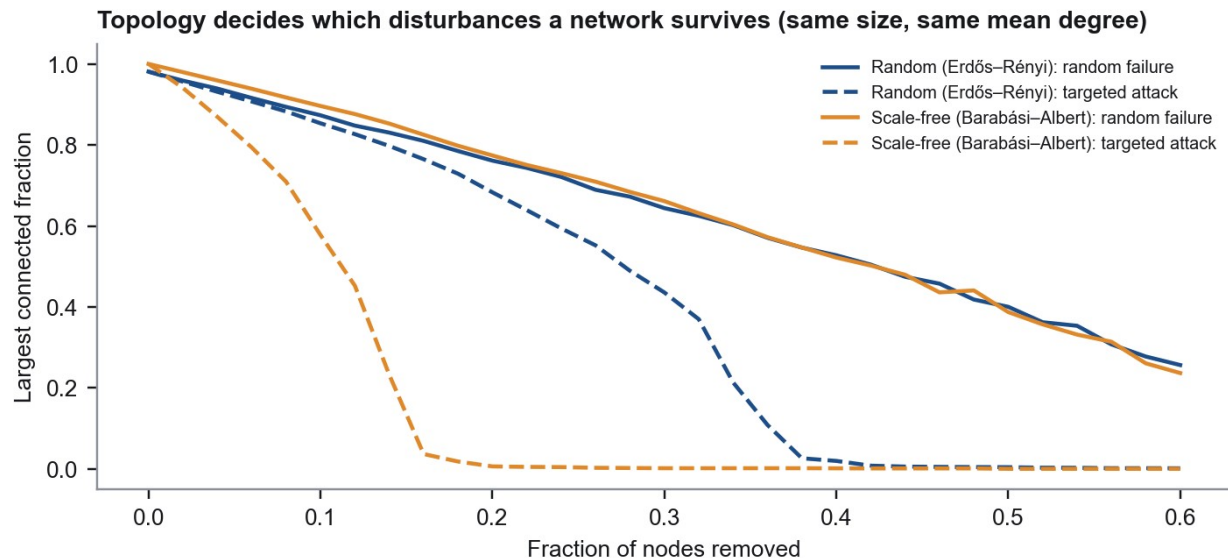


Figure 17. Topology decides which disturbances a network survives. Largest connected fraction of a random (Erdős–Rényi) and a scale-free (Barabási–Albert) network of 4,000 nodes and mean degree 4 as nodes are removed at random (solid) or in order of degree (dashed).

Source: H Heuristics calculation after Albert, Jeong and Barabási (2000).

The theoretical basis is percolation. A network with degree distribution $P(k)$ keeps a giant connected component as long as the [Molloy–Reed criterion](#) holds:

$$\kappa = \langle k^2 \rangle / \langle k \rangle > 2 \quad (13)$$

Hubs make $\langle k^2 \rangle$ large, so random removal barely affects κ ; removing hubs collapses it. The same criterion governs the spread of epidemics on contact networks, where [hubs remove the epidemic threshold](#), and the resilience of ecological and infrastructure networks. It is one of the clearest cases of shared mathematics in the report, Grade A in theory and B in its application to real networks, whose structure is often [less scale-free](#) than early studies suggested.

9.8 Dissolution: crisis, collapse and creative destruction

Human systems dissolve at every scale: firms fail, technologies are abandoned, institutions decay, cities shrink, states collapse. Joseph Schumpeter called the process by which new firms and technologies destroy old ones [creative destruction](#), and it is civilisation's clearest counterpart of the release and reorganisation phases of the adaptive cycle. Societal collapse, in Tainter's sense of a rapid loss of social complexity, has occurred many times. The framework's contribution is to ask the same questions of every case: which flows sustained the structure, what maintained it, which threshold was crossed, and what was recycled into the systems that followed.

9.9 Civilisation through the six layers

Table 9. Civilisation and human systems through the six-layer framework

Layer	Main mechanism	Governing relation	Grade
1 Constraints	Energy; materials; geography; cognition; law and norms	Energy–wealth coupling; institutional rules	A to B
2 Flows	Trade; migration; finance; communication	Gravity models; input–output accounts	A
3 Emergence	Cities; firms; product space; infrastructure networks	Urban scaling $Y \propto N^\beta$; Zipf's law	B
4 Persistence	Institutions; insurance; maintenance; policy	Diminishing returns to complexity	B to C
5 Transformation	Diffusion; learning curves; convergence; lock-in	Bass model; Wright's law; increasing returns	A to B
6 Dissolution	Crises; cascades; collapse; creative destruction	Percolation; interdependent networks; adaptive cycle	B to C

Source: H Heuristics synthesis of the studies cited in Section 9 and *The Architecture of Creation and Development* (2026).

10

RECURRING STRUCTURES



10. Recurring Structures Across Domains

10.1 Five structures, many mechanisms

The domain sections found the same structures again and again: branching networks, nested hierarchies, modules, feedback loops and thresholds. This section examines each in turn and asks a single question of it: when the structure recurs, is it because the same mechanism produced it, or because different mechanisms converged on the same solution to the same problem? The distinction is the heart of the unification question. If the mechanisms are shared, the architecture is a theory. If only the problems are shared, the architecture is a comparative map, still useful but much more modest.

10.2 Branching networks

Branching networks appear wherever something must be distributed from a point to a volume or collected from a volume to a point: rivers drain landscapes, trees and vessels supply tissues, roots and mycelia gather nutrients, lightning discharges a cloud, and roads, pipes and power lines serve settlements. Some branching networks are optimised. Cecil Murray showed in 1926 that blood vessels minimise the combined cost of pumping blood and maintaining its volume when the radius of a parent vessel and its daughters satisfy [Murray's law](#):

$$r_0^3 = r_1^3 + r_2^3 \quad (14)$$

[Banavar, Maritan and Rinaldo](#) showed that efficient transport networks of any kind share general scaling properties, which is one root of the WBE argument in Section 6. But other branching networks are not optimised at all. [Diffusion-limited aggregation](#), in which particles wander randomly until they stick to a growing cluster, produces branched structures like mineral dendrites and electrodeposits purely because the tips of a cluster are more exposed to arriving particles than its fjords.

Figure 18 compares three branching networks generated for this report by unrelated mechanisms. The first is a diffusion-limited aggregate of 5,000 particles, a model of physical growth. The second is grown by *space colonisation*, an algorithm used to model leaf venation in which growing tips extend toward scattered resource points and claim them, a model of biological growth toward resources. The third is the minimum spanning network connecting about 2,200 points clustered like settlements, the shortest set of links that joins them all, a model of engineered infrastructure. All three were analysed in the same way: their fractal dimension was estimated by box counting, and their branches were ranked by [Strahler order](#), the system used to classify river tributaries.

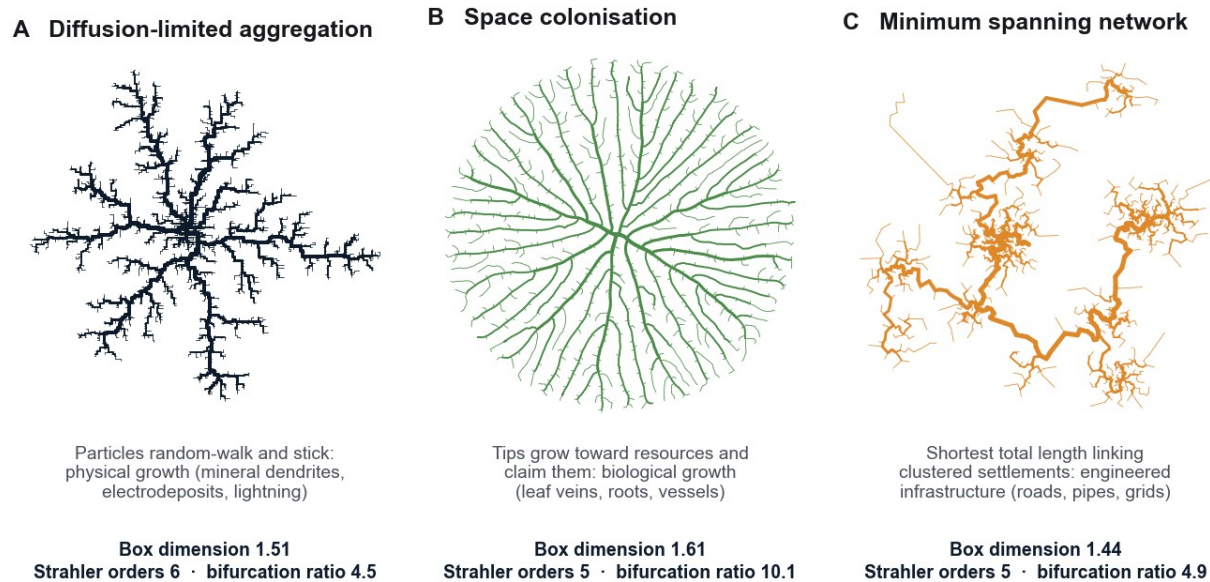


Figure 18. Three branching networks, three unrelated mechanisms. A: diffusion-limited aggregation (random walkers stick on contact). B: space colonisation (tips grow toward resource points). C: minimum spanning network on clustered points (shortest total length). Line width increases with Strahler order. Box dimension and the Strahler bifurcation ratio are computed for each.

Source: H Heuristics calculation. DLA on a square lattice; space colonisation with 4,000 attractors, influence radius 9 and kill radius 1.6; minimum spanning tree on the Delaunay graph of 2,207 points in 14 clusters. Box dimensions are finite-size estimates; large DLA clusters have dimension ≈ 1.71 .

The results show how weakly appearance constrains mechanism. All three structures are visibly tree-like and fractal-looking, with box-counting dimensions between 1.44 and 1.61 at the scales measured. Two of them, the physical aggregate and the engineered network, have Strahler bifurcation ratios of 4.5 and 4.9, inside the range of 3 to 5 typical of natural river networks. A geomorphologist given only those numbers might well conclude that they were rivers. The biologically inspired network, by contrast, has a bifurcation ratio of 10.1, because resource-seeking growth produces many short side twigs. In other words, two networks with no causal relation to rivers match river statistics, while one built on the most river-like logic, growth along a gradient, does not. The structures share a problem, filling or connecting space with branching paths, and that problem constrains their form. They do not share a mechanism.

The [constructal law](#) of Adrian Bejan proposes that all flow systems evolve to provide easier access for their currents, explaining branching in rivers, lungs and traffic alike. It is a bold unifying principle. Its weakness is the one this test exposes: it predicts that flow systems will branch, which they do, but it does not discriminate between mechanisms that produce branching for different reasons, and it is not clear what observation would refute it. The report grades it C.

10.3 Hierarchy

Nested hierarchy is the most widespread structural pattern in the report: quarks in nucleons in atoms in molecules in cells in organisms in societies; stars in clusters in galaxies in groups in the cosmic web; neighbourhoods in cities in regions in a world economy. Herbert Simon offered a general reason in [The Architecture of Complexity](#). He imagined two watchmakers, Tempus and Hora, each assembling watches of 1,000 parts and each interrupted from time to time. Tempus builds each watch as a single sequence, and an interruption makes the partial assembly fall apart. Hora builds stable sub-assemblies of ten parts,

combines them into larger assemblies of ten, and so on, so that an interruption costs only the current sub-assembly.

The expected number of steps to complete a run of n consecutive parts when each step is interrupted with probability p is

$$E(n) = [(1 - p)^{-n} - 1] / p \quad (15)$$

Tempus needs $E(1000)$; Hora needs 111 runs of ten, $111 E(10)$. Figure 19 computes both and checks Hora's with a Monte Carlo simulation. With a 1 per cent chance of interruption per step, Tempus expects about 1.6 million steps per watch and Hora about 1,170, a ratio of about 1,400. The advantage grows explosively with the interruption rate.

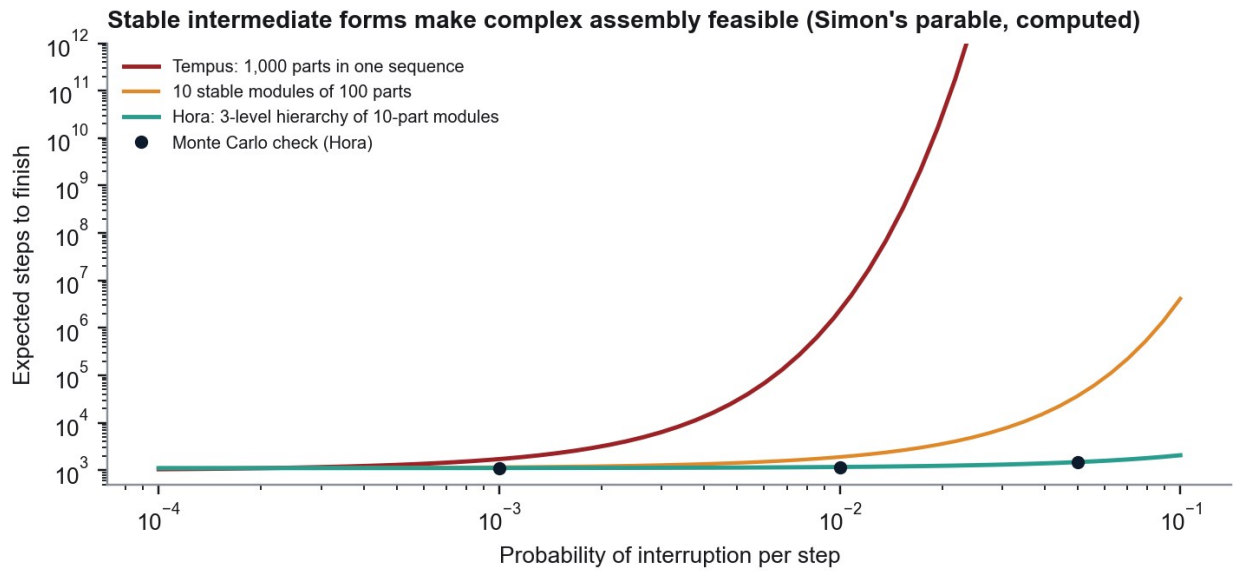


Figure 19. Stable intermediate forms make complex assembly feasible. Expected steps to assemble 1,000 parts as a single sequence (Tempus), as ten stable modules of 100, and as a three-level hierarchy of ten-part modules (Hora), as a function of the probability of interruption per step. Dots: Monte Carlo check of the Hora calculation.

Source: H Heuristics calculation of Simon's (1962) parable; Monte Carlo with 300 replicates per point.

Simon's argument does not depend on what the parts are. Any process that builds structure step by step in a disturbed environment will build hierarchies faster than flat structures, provided intermediate stages are stable. Atoms are stable intermediates for molecules; cells for organisms; firms for economies. This is one of the few cross-domain arguments that reaches rung 4 of the ladder, a shared mechanism, because the selective advantage of stable intermediates is the same process wherever it operates. Its domain is limited to systems built by assembly: it says nothing about why the cosmic web is hierarchical, which owes to gravitational instability acting on fluctuations at every scale.

10.4 Modularity

Modules are groups of components more densely connected to each other than to the rest of a system. Network scientists measure modularity with Newman's Q , the fraction of links that fall within modules minus the fraction expected by chance:

$$Q = \sum_m [L_m / L - (d_m / 2L)^2] \quad (16)$$

where L_m is the number of links inside module m , d_m the total degree of its nodes and L the total number of links. Modularity is common in cells, brains, ecosystems, firms and infrastructure. It offers two benefits: changes in one module need not disrupt others, which aids evolvability and repair, and failures in one module need not spread. It has one cost: useful changes also spread slowly.

Figure 20 quantifies the trade-off. Networks of 1,000 nodes in twenty modules with the same mean degree were generated with between 0.5 and 40 per cent of their links running between modules. A harmful shock was modelled as a cascade in which each affected node passes the shock to each neighbour with a probability of 0.25. With 0.5 per cent of links between modules, shocks affected on average 6 per cent of nodes and reached fewer than two modules. With 5 per cent between-module links, shocks affected 45 per cent of nodes; with 20 per cent, 77 per cent. A beneficial innovation spreading deterministically through the same networks behaved in reverse: it needed 278 steps to reach 90 per cent of nodes in the most modular networks, often failing to reach isolated modules at all, but only 9 steps with 2 per cent between-module links and 5 with 20 per cent.

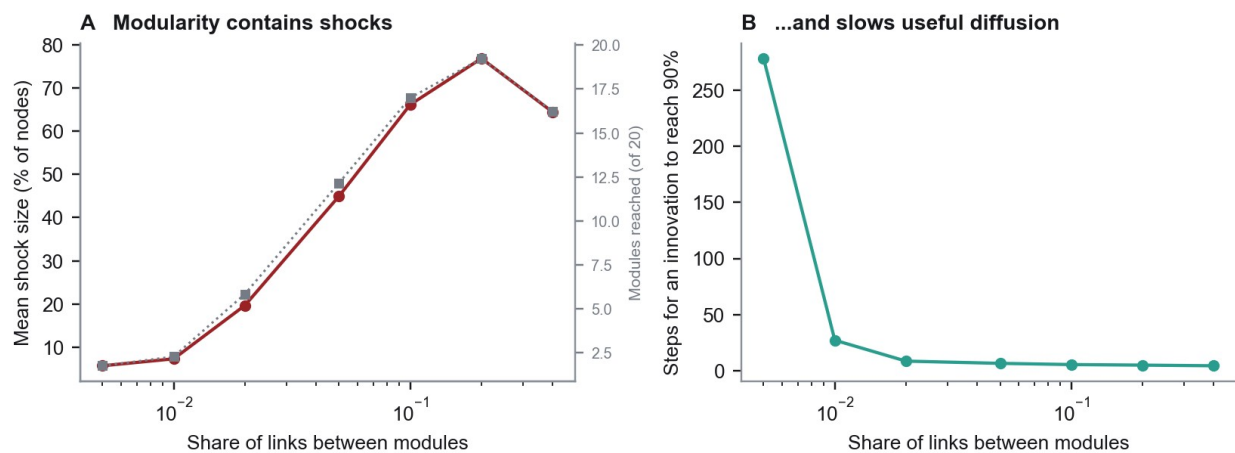


Figure 20. The modularity trade-off. Networks of twenty modules of fifty nodes with mean degree 8. Panel A: mean size of a probabilistic cascade (red) and number of modules it reaches (grey) as the share of links between modules rises. Panel B: steps for a deterministic beneficial innovation to reach 90 per cent of nodes.

Source: H Heuristics calculation. Stochastic block model; 25 networks per point; transmission probability 0.25 for shocks; innovation runs capped at 400 steps.

The trade-off appears in every domain where modularity has been studied: compartmentalised ecosystems contain diseases but slow recolonisation; segmented financial systems contain contagion but allocate capital less efficiently; modular power grids limit blackouts but cannot share reserves as freely. It is the basis of hypothesis H7 in Section 12.

10.5 Feedback loops

Feedback is the structure through which systems persist and change. A feedback loop is negative if it opposes a disturbance and positive if it amplifies one. Two properties determine what a loop does: its *gain*, how strongly the output feeds back to the input, and its *delay*, how long the feedback takes. Figure 21 shows both. In Panel A, a disturbance decays if the loop gain is below one, persists if it equals one and grows until it meets a limit if it exceeds one. In Panel B, a population regulated by negative feedback with a delay τ , described by [Hutchinson's](#) delayed logistic equation,

$$\frac{dN}{dt} = r N(t) \left[1 - N(t - \tau) / K \right] \quad (17)$$

settles smoothly when $\tau\tau = 0.5$, oscillates and settles when $\tau\tau = 1.3$ and cycles indefinitely when $\tau\tau = 1.75$, above the critical value of $\pi/2$. A stabilising loop becomes a source of oscillation when it is too slow.

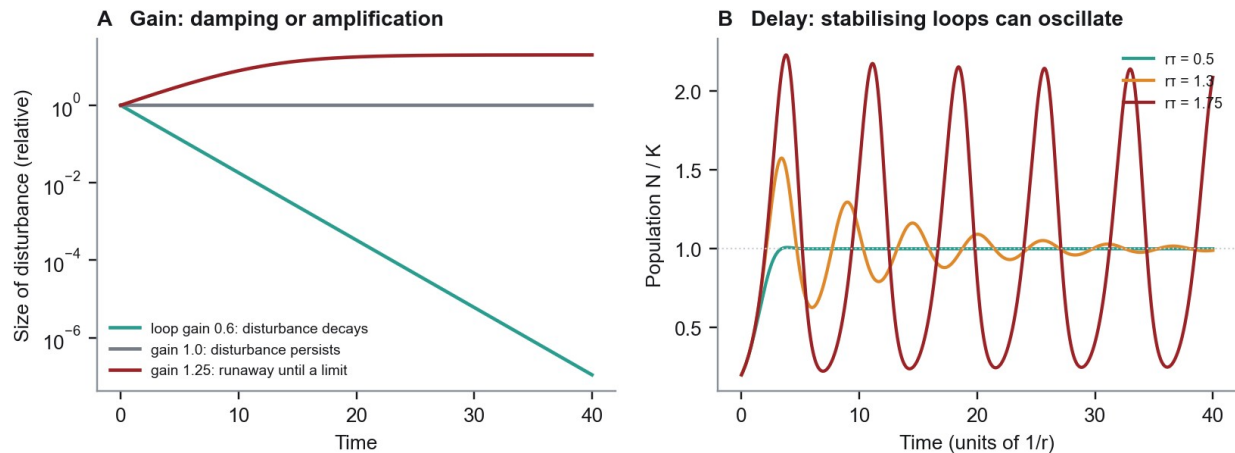


Figure 21. Feedback with gain and delay. Panel A: response of a disturbance to loop gains below, at and above one. Panel B: Hutchinson's delayed logistic equation for three values of the product of growth rate and delay; above $\tau\tau = \pi/2$ the stabilising loop produces sustained oscillation.

Source: H Heuristics calculation. Euler integration with step 0.01.

These properties are mathematical and therefore shared across every domain in which feedback operates. Stellar pulsation, predator–prey cycles, hormonal rhythms, commodity price cycles and business cycles have all been modelled as delayed negative feedback. The shared mathematics licenses a transferable prediction: a regulator that responds too slowly relative to the system's own growth will produce oscillation rather than stability. That prediction has been confirmed in engineering, physiology and ecology, and it applies to policy: central banks and climate policy face the same delay problem. The report grades the mathematical claim A and its application to particular systems A to B depending on how well the loop is identified.

10.6 Thresholds and tipping points

Thresholds appear when positive feedback creates two or more stable states. The simplest mathematical form, the normal form of a [fold bifurcation](#), is

$$dx/dt = c + x - x^3 \quad (18)$$

For values of the driver c between about -0.385 and $+0.385$ the system has two stable states, and which one it occupies depends on its history (Figure 22, Panel A). When c passes either limit, the occupied state disappears and the system jumps to the other. Reversing the driver does not reverse the jump until the other threshold is reached: the system shows hysteresis. Lakes switching between clear and turbid water, savannas and forests, the Atlantic overturning circulation in some models, ice sheets and some financial and social systems have all been described with this structure.

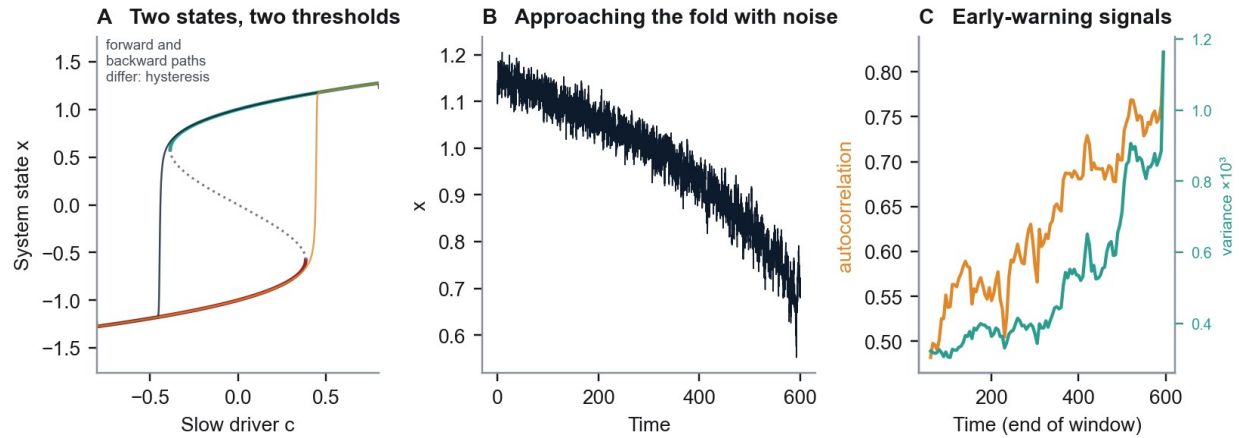


Figure 22. Thresholds and early warning. Panel A: equilibria of a fold bifurcation (stable branches coloured, unstable dotted) with forward and backward paths showing hysteresis. Panel B: a noisy system slowly driven toward the fold. Panel C: autocorrelation and variance of fluctuations in a sliding window rise before the transition. Source: *H Heuristics* calculation. Euler–Maruyama integration, noise intensity 0.045; indicators computed on detrended residuals in windows of 6,000 steps.

The deeper point is that systems near such a threshold share dynamics that do not depend on what they are made of. As the stable state approaches the fold, the restoring force that pulls the system back after a disturbance weakens. Recovery slows, a phenomenon called [critical slowing down](#), and fluctuations become larger and more correlated in time. Linearising Equation 18 about the stable state gives a recovery rate λ that goes to zero at the fold; for small noise of intensity σ , the lag-one autocorrelation and variance of fluctuations sampled at interval Δt are approximately

$$\rho_1 \approx e^{-\lambda \Delta t}, \quad \text{Var}(x) \approx \sigma^2 / 2\lambda \quad (19)$$

both of which rise as $\lambda \rightarrow 0$. In the simulation of Panel B, the system was driven slowly toward the fold with noise. Over the run, the lag autocorrelation of its fluctuations rose from 0.48 to 0.82 and their variance increased 3.6-fold before the jump, with a Kendall rank correlation of 0.81 between autocorrelation and time. [Scheffer and colleagues](#) showed that these indicators are generic to fold-type transitions, and they have been found before transitions in climate records, lakes, epileptic seizures and some financial markets. This is the most clearly predictive cross-domain result in the report: knowledge of the mathematics of one system near a fold gives a testable prediction for any other near a fold.

The result has limits that are as important as its power. Not all abrupt transitions are folds; some are driven by large shocks or by noise and give no warning. Rising autocorrelation can appear for other reasons. And the indicators say that a threshold is approaching, not where it is. The report grades the generic theory A, its empirical performance B.

10.7 One structure, many causes

Table 10. Recurring structures across domains and the distinct mechanisms that produce them

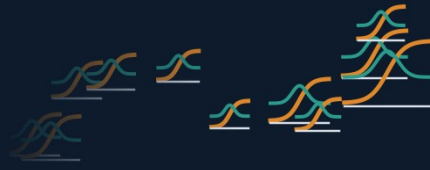
Structure	Universe	Life	Planet	Intelligence	Civilisation
Branching networks	Filaments of the cosmic web (gravity)	Vessels, airways, veins (growth plus optimisation)	Rivers, deltas, lightning (erosion, discharge)	Dendrites and axons (guided growth)	Roads, grids, pipes (cost minimisation)
Hierarchy	Stars, galaxies, clusters (hierarchical collapse)	Molecules to organisms (stable assembly, transitions)	Grains to plates; weather to climate	Neurons to areas to networks	Firms, cities, states (coordination)
Modularity	Weak; halo substructure	Pathways, organs, gene networks (varying selection)	Watersheds, biomes	Cortical areas; functional networks	Sectors, supply chains, grids (design, specialisation)
Feedback	Stellar thermostat; feedback from star formation	Homeostasis; predator–prey	Weathering thermostat; ice–albedo	Prediction error; reward learning	Prices, policy, insurance
Thresholds	Jeans collapse; ignition of fusion	Population collapse; error thresholds	Ice sheets, overturning, biomes	Memory capacity; seizures	Bank runs, cascades, revolutions
Heavy tails	Solar flares; halo masses	Extinction sizes; abundance	Earthquakes; floods	Neuronal avalanches	City and firm sizes; wars

Source: H Heuristics synthesis of Sections 5 to 9. Mechanisms in parentheses differ across domains even where the structure is the same.

Finding. Recurring structures are best understood as recurring solutions to recurring problems. Distributing flows through space favours branching; assembling under disturbance favours hierarchy; changing environments and costly connections favour modularity; regulation requires feedback; and positive feedback creates thresholds. The problems are shared across domains. The mechanisms that solve them usually are not.

11

QUANTITATIVE TESTS



11. Quantitative Tests: Do Cross-Domain Similarities Predict?

11.1 The testing strategy

A cross-domain similarity has explanatory value if it points to a shared cause, and predictive value if knowledge of one system allows a quantitative statement about another. Both can be tested. The models in this report were designed as tests rather than illustrations, and this section collects their results under six questions. Each test was chosen because it could have come out the other way.

11.2 Test 1: Do similar structures share mechanisms?

The branching comparison of Section 10.2 is the cleanest test. If similar structure implied similar mechanism, networks produced by unrelated processes should be distinguishable by their statistics, and networks matching river statistics should be river-like in mechanism. Neither held. A random-aggregation cluster and a length-minimising infrastructure network both matched the Strahler bifurcation ratios of rivers (4.5 and 4.9), while a resource-seeking growth model did not (10.1). The box-counting dimensions of all three fell within 0.17 of one another. **Result: similar structure is weak evidence of shared mechanism.** This supports H5.

11.3 Test 2: Do heavy tails identify their generators?

Heavy-tailed distributions, in which rare events are far larger than typical ones, are among the most cited signatures of a unified complexity. Earthquake magnitudes, city sizes, firm sizes, word frequencies, wealth, wars, extinctions and neuronal avalanches have all been described as following power laws, and power laws have been taken as evidence of self-organised criticality. Figure 23 tests whether the shape of a distribution identifies its generator. Four different processes were simulated.

- **A Bak–Tang–Wiesenfeld sandpile** on a 48×48 grid, the canonical model of self-organised criticality, generating about 19,000 avalanches.
- **A preferential-attachment network** of 30,000 nodes, in which new nodes link to existing ones in proportion to their degree, following [Barabási and Albert](#) and, earlier, [Herbert Simon's](#) model of skewed distributions.
- **Random multiplicative growth with a floor**, in which 30,000 units such as firms or cities grow by random proportional shocks but cannot fall below a minimum size, the mechanism Gabaix proposed for Zipf's law of cities.
- **Pure multiplicative growth without a floor**, which produces a lognormal distribution.

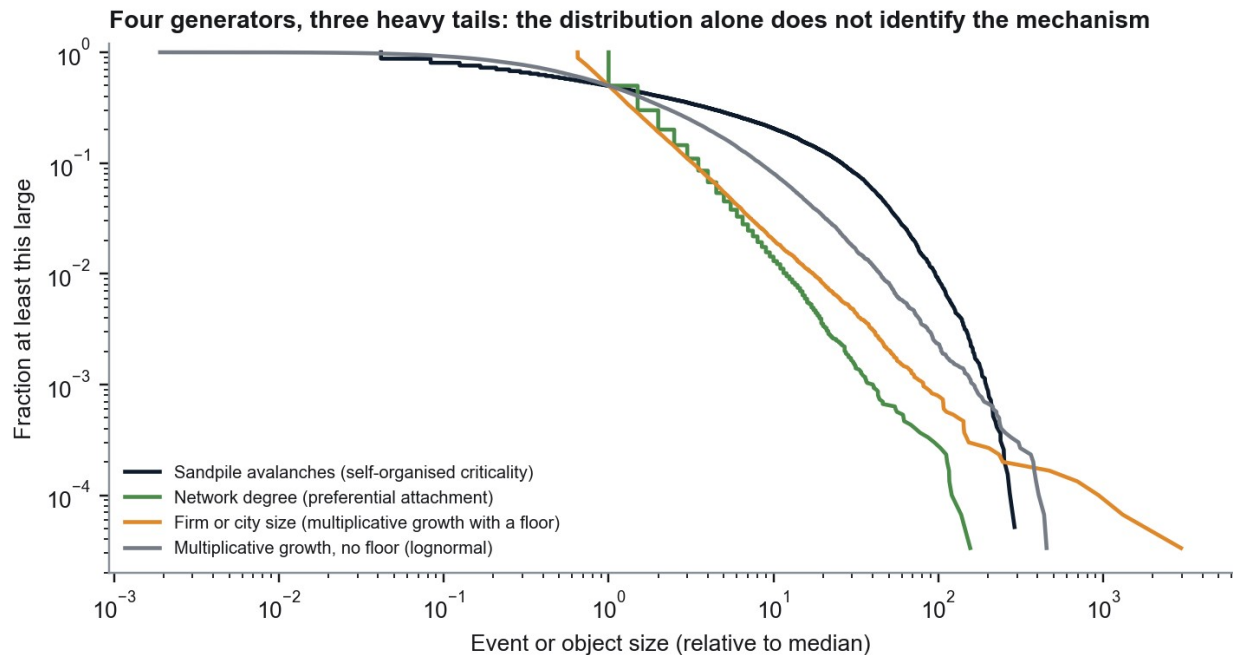


Figure 23. Four generators of heavy-tailed data. Complementary cumulative distributions of sandpile avalanche sizes, preferential-attachment degrees, multiplicative growth with a floor and pure multiplicative growth, each scaled to its median. Three show approximate power-law tails over two or more decades; the lognormal is also heavy-tailed over the range shown.

Source: *H Heuristics calculation. Tail exponents of the probability density estimated by maximum likelihood (Clauset, Shalizi and Newman, 2009): sandpile 1.4 above size 10 (with finite-size cut-off); network degree 2.8 above degree 6; multiplicative growth with floor 2.1 above size 3.*

Three of the four produced approximate power-law tails over two or more decades, with maximum-likelihood exponents for the probability density of 1.4, 2.8 and 2.1, and the fourth produced a lognormal that is also heavy-tailed and, over a limited range, hard to distinguish from a power law. The mechanisms are entirely different: a critical state maintained by slow driving and fast relaxation; a rich-get-richer growth rule; and proportional growth against a barrier. **Result: a heavy tail, or even a power law, does not identify its generator.** This is consistent with careful reviews by [Newman](#), [Mitzenmacher](#), [Clauset](#), [Shalizi and Newman](#) and [Stumpf and Porter](#), and with the finding that strictly [scale-free networks are rare](#). It is the main reason the report grades self-organised criticality as a general principle D.

11.4 Test 3: Does connectivity shape outcomes consistently?

Three models tested hypothesis H2. In each, connectivity strongly shaped outcomes, confirming the hypothesis in its weak form. In none did it do so in a single direction.

- **Contagion (Figure 16).** Random shortcuts accelerated simple contagion more than thirtyfold but stopped complex contagion.
- **Robustness (Figure 17).** Hub-dominated topology made no difference to random failure but turned targeted removal of 20 per cent of nodes from a survivable loss into total fragmentation.
- **Modularity (Figure 20).** Fewer links between modules cut the size of shocks by a factor of thirteen and slowed beneficial diffusion by a factor of fifty.

Result: topology is a powerful determinant of outcomes, but its effect depends on what is spreading and how. A unified claim about connectivity must therefore be indexed by mechanism. This is

a strong argument for the framework's insistence on keeping layer 2 (flows and their mechanisms) separate from layer 3 (structure).

There is also a positive result. [Gao, Barzel and Barabási](#) showed that the resilience of many high-dimensional networked systems, from gene regulation to ecological mutualism, can be collapsed onto a one-dimensional effective equation whose single parameter is a weighted average connectivity. Systems from different domains then fall on the same resilience curve. This is a genuine shared-mathematics result, achieved precisely by specifying the dynamics on each network rather than the topology alone.

11.5 Test 4: Do thresholds share universal warning signals?

The fold-bifurcation simulation of Figure 22 gave a clear yes within its assumptions: autocorrelation and variance rose steadily before the jump. Because the result follows from the mathematics of Equation 19 and not from any property of the simulated system, it transfers to any system approaching a fold. Empirical studies have found the signals before past climate transitions, ecosystem shifts and some physiological and financial events, and [anticipating critical transitions](#) is now an established research area. **Result: shared mathematics near shared bifurcations yields transferable predictions.** This supports H4 and H8. It is also the clearest demonstration of what the unification ladder means by rung 3.

11.6 Test 5: Does persistence require a minimum flow?

Hypothesis H3 holds that organised systems require continuing flows to maintain their structure. Figure 24 tests a stronger form: that the requirement creates a threshold. In the model, a structure S captures the flow J that sustains it with an efficiency that rises with its own organisation, and decays at a rate δ :

$$dS/dt = \eta J S^2 / (S^2 + h^2) - \delta S \quad (20)$$

This simple form captures something common to stars, cells, ecosystems and institutions: a disorganised system cannot capture the flow it needs to organise. The model has an organised steady state only when the flow exceeds a minimum, $J_c = 2\delta h/\eta$. Below that, the only stable state is collapse. Panel B of Figure 24 drives two such structures with the same slow decline in supply. The structure with higher maintenance costs ($\delta = 0.15$) was smaller to begin with and collapsed at time 237, while the one with lower costs ($\delta = 0.10$) survived until time 313. Both collapsed abruptly after a long gradual decline, and both did so *after* the supply had fallen below their thresholds, because a system lingers near a vanished steady state before it falls.

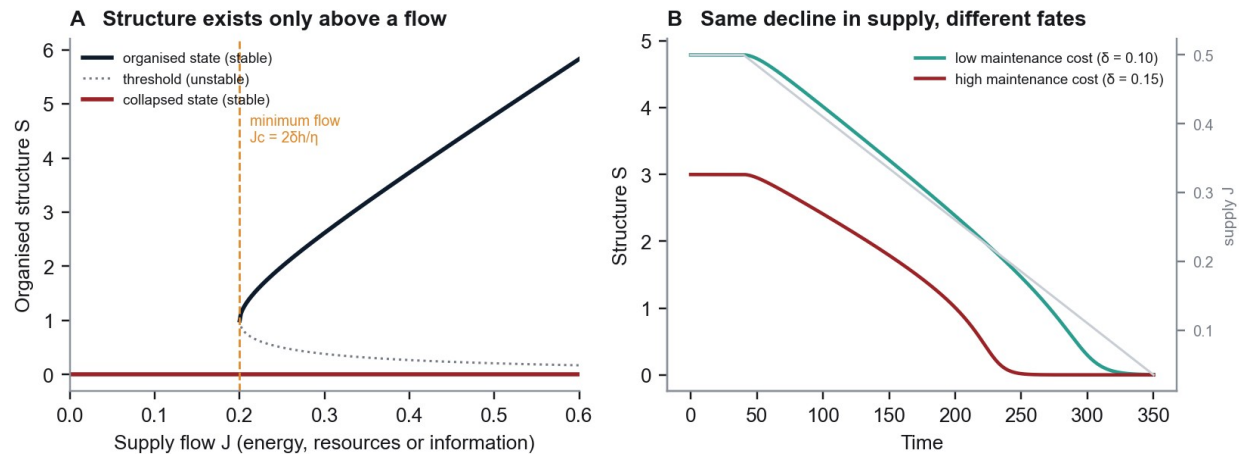


Figure 24. Persistence requires maintenance, and maintenance creates thresholds. Panel A: steady states of a structure that captures flow in proportion to its own organisation; an organised state exists only above a minimum flow J_c . Panel B: two structures with different maintenance costs under the same slowly declining supply (grey, right axis).

Source: H Heuristics model, original to this report. $\eta = 1$, $h = 1$; Euler integration with step 0.05.

Result: if structure is needed to capture the flow that sustains it, persistence has a threshold, collapse is abrupt and delayed, and higher maintenance costs raise the threshold. The result supports H3 and links it to H4. It also gives a precise form to Tainter's argument about the rising costs of social complexity: a society that adds maintenance obligations raises the minimum flow it needs and becomes more vulnerable to a decline in its resource base. The model is deliberately minimal and the report grades its application to any specific system C until tested against data.

11.7 Test 6: Do scaling exponents transfer?

Organisms and cities both show power-law scaling with size. If the scaling arose from a shared mechanism, exponents should be similar or related in a predictable way. They are not (Figure 15). Biological rates scale sublinearly with mass ($\beta \approx 3/4$), so that per-unit rates fall with size; urban socio-economic outputs scale superlinearly with population ($\beta \approx 1.15$), so that per-capita rates rise. The WBE calculation of Figure 11 further showed that even within biology the exponent depends on the network's flow regime and depth. **Result: scaling laws share a mathematical form but not a value or a mechanism; exponents do not transfer across domains.** The scaling of machine-learning performance with compute, discussed in Section 8, is a third, unrelated case.

11.8 Summary of tests

Table 11. Quantitative tests of cross-domain claims

Test	Model	Key result	Verdict	Hypotheses
Shared structure, shared mechanism?	DLA, space colonisation, minimum spanning tree	Unrelated mechanisms give $D = 1.44 - 1.61$; two match river bifurcation ratios	No	H5
Heavy tails identify generator?	Sandpile, preferential attachment, multiplicative growth	Three generators give power-law tails with $\alpha = 1.4-2.8$	No	H5
Connectivity shapes outcomes?	Contagion, robustness, modular cascades	Large effects in every model; direction depends on mechanism	Yes, mechanism-indexed	H2, H7
Universal warning signals?	Noisy fold bifurcation	Autocorrelation $0.48 \rightarrow 0.82$; variance $\times 3.6$ before transition	Yes, near folds	H4, H8
Minimum flow for persistence?	Flow-capture maintenance model	Threshold $J_c = 2\delta h/\eta$; costlier structures collapse earlier	Yes, in model	H3
Exponents transfer?	WBE network; urban data	$\beta \approx 3/4$ (organisms) vs 1.15 (cities); WBE value depends on regime	No	H5, H8
Hierarchy speeds assembly?	Simon's watchmakers	Hierarchy $\approx 1,400$ times faster at 1% interruption	Yes	H6
Constraints bound forms?	Mass-radius map	All structures within quantum, gravitational and density limits	Yes	H1

Source: H Heuristics calculations reported in Sections 4 to 11.

11.9 The evidence matrix

Combining the tests with the domain sections gives an evidence matrix for fourteen candidate principles across the five domains (Figure 25). Each cell records the strength of evidence that the principle operates in that domain, not that it operates by the same mechanism. Four principles are supported at Grade A or B in every domain: order sustained by energy throughput, constraints bounding the space of forms, nested hierarchy and negative feedback. Most others are supported in four. Self-organised criticality is the only candidate that is not well supported in any domain.

	Universe	Life	Planet	Intelligence	Civilisation	A or B
Order sustained by energy throughput	A	A	A	A	A	5 / 5
Constraints bound the space of forms	A	A	A	B	B	5 / 5
Nested hierarchy of levels	A	A	B	B	A	5 / 5
Selection, learning or retention of variants	D	A	C	A	B	3 / 5
Negative feedback and regulation	A	A	B	B	B	5 / 5
Thresholds and alternative stable states	A	B	B	B	C	4 / 5
Branching transport networks	C	A	A	B	A	4 / 5
Diffusion and S-shaped spread	n/a	B	B	B	A	4 / 5
Heavy-tailed size distributions	B	C	A	B	B	4 / 5
Modular organisation	n/a	A	B	A	B	4 / 5
Power-law scaling with size	B	B	C	B	B	4 / 5
Information storage and transmission	D	A	C	A	A	3 / 5
Release and reorganisation cycles	B	B	B	C	C	3 / 5
Self-organised criticality	D	C	C	C	D	0 / 5

A Established
 B Well supported
 C Plausible or contested
 D Speculative
 Not applicable

Figure 25. The evidence matrix. Strength of evidence that each candidate principle operates in each domain, on the report's four-level scale. The right column counts domains with Grade A or B.

Source: H Heuristics assessment based on the literature and calculations in Sections 4 to 11. Grades refer to operation of the principle in the domain, not to the identity of mechanisms across domains.

The matrix should be read alongside the ladder. A principle can be present in every domain and still be unified only at rung 2, as hierarchy largely is. The next two sections turn the matrix into hypotheses that can be tested and limits that must be respected.

12

RESEARCH HYPOTHESES



12. Research Hypotheses

12.1 From framework to propositions

A framework becomes science when it makes claims that could be false. This section states eight hypotheses. The first five correspond to the propositions identified in the planning of this synthesis; the last three are added on the strength of the tests in Section 11. Each is stated with its rationale, a prediction, a test and the observation that would count against it. Each is labelled as an original H Heuristics proposition, though most build on the literature cited.

H1. Constrained emergence

Statement. Complex structures emerge within boundaries established by the physical, chemical, biological or institutional conditions of their respective systems, and those boundaries explain more of the observed range of structures than the generative mechanisms do.

Rationale. The mass–radius map (Figure 9) shows every known physical structure confined to a band set by three limits; diffusion limits cell size; energy budgets limit brain size; institutional rules limit what organisations can form. **Prediction.** In any domain, the set of observed structures will cluster near the edges of the feasible region where constraints bind, rather than fill it uniformly. **Test.** Compare models with and without constraints to determine how much of the variance in observed structures each explains. **Would count against.** Finding that observed structures fill feasible space uniformly, or that removing a constraint from a model leaves the range of emergent structures unchanged.

H2. Connectivity shapes outcomes

Statement. Network topology influences the propagation of resources, information, disturbances and adaptive responses, and the direction of its effect is determined by the mechanism of propagation.

Rationale. In the contagion, robustness and modularity tests, topology changed outcomes by factors of ten to a hundred, but in opposite directions for simple and complex contagion and for random and targeted failure. **Prediction.** Interventions that add long-range links will accelerate the spread of information and infections but slow the adoption of behaviours requiring social reinforcement. **Test.** Compare network models across ecological, technological and economic systems, classifying each process by its transmission mechanism. **Would count against.** Finding a consistent effect of a topological feature, such as clustering, across processes with different transmission mechanisms.

H3. Persistence requires maintenance

Statement. Many organised systems require continuing flows of energy, resources or information to maintain their structures; where structure is needed to capture those flows, persistence has a minimum-flow threshold that rises with maintenance cost.

Rationale. Equation 3 requires entropy export for any persistent structure; the model of Figure 24 shows how the requirement creates a threshold. **Prediction.** Across systems of a given type, those with higher maintenance costs relative to throughput will have shorter lifetimes and collapse at higher levels of resource supply. **Test.** Examine the relationship between maintenance requirements, resource availability and system longevity in stars (mass and lifetime), organisms (metabolic rate and lifespan), infrastructure (maintenance spending and failure rates) and polities. **Would count against.** Finding that systems with high maintenance costs are no more vulnerable to supply declines than those with low costs.

H4. Feedback changes system trajectories

Statement. Feedback mechanisms can stabilise systems, amplify disturbances or produce nonlinear transitions, and the outcome is determined by loop gain, delay and the presence of competing loops.

Rationale. Figure 21 shows gain and delay determining damping, persistence, runaway and oscillation; Figure 22 shows competing loops creating alternative states and thresholds. **Prediction.** Systems in which stabilising feedback is slow relative to their growth rate will oscillate; systems approaching a fold will show rising autocorrelation and variance. **Test.** Identify feedback strength, response delays and thresholds in different system models and test whether predicted oscillation and early-warning signals appear in data. **Would count against.** Systematic failure of early-warning indicators before fold-type transitions that have been independently identified.

H5. Similar structures need not share a mechanism

Statement. Distinct processes can generate comparable structural patterns without being governed by identical causal laws, and structural similarity alone is weak evidence of shared mechanism.

Rationale. Three unrelated mechanisms produced similar branching networks; four produced heavy tails. **Prediction.** For any recurring structure, it will be possible to find at least two causally distinct generators that reproduce its standard summary statistics. **Test.** Compare the mechanisms and mathematical conditions underlying superficially similar structures, and develop statistics that discriminate between them, as Strahler ratios partly did here. **Would count against.** Finding that a class of structures can be generated by only one mechanism, so that structure does identify cause.

H6. Hierarchy through stable intermediates

Statement. Where complex structures are built by sequential assembly in a disturbed environment, they will be hierarchical, with stable intermediate levels, because hierarchical assembly is exponentially faster than flat assembly.

Rationale. Simon's argument, computed in Figure 19, gives a 1,400-fold advantage at a 1 per cent interruption rate. **Prediction.** Assembled systems in more disturbed environments will have more levels and smaller modules. **Test.** Compare hierarchy depth and module size against disturbance rates in protein complexes, organisms, organisations and engineered products. **Would count against.** Finding flat assembled structures that persist in highly disturbed environments without other explanations.

H7. The efficiency–resilience trade-off

Statement. Features that increase a system's efficiency under normal conditions, including tight coupling, high connectivity and removal of redundancy, tend to reduce its ability to contain and recover from shocks.

Rationale. The modularity test showed a direct trade-off between shock containment and the speed of beneficial diffusion; the adaptive cycle and the analysis of banking networks describe the same pattern.

Prediction. Across ecosystems, supply chains, power grids and financial systems, measures of efficiency and measures of shock containment will be negatively correlated. **Test.** Assemble paired measures of efficiency and resilience across many systems of each type. **Would count against.** Finding that the most efficient systems of a type are also the most resilient.

H8. Transfer requires a shared regime

Statement. Quantitative predictions transfer between domains when, and largely only when, the systems share a dynamical regime, such as proximity to the same type of bifurcation or membership of the same universality class.

Rationale. Early-warning theory transferred because all folds share Equation 19; scaling exponents did not transfer because organisms and cities are not in a shared regime. The [renormalisation-group](#) explanation of universality and the [compression of parameter space](#) explain why. **Prediction.** Cross-domain predictions will be most accurate for systems near critical points and least accurate for systems far from them. **Test.** Score the accuracy of published cross-domain predictions against independent assessments of whether the systems share a regime. **Would count against.** Finding accurate transfer between systems in demonstrably different regimes.

12.2 Summary

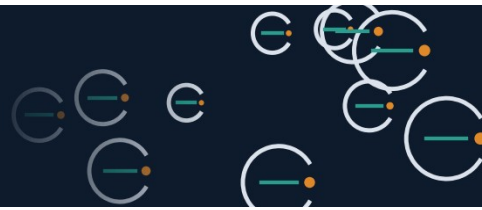
Table 12. Eight testable hypotheses and their current status

Hypothesis	Core test	Status in this report	Grade
H1 Constrained emergence	Variance in structures explained by constraints versus mechanisms	Supported by mass–radius map and domain constraints	B
H2 Connectivity shapes outcomes	Topology effects classified by transmission mechanism	Supported; direction mechanism-dependent	A (models), B (data)
H3 Persistence requires maintenance	Maintenance cost against longevity and collapse threshold	Supported in model; empirical test needed	B (general), C (threshold form)
H4 Feedback changes trajectories	Gain, delay and early-warning signals in data	Supported; warning signals generic near folds	A (theory), B (data)
H5 Similar structures, different mechanisms	Multiple generators for each recurring structure	Strongly supported by branching and heavy-tail tests	A
H6 Hierarchy through stable intermediates	Hierarchy depth against disturbance rate	Supported in model	B
H7 Efficiency–resilience trade-off	Paired efficiency and resilience measures	Supported in model and case studies	B
H8 Transfer requires shared regime	Accuracy of cross-domain predictions by regime	Consistent with all tests here	C

Source: H Heuristics. Grades summarise current evidence; each hypothesis is offered for testing.

13

THE LIMITS OF UNIFICATION



13. The Limits of Unification

13.1 Why limits belong in a synthesis

A synthesis that ended with Section 12 would leave an impression of more unity than the evidence supports. This section sets out the limits: the reasons why a unified architecture of reality, if it exists, must be modest. The limits are of four kinds. Some concern reduction, the relation between levels. Some concern teleology, the temptation to read direction into history. Some concern analogy, the ease with which resemblance passes for explanation. And some concern the irreducibly particular, the features of reality that no general architecture can capture.

13.2 The limits of reduction

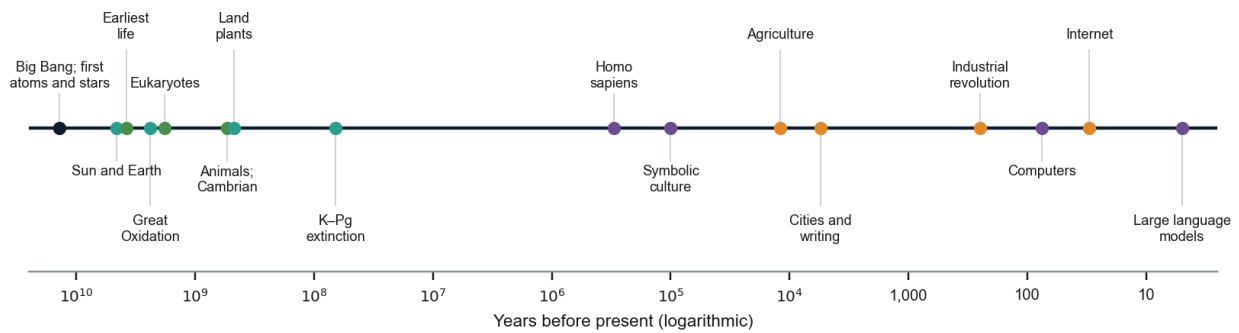
The [unity of science](#) was once understood as reduction: biology would be derived from chemistry, chemistry from physics, and the special sciences would eventually disappear into a single fundamental theory. That programme has not succeeded and most philosophers of science no longer expect it to. Jerry Fodor argued in [Special Sciences](#) that the kinds studied by economics or psychology are *multiply realisable*: a currency can be shells, coins or database entries, and nothing at the level of physics groups them together. Anderson's [More Is Different](#) made the complementary point from physics: even when reduction is possible in principle, each level has its own laws that must be discovered at that level.

This report's framework is consistent with both arguments because it does not attempt reduction. Its layers are questions, not levels of a hierarchy from which one can be derived from another. But the arguments set a limit. The framework cannot be expected to *derive* the behaviour of a city from the behaviour of its people, or of an ecosystem from its genes, any more than physics can derive the price of wheat. It can describe what every level has in common as a problem, and in some cases identify a shared mathematics. It cannot dissolve the special sciences. A claim that it does would be a sign that the framework had become a [reductionist](#) programme by another name.

13.3 The danger of teleological reasoning

The most seductive error in synthesis is to read the history of the universe as a story that leads somewhere: from simple to complex, from matter to life to mind to us. Popular accounts of cosmic evolution often present a timeline in which novelties arrive faster and faster, with intelligence and technology as the culmination. Figure 26 shows why that impression must be treated with caution. Panel A plots major events on a logarithmic time axis, as is usual; novelty appears to accelerate toward the present. Panel B plots the same events on a linear axis: almost all of them crowd into the last tenth of cosmic history, and the first 9 billion years are empty of the events that a human-centred list includes.

A On a logarithmic axis, novelty seems to accelerate toward the present



B On a linear axis, the same record is a long quiet history and a recent burst

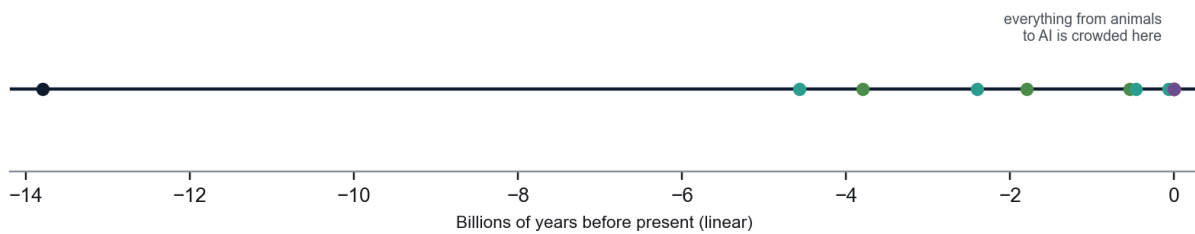


Figure 26. Teleology by axis. Panel A: major events in cosmic, biological and human history on a logarithmic time axis, where novelty appears to accelerate steadily toward the present. Panel B: the same events on a linear axis. The impression of a directed acceleration depends partly on the choice of events and of axis.

Source: *H Heuristics*. Dates from the studies cited in Sections 5 to 9; event selection is illustrative and deliberately conventional.

Two effects combine. The first is the axis: a logarithmic scale compresses the distant past and expands the recent, so that any list of events with roughly equal numbers per order of magnitude will look like acceleration. The second is selection: the events chosen are those that led to us, so the list is a genealogy, not a sample. A list chosen by a different criterion, such as the formation of the largest structures or the most energetic events, would show no acceleration at all. There are genuine accelerations within domains: technological change has sped up, and cumulative culture allows faster change than genetic evolution. But these are explained by specific mechanisms, such as the faster transmission of learned information, not by a cosmic tendency.

Biology has a long history of warnings about this error. Stephen Jay Gould and Richard Lewontin's critique of the [adaptationist programme](#) warned against assuming that every feature is an optimal solution to a problem. The philosophy of [teleology in biology](#) distinguishes the legitimate use of functional language, a heart is *for* pumping because hearts that pumped were selected, from illegitimate claims of purpose in nature. The framework uses functional language only where there is selection or design. It does not describe stars as trying to persist, ecosystems as aiming at climax or the universe as striving for complexity.

Complexity does not increase universally. Parasites lose organs; cave fish lose eyes; simplified economies follow collapse; most of the universe's matter is in simple states. Where local complexity increases, it is because a gradient is being dissipated and a mechanism is available to build structure from it. The second law permits this; it does not require it.

13.4 The limits of analogy

Analogies are indispensable in science and dangerous in synthesis. The cosmic web looks like a neural network; the city has been called an organism since antiquity; the economy is described as an ecosystem; the brain as a computer; the Earth as a living being. Each analogy has suggested productive research and each has also misled. Treating the city as an organism suggests that it has a natural size, a life cycle and a purpose, none of which holds. Treating the brain as a computer suggested for decades that cognition is symbol manipulation, a view that the success of connectionist models has substantially revised. The unification ladder is designed to discipline analogy by asking, of each, which rung it reaches and what inferences it therefore licenses.

Some cross-domain claims fail in ways that are themselves instructive (Table 13).

Table 13. Characteristic failure modes of unifying claims

Failure mode	Example	Symptom	Safeguard
Resemblance taken as mechanism	Cosmic web and neural networks	Visual similarity cited as evidence	Ask for a shared generator and a discriminating statistic
Universal law from a common pattern	Power laws as proof of criticality	Power-law fit on limited range	Fit alternatives; test the mechanism directly
Unfalsifiable generality	Strongest forms of the free-energy and maximum-entropy-production principles	No observation could contradict the claim	Require a stated defeater
Single metric for complexity	Energy rate density as complexity	Counterexamples ignored	Track several quantities separately
Teleology	Complexity as the universe's direction	Selected events, logarithmic axes	Sample events by a neutral criterion
Category error in selection	Selection among non-replicators	No heredity identified	Specify what is copied and how
Exponent transfer	Biological 3/4 applied to cities or firms	Same equation, different sign of effect	Establish a shared regime first

Source: H Heuristics. Failure modes compiled from the literature reviewed in Section 2 and the tests of Section 11.

13.5 Unfalsifiable grand principles

Several principles proposed to unify the sciences of organisation share a troubling property: in their most general forms they are difficult or impossible to refute. Maximum entropy production, the strongest forms of the free-energy principle, the constructal law and strong Gaia each make specific claims that can be tested in particular applications, and each also has a general form that can accommodate almost any outcome. This is not a criticism of the researchers, who are usually careful about the distinction, but of the way the principles are used in synthesis. A principle that explains everything has stopped being a hypothesis and become a description language. Description languages can be valuable, but they should not be mistaken for laws. The report's hypotheses were written with stated defeaters for this reason.

13.6 What may not reduce to a common architecture

Some features of reality may not fit any common architecture, and a responsible synthesis must say so.

- **Historical particulars.** The specific sequence of events that produced the Moon, the Chicxulub impact, the evolution of eukaryotes or the industrial revolution is not predictable from general principles. Evolution's [contingency](#) and technology's [lock-in](#) mean that history is part of the explanation of every complex system, and history is by definition not general.
- **Singular systems.** There is one observable universe, one known origin of life and one biosphere. Comparative methods require many cases; for these the framework can describe but not test.
- **Meaning, value and normativity.** Civilisation includes laws, moral norms and meanings that are not reducible to flows and structures. Shannon information is blind to meaning, and the framework's layers say nothing about which outcomes are good.
- **Consciousness.** Whether subjective experience is an emergent property of information processing, and if so of what kind, is an open problem the framework does not address.
- **The constraints themselves.** The framework takes physical law as given. Why the laws and constants have the values they do, and whether, as the [mathematical universe hypothesis](#) proposes, mathematics is the deepest layer of all, are questions beyond any comparative architecture.

Limit. A unified architecture can identify the problems all complex systems must solve and the mathematical forms their solutions share. It cannot replace the particular histories, mechanisms and meanings that make each system what it is.

14

IMPLICATIONS



14. Implications

14.1 For science

The first implication is methodological. Cross-domain research produces its best results when it moves from structure to dynamics and from analogy to mathematics. Comparing pictures of networks is rarely informative; comparing the equations that govern flows on them often is. Research programmes that aim at unification should therefore invest in methods that discriminate between mechanisms producing similar patterns, in the style of the branching and heavy-tail tests, rather than in methods that detect patterns alone.

The second implication is about data. Most domain sciences collect data in forms that cannot be compared with other domains. A shared ontology of the six layers, with common definitions of throughput, maintenance cost, connectivity, modularity and recovery time, would allow the evidence matrix of Figure 25 to be filled from data rather than judgement. Shared benchmark datasets of networks, scaling relations and time series before transitions would allow cross-domain methods to be tested fairly.

The third implication is about training. Some of the most productive cross-domain results, from the spin-glass theory of memory to the ecology of banking, came from researchers who carried tools from one field to another. Training that combines a deep specialism with fluency in the shared mathematics of feedback, networks, scaling and bifurcations would produce more of them.

14.2 For policy and resilience

The framework has practical implications wherever societies manage complex systems under stress, which is the subject of much of H Heuristics' research on [systemic risk and the polycrisis](#).

- **Watch the thresholds, not only the trends.** Systems with alternative stable states can change abruptly after long periods of apparent stability. Early-warning indicators such as rising autocorrelation are generic and inexpensive to monitor, and should be built into the surveillance of climate, ecosystems, financial systems and infrastructure, with their limits understood.
- **Budget for maintenance.** Persistence requires a continuing flow. Infrastructure, institutions and ecosystems that are built without provision for their maintenance raise their own collapse thresholds. The maintenance model suggests that maintenance budgets are not overheads but conditions of existence.
- **Design modularity deliberately.** Tightly coupled, highly connected systems are efficient and fragile. Firebreaks, circuit breakers, islandable microgrids and diversified supply chains trade a little efficiency for a large gain in shock containment. The modularity test quantifies the trade-off.

- **Protect the hubs.** Hub-dominated networks are robust to random failure and fragile to the loss of hubs, whether by attack or by correlated failure. Ports, data centres, financial clearing houses and key suppliers deserve protection in proportion to their centrality.
- **Match diffusion strategy to mechanism.** Information spreads best through long-range ties; costly behaviours and technologies that need social reinforcement spread best through clustered networks. Programmes that seek to accelerate the adoption of clean technologies or health practices should design for complex contagion where reinforcement matters.
- **Mind the delays.** Regulators that act too slowly relative to the systems they regulate create oscillation. Policy feedback loops should be shortened where possible and their delays explicitly accounted for.

14.3 For the Architecture of Creation series

For the series, the synthesis offers a common grammar. Each earlier report can now be read as an application of the six layers to one domain, and the evidence matrix shows where the series' claims are strongest and weakest. The synthesis also corrects some impressions the earlier reports may have left. The foundational report emphasised recurrence; this one shows that recurrence often hides diverse mechanisms. The universe and Earth reports emphasised self-organisation; this one emphasises that self-organisation is always paid for by a flow. The development report emphasised diffusion; this one shows that diffusion's dependence on network structure reverses with its mechanism.

14.4 Ten working heuristics

The framework can be condensed into ten questions that can be asked of any system, from a galaxy to a firm.

1. **Find the constraints.** What is impossible here, and which limits bind? Draw the feasible region before explaining what is in it.
2. **Follow the flow.** What gradient drives the system, how large is its throughput and where does the entropy go?
3. **Name the structure.** What has emerged that can be described with fewer variables than its parts, and at how many levels?
4. **Price the maintenance.** What does it cost to keep this structure in being, and what is the minimum flow below which it cannot exist?
5. **Map the feedback.** Which loops stabilise and which amplify, with what gain and what delay?
6. **Locate the thresholds.** Are there alternative states? Is the system near one, and is it slowing down?
7. **Index connectivity by mechanism.** What is spreading, how does it spread, and does that mechanism favour clustered or random connections?
8. **Distrust resemblance.** If this system looks like another, can the two be generated by different mechanisms? Usually they can.
9. **Place the claim on the ladder.** Is a cross-domain comparison a metaphor, an analogy, shared mathematics, shared mechanism or shared law? Infer only what that rung licenses.
10. **Respect the particular.** What in this system is history, accident or meaning that no general architecture will explain?

14.5 A research programme

Establishing stronger claims for a unified architecture requires a programme of work over the next decade (Figure 27). In the near term, the priority is a common ontology, open benchmark datasets and pre-registered tests of the eight hypotheses in at least three domains each. In the medium term, it is methods that identify mechanisms from data, coupled multi-scale models that link planetary, economic and institutional dynamics, and prospective rather than retrospective tests of early-warning systems. In the long term, it is a formal theory of when coarse-grained models transfer across substrates, which would turn hypothesis H8 into a theorem, and a thermodynamics of adaptive and learning systems that would connect layers 2 and 4 rigorously.

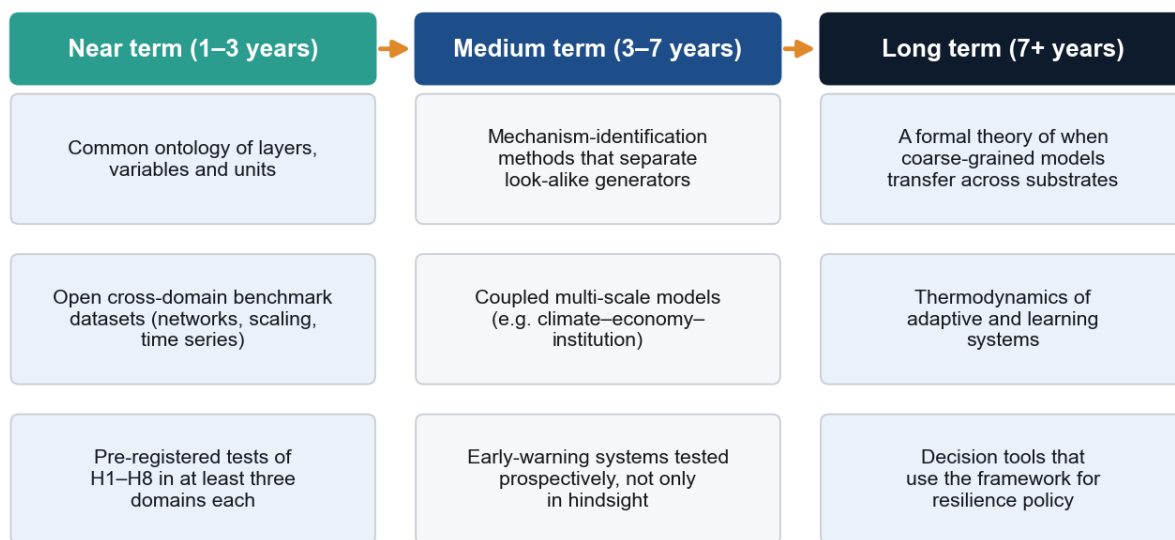


Figure 27. A research programme for a unified architecture. Near-term work builds shared definitions, data and tests; medium-term work develops methods to identify mechanisms and couple scales; long-term work aims at formal theory and practical tools.

Source: H Heuristics. Illustrative.

15

VERDICT



15. Conclusion: Is a Unified Architecture Scientifically Defensible?

15.1 The answer

The report began with a question: can a common architecture explain how reality generates, organises, sustains and transforms complex systems across different scales of existence? The answer it reaches is a qualified yes. A unified architecture of reality is scientifically defensible as a *comparative framework*, a structured way of asking the same questions of every system and of identifying which answers are shared. It is not defensible as a *single theory* in which one mechanism generates every structure or one quantity measures every kind of order. The difference between the two is the difference between a map of the problems that complex systems face and a claim about how all of them solve those problems.

Judged by the four criteria of Section 1.3, the framework succeeds on coverage: the six layers applied without strain to galaxies, cells, planets, brains and cities. It succeeds on discrimination when it is used with the unification ladder: the tests separated shared mechanism from shared appearance. It succeeds on prediction in a specific and important class of cases, those in which systems share a dynamical regime, such as the approach to a fold. And it is falsifiable, because its hypotheses state what would count against them. Where it fails, by predicting nothing, it fails honestly and in identifiable places.

15.2 Which principles generalise

Figure 28 ranks the fourteen candidate principles of the evidence matrix by a cross-domain evidence score and marks the highest rung of the ladder each reaches. Three groups emerge (Table 14).

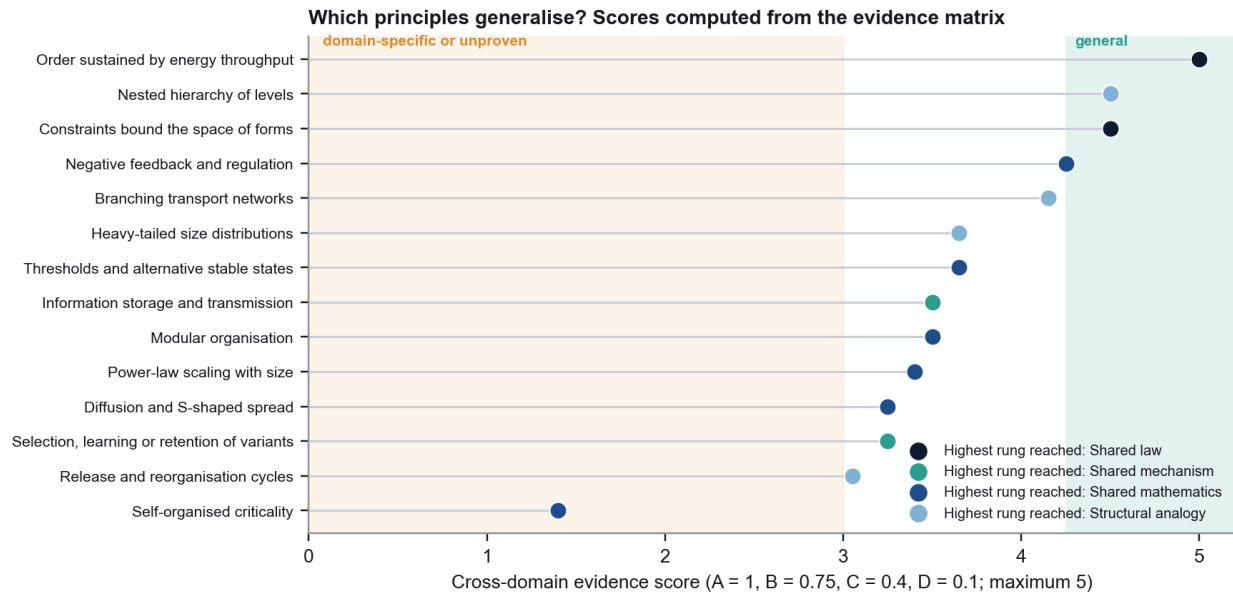


Figure 28. Which principles generalise across domains. Each candidate principle is scored by summing its evidence grades across the five domains (A = 1, B = 0.75, C = 0.4, D = 0.1), and coloured by the highest rung of the unification ladder that cross-domain claims about it reach.

Source: H Heuristics calculation from the evidence matrix (Figure 25).

Table 14. The verdict: what generalises, what is shared only as mathematics or analogy, and what remains domain-specific or unproven

Group	Principles	Basis	What it licenses
Generalises as law or constraint	Order requires free-energy throughput and entropy export; constraints bound the space of forms; information processing has a thermodynamic cost	Second law; conservation; Landauer; feasibility limits	Firm predictions about what cannot happen and what must be paid
Generalises as shared mathematics	Feedback with gain and delay; fold thresholds and critical slowing down; percolation and robustness; replicator and diffusion dynamics; hierarchy through stable intermediates	Identical equations near identical regimes; universality	Transferable predictions where the regime is shared
Shared as problem, not mechanism	Branching networks; hierarchy in general; modularity; heavy tails; power-law scaling; adaptive cycles	Convergent solutions to common problems	Where to look; not why
Domain-specific	Natural selection with heredity; quarter-power metabolic scaling; superlinear urban scaling; stellar nucleosynthesis; institutional rules	Mechanisms tied to particular substrates	Explanations within the domain only
Contested or unproven as general principles	Self-organised criticality; maximum entropy production; strong Gaia; free-energy principle as theory of all self-organisation; selection among non-replicators; directional increase of complexity	Partial evidence; generality not established	Hypotheses for testing

Source: H Heuristics synthesis of Sections 4 to 14.

The first group is small but foundational. Every persistent structure examined, without exception, is sustained by a throughput of free energy and exports entropy; every domain is bounded by constraints that rule out most conceivable forms; and every act of information processing pays a thermodynamic cost. These are physical law. They are the bedrock of the architecture, and they are constraints rather than generators: they say what cannot happen, not what will.

The second group is the architecture's most useful part. Feedback, thresholds, percolation, diffusion and selection dynamics have the same mathematics wherever they occur, and where systems share a regime, predictions transfer. The early-warning signals of Figure 22, the robustness results of Figure 17 and the capacity threshold of Figure 14 are examples. This is unification in the sense that physics has long recognised in universality: not identity of substance but identity of behaviour near particular kinds of instability.

The third group contains most of the recurring structures that motivated the series. Branching, hierarchy, modularity, heavy tails and scaling recur because the problems that produce them recur: distributing flows through space, assembling under disturbance, adapting to changing environments, aggregating many small processes, growing in proportion to size. The structures are shared; the mechanisms usually are not. Their recurrence is real and worth studying, but it is evidence about the problem, not about the cause.

15.3 Which remain domain-specific

Much of what makes each domain interesting is specific to it. Natural selection requires heredity, which only life and its descendants possess. Quarter-power scaling, if it holds, is a property of biological supply networks; urban superlinearity is a property of social interaction; their opposite signs show that no single scaling law covers both. Stellar nucleosynthesis, plate tectonics, synaptic plasticity and property rights are each the work of particular machinery that the framework can locate but not explain. The proper relation between the architecture and the domain sciences is therefore one of mutual dependence: the domain sciences supply the mechanisms, and the architecture supplies the comparison.

15.4 What research would establish stronger claims

Four kinds of research would allow stronger claims than this report can make.

1. **Discriminating statistics.** For each recurring structure, methods that distinguish its possible generators from data. Strahler ratios partly separated the branching mechanisms here; similar tools are needed for heavy tails, networks and scaling.
2. **Comparable data across domains.** Measurements of throughput, maintenance cost, connectivity and recovery made in the same units and by the same protocols in physical, biological, planetary, cognitive and social systems, so that hypotheses H1, H3 and H7 can be tested quantitatively.
3. **Prospective tests.** Early-warning methods and other cross-domain predictions tested before the events they predict, not reconstructed after them.
4. **Formal theory of transfer.** A mathematical account of when a coarse-grained model of one system applies to another, building on renormalisation, parameter-space compression and information-theoretic measures of emergence. Such a theory would convert hypothesis H8 from an empirical generalisation into a result, and would say precisely how far a unified architecture can reach.

15.5 Closing

The Architecture of Creation series set out to ask why the same forms recur across unrelated systems. Its reports followed that question from the cosmic web to the global economy. This synthesis has found that the forms recur for three different reasons: because some principles are physical law and bind everything; because some mathematics is shared by every system near the same kind of instability; and because many problems are shared by every system that must distribute flows, assemble parts, survive disturbance and change. Only the first two are unification in the strict sense. The third is something perhaps more interesting: evidence that reality, working through utterly different mechanisms, keeps arriving at the same small set of solutions.

That is the architecture this report has tried to describe. It is not a blueprint, because there is no architect and no plan. It is not a single mechanism, because the mechanisms are many. It is a set of constraints, flows and problems that every organised system must contend with, and a set of forms that the solutions tend to take. Seeing it clearly does not reduce the sciences to one. It allows each to see what it shares with the others, and to borrow, carefully, what works.

Final verdict. A unified architecture of reality is real but modest: a shared set of constraints, a shared mathematics of feedback, thresholds and networks, and a shared set of problems, solved by mechanisms that remain irreducibly plural.

References

The list below gives full details for every primary source cited by DOI in the text, generated from the DOI registry metadata. Reference articles linked for concepts, and works cited by other stable links, are not repeated here; they include Simon (1962), *The Architecture of Complexity*, Proceedings of the American Philosophical Society 106, 467–482; Kaplan et al. (2020), *Scaling Laws for Neural Language Models*, arXiv:2001.08361; and Harper (2009), *The Replicator Equation as an Inference Dynamic*, arXiv:0911.1763.

- Albert, R. et al. (2000). Error and attack tolerance of complex networks. *Nature* 406, 378–382. [doi:10.1038/35019019](https://doi.org/10.1038/35019019)
- Allesina, S. & Tang, S. (2012). Stability criteria for complex ecosystems. *Nature* 483, 205–208. [doi:10.1038/nature10832](https://doi.org/10.1038/nature10832)
- Alon, U. (2007). Network motifs: theory and experimental approaches. *Nature Reviews Genetics* 8, 450–461. [doi:10.1038/nrg2102](https://doi.org/10.1038/nrg2102)
- Amit, D. J. et al. (1985). Storing Infinite Numbers of Patterns in a Spin-Glass Model of Neural Networks. *Physical Review Letters* 55, 1530–1533. [doi:10.1103/PhysRevLett.55.1530](https://doi.org/10.1103/PhysRevLett.55.1530)
- Anderson, P. W. (1972). More Is Different. *Science* 177, 393–396. [doi:10.1126/science.177.4047.393](https://doi.org/10.1126/science.177.4047.393)
- Arthur, W. B. (1989). Competing Technologies, Increasing Returns, and Lock-In by Historical Events. *The Economic Journal* 99, 116. [doi:10.2307/2234208](https://doi.org/10.2307/2234208)
- Attwell, D. & Laughlin, S. B. (2001). An Energy Budget for Signaling in the Grey Matter of the Brain. *Journal of Cerebral Blood Flow & Metabolism* 21, 1133–1145. [doi:10.1097/00004647-200110000-00001](https://doi.org/10.1097/00004647-200110000-00001)
- Bak, P. et al. (1987). Self-organized criticality: An explanation of the 1/f noise. *Physical Review Letters* 59, 381–384. [doi:10.1103/PhysRevLett.59.381](https://doi.org/10.1103/PhysRevLett.59.381)
- Banavar, J. R. et al. (1999). Size and form in efficient transportation networks. *Nature* 399, 130–132. [doi:10.1038/20144](https://doi.org/10.1038/20144)
- Bar-On, Y. M. et al. (2018). The biomass distribution on Earth. *Proceedings of the National Academy of Sciences* 115, 6506–6511. [doi:10.1073/pnas.1711842115](https://doi.org/10.1073/pnas.1711842115)
- Barabási, A. L. & Albert, R. (1999). Emergence of Scaling in Random Networks. *Science* 286, 509–512. [doi:10.1126/science.286.5439.509](https://doi.org/10.1126/science.286.5439.509)
- Batty, M. (2008). The Size, Scale, and Shape of Cities. *Science* 319, 769–771. [doi:10.1126/science.1151419](https://doi.org/10.1126/science.1151419)
- Beggs, J. M. & Plenz, D. (2003). Neuronal Avalanches in Neocortical Circuits. *The Journal of Neuroscience* 23, 11167–11177. [doi:10.1523/JNEUROSCI.23-35-11167.2003](https://doi.org/10.1523/JNEUROSCI.23-35-11167.2003)
- Bejan, A. & Lorente, S. (2010). The constructal law of design and evolution in nature. *Philosophical Transactions of the Royal Society B: Biological Sciences* 365, 1335–1347. [doi:10.1098/rstb.2009.0302](https://doi.org/10.1098/rstb.2009.0302)
- Bertalanffy, L. V. (1950). An outline of general system theory. *The British Journal for the Philosophy of Science* 1, 134–165. [doi:10.1093/bjps/1.2.134](https://doi.org/10.1093/bjps/1.2.134)
- Bettencourt, L. M. A. et al. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences* 104, 7301–7306. [doi:10.1073/pnas.0610172104](https://doi.org/10.1073/pnas.0610172104)
- Bettencourt, L. M. A. (2013). The Origins of Scaling in Cities. *Science* 340, 1438–1441. [doi:10.1126/science.1235823](https://doi.org/10.1126/science.1235823)
- Blount, Z. D. et al. (2008). Historical contingency and the evolution of a key innovation in an experimental population of *Escherichia coli*. *Proceedings of the National Academy of Sciences* 105, 7899–7906. [doi:10.1073/pnas.0803151105](https://doi.org/10.1073/pnas.0803151105)
- Blount, Z. D. et al. (2018). Contingency and determinism in evolution: Replaying life's tape. *Science* 362, eaam5979. [doi:10.1126/science.aam5979](https://doi.org/10.1126/science.aam5979)
- Boers, N. (2021). Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. *Nature Climate Change* 11, 680–688. [doi:10.1038/s41558-021-01097-4](https://doi.org/10.1038/s41558-021-01097-4)
- Bond, J. R. et al. (1996). How filaments of galaxies are woven into the cosmic web. *Nature* 380, 603–606. [doi:10.1038/380603a0](https://doi.org/10.1038/380603a0)
- Boyd, R. et al. (2011). The cultural niche: Why social learning is essential for human adaptation. *Proceedings of the National Academy of Sciences* 108, 10918–10925. [doi:10.1073/pnas.1100290108](https://doi.org/10.1073/pnas.1100290108)
- Broido, A. D. & Clauset, A. (2019). Scale-free networks are rare. *Nature Communications* 10, 1017. [doi:10.1038/s41467-019-08746-5](https://doi.org/10.1038/s41467-019-08746-5)
- Brown, J. H. et al. (2004). Toward a metabolic theory of ecology. *Ecology* 85, 1771–1789. [doi:10.1890/03-9000](https://doi.org/10.1890/03-9000)

- Buldyrev, S. V. et al. (2010). Catastrophic cascade of failures in interdependent networks. *Nature* 464, 1025-1028. [doi:10.1038/nature08932](https://doi.org/10.1038/nature08932)
- Bullmore, E. & Sporns, O. (2009). Complex brain networks: graph theoretical analysis of structural and functional systems. *Nature Reviews Neuroscience* 10, 186-198. [doi:10.1038/nrn2575](https://doi.org/10.1038/nrn2575)
- Bullmore, E. & Sporns, O. (2012). The economy of brain network organization. *Nature Reviews Neuroscience* 13, 336-349. [doi:10.1038/nrn3214](https://doi.org/10.1038/nrn3214)
- Bérut, A. et al. (2012). Experimental verification of Landauer's principle linking information and thermodynamics. *Nature* 483, 187-189. [doi:10.1038/nature10872](https://doi.org/10.1038/nature10872)
- Centola, D. & Macy, M. (2007). Complex Contagions and the Weakness of Long Ties. *American Journal of Sociology* 113, 702-734. [doi:10.1086/521848](https://doi.org/10.1086/521848)
- Chaisson, E. J. (2011). Energy rate density as a complexity metric and evolutionary driver. *Complexity* 16, 27-40. [doi:10.1002/cplx.20323](https://doi.org/10.1002/cplx.20323)
- Clauset, A. et al. (2009). Power-Law Distributions in Empirical Data. *SIAM Review* 51, 661-703. [doi:10.1137/070710111](https://doi.org/10.1137/070710111)
- Clune, J. et al. (2013). The evolutionary origins of modularity. *Proceedings of the Royal Society B: Biological Sciences* 280, 20122863. [doi:10.1098/rspb.2012.2863](https://doi.org/10.1098/rspb.2012.2863)
- Comin, D. & Hobbijn, B. (2010). An Exploration of Technology Diffusion. *American Economic Review* 100, 2031-2059. [doi:10.1257/aer.100.5.2031](https://doi.org/10.1257/aer.100.5.2031)
- Couzin, I. D. et al. (2005). Effective leadership and decision-making in animal groups on the move. *Nature* 433, 513-516. [doi:10.1038/nature03236](https://doi.org/10.1038/nature03236)
- Crutchfield, J. P. & Young, K. (1989). Inferring statistical complexity. *Physical Review Letters* 63, 105-108. [doi:10.1103/PhysRevLett.63.105](https://doi.org/10.1103/PhysRevLett.63.105)
- Crutchfield, J. P. (2012). Between order and chaos. *Nature Physics* 8, 17-24. [doi:10.1038/nphys2190](https://doi.org/10.1038/nphys2190)
- Dakos, V. et al. (2008). Slowing down as an early warning signal for abrupt climate change. *Proceedings of the National Academy of Sciences* 105, 14308-14312. [doi:10.1073/pnas.0802430105](https://doi.org/10.1073/pnas.0802430105)
- Dalin, C. et al. (2012). Evolution of the global virtual water trade network. *Proceedings of the National Academy of Sciences* 109, 5989-5994. [doi:10.1073/pnas.1203176109](https://doi.org/10.1073/pnas.1203176109)
- Davies, J. H. & Davies, D. R. (2010). Earth's surface heat flux. *Solid Earth* 1, 5-24. [doi:10.5194/se-1-5-2010](https://doi.org/10.5194/se-1-5-2010)
- DeLong, J. P. et al. (2010). Shifts in metabolic scaling, production, and efficiency across major evolutionary transitions of life. *Proceedings of the National Academy of Sciences* 107, 12941-12945. [doi:10.1073/pnas.1007783107](https://doi.org/10.1073/pnas.1007783107)
- Deutsch, D. & Marletto, C. (2015). Constructor theory of information. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences* 471, 20140540. [doi:10.1098/rspa.2014.0540](https://doi.org/10.1098/rspa.2014.0540)
- Dodds, P. et al. (2001). Re-examination of the "3/4-law" of Metabolism. *Journal of Theoretical Biology* 209, 9-27. [doi:10.1006/jtbi.2000.2238](https://doi.org/10.1006/jtbi.2000.2238)
- Dunne, J. A. et al. (2002). Food-web structure and network theory: The role of connectance and size. *Proceedings of the National Academy of Sciences* 99, 12917-12922. [doi:10.1073/pnas.192407699](https://doi.org/10.1073/pnas.192407699)
- Egan, C. A. & Lineweaver, C. H. (2010). A larger estimate of the entropy of the universe. *The Astrophysical Journal* 710, 1825-1834. [doi:10.1088/0004-637X/710/2/1825](https://doi.org/10.1088/0004-637X/710/2/1825)
- Elhacham, E. et al. (2020). Global human-made mass exceeds all living biomass. *Nature* 588, 442-444. [doi:10.1038/s41586-020-3010-5](https://doi.org/10.1038/s41586-020-3010-5)
- England, J. L. (2013). Statistical physics of self-replication. *The Journal of Chemical Physics* 139, 121923. [doi:10.1063/1.4818538](https://doi.org/10.1063/1.4818538)
- Fisher, J. & Pry, R. (1971). A simple substitution model of technological change. *Technological Forecasting and Social Change* 3, 75-88. [doi:10.1016/S0040-1625\(71\)80005-7](https://doi.org/10.1016/S0040-1625(71)80005-7)
- Fodor, J. A. (1974). Special sciences (or: The disunity of science as a working hypothesis). *Synthese* 28, 97-115. [doi:10.1007/BF00485230](https://doi.org/10.1007/BF00485230)
- Frank, S. A. (2009). The common patterns of nature. *Journal of Evolutionary Biology* 22, 1563-1585. [doi:10.1111/j.1420-9101.2009.01775.x](https://doi.org/10.1111/j.1420-9101.2009.01775.x)
- Friston, K. (2010). The free-energy principle: a unified brain theory? *Nature Reviews Neuroscience* 11, 127-138. [doi:10.1038/nrn2787](https://doi.org/10.1038/nrn2787)
- Gabaix, X. (1999). Zipf's Law for Cities: An Explanation. *The Quarterly Journal of Economics* 114, 739-767. [doi:10.1162/003355399556133](https://doi.org/10.1162/003355399556133)
- Gao, J. et al. (2016). Universal resilience patterns in complex networks. *Nature* 530, 307-312. [doi:10.1038/nature16948](https://doi.org/10.1038/nature16948)

- Garrett, T. J. (2011). Are there basic physical constraints on future anthropogenic emissions of carbon dioxide? *Climatic Change* 104, 437-455. [doi:10.1007/s10584-009-9717-9](https://doi.org/10.1007/s10584-009-9717-9)
- Gerhart, J. & Kirschner, M. (2007). The theory of facilitated variation. *Proceedings of the National Academy of Sciences* 104, 8582-8589. [doi:10.1073/pnas.0701035104](https://doi.org/10.1073/pnas.0701035104)
- Goldenfeld, N. & Kadanoff, L. P. (1999). Simple Lessons from Complexity. *Science* 284, 87-89. [doi:10.1126/science.284.5411.87](https://doi.org/10.1126/science.284.5411.87)
- Gould, S. J. & Lewontin, R. C. (1979). The spandrels of San Marco and the Panglossian paradigm: a critique of the adaptationist programme. *Proceedings of the Royal Society of London. Series B. Biological Sciences* 205, 581-598. [doi:10.1098/rspb.1979.0086](https://doi.org/10.1098/rspb.1979.0086)
- Griliches, Z. (1957). Hybrid Corn: An Exploration in the Economics of Technological Change. *Econometrica* 25, 501. [doi:10.2307/1905380](https://doi.org/10.2307/1905380)
- Haff, P. K. (2014). Technology as a geological phenomenon: implications for human well-being. *Geological Society, London, Special Publications* 395, 301-309. [doi:10.1144/SP395.4](https://doi.org/10.1144/SP395.4)
- Haken, H. (1975). Cooperative phenomena in systems far from thermal equilibrium and in nonphysical systems. *Reviews of Modern Physics* 47, 67-121. [doi:10.1103/RevModPhys.47.67](https://doi.org/10.1103/RevModPhys.47.67)
- Haldane, A. G. & May, R. M. (2011). Systemic risk in banking ecosystems. *Nature* 469, 351-355. [doi:10.1038/nature09659](https://doi.org/10.1038/nature09659)
- Hartwell, L. H. et al. (1999). From molecular to modular cell biology. *Nature* 402, C47-C52. [doi:10.1038/35011540](https://doi.org/10.1038/35011540)
- Hatton, I. A. et al. (2019). Linking scaling laws across eukaryotes. *Proceedings of the National Academy of Sciences* 116, 21616-21622. [doi:10.1073/pnas.1900492116](https://doi.org/10.1073/pnas.1900492116)
- Hazen, R. M. et al. (2008). Mineral evolution. *American Mineralogist* 93, 1693-1720. [doi:10.2138/am.2008.2955](https://doi.org/10.2138/am.2008.2955)
- Helbing, D. (2013). Globally networked risks and how to respond. *Nature* 497, 51-59. [doi:10.1038/nature12047](https://doi.org/10.1038/nature12047)
- Herculano-Houzel, S. (2009). The human brain in numbers: a linearly scaled-up primate brain. *Frontiers in Human Neuroscience* 3. [doi:10.3389/neuro.09.031.2009](https://doi.org/10.3389/neuro.09.031.2009)
- Hidalgo, C. A. et al. (2007). The Product Space Conditions the Development of Nations. *Science* 317, 482-487. [doi:10.1126/science.1144581](https://doi.org/10.1126/science.1144581)
- Hidalgo, C. A. & Hausmann, R. (2009). The building blocks of economic complexity. *Proceedings of the National Academy of Sciences* 106, 10570-10575. [doi:10.1073/pnas.0900943106](https://doi.org/10.1073/pnas.0900943106)
- Hidalgo, J. et al. (2014). Information-based fitness and the emergence of criticality in living systems. *Proceedings of the National Academy of Sciences* 111, 10095-10100. [doi:10.1073/pnas.1319166111](https://doi.org/10.1073/pnas.1319166111)
- Hoel, E. P. et al. (2013). Quantifying causal emergence shows that macro can beat micro. *Proceedings of the National Academy of Sciences* 110, 19790-19795. [doi:10.1073/pnas.1314922110](https://doi.org/10.1073/pnas.1314922110)
- Holling, C. S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics* 4, 1-23. [doi:10.1146/annurev.es.04.110173.000245](https://doi.org/10.1146/annurev.es.04.110173.000245)
- Holling, C. S. (2001). Understanding the Complexity of Economic, Ecological, and Social Systems. *Ecosystems* 4, 390-405. [doi:10.1007/s10021-001-0101-5](https://doi.org/10.1007/s10021-001-0101-5)
- Homer-Dixon, T. et al. (2015). Synchronous failure: the emerging causal architecture of global crisis. *Ecology and Society* 20, art6. [doi:10.5751/ES-07681-200306](https://doi.org/10.5751/ES-07681-200306)
- Hopfield, J. J. (1982). Neural networks and physical systems with emergent collective computational abilities. *Proceedings of the National Academy of Sciences* 79, 2554-2558. [doi:10.1073/pnas.79.8.2554](https://doi.org/10.1073/pnas.79.8.2554)
- Ives, A. R. & Carpenter, S. R. (2007). Stability and Diversity of Ecosystems. *Science* 317, 58-62. [doi:10.1126/science.1133258](https://doi.org/10.1126/science.1133258)
- Jaynes, E. T. (1957). Information Theory and Statistical Mechanics. *Physical Review* 106, 620-630. [doi:10.1103/PhysRev.106.620](https://doi.org/10.1103/PhysRev.106.620)
- Jeans, J. H. (1902). I. The stability of a spherical nebula. *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character* 199, 1-53. [doi:10.1098/rsta.1902.0012](https://doi.org/10.1098/rsta.1902.0012)
- Jumper, J. et al. (2021). Highly accurate protein structure prediction with AlphaFold. *Nature* 596, 583-589. [doi:10.1038/s41586-021-03819-2](https://doi.org/10.1038/s41586-021-03819-2)
- Kashtan, N. & Alon, U. (2005). Spontaneous evolution of modularity and network motifs. *Proceedings of the National Academy of Sciences* 102, 13773-13778. [doi:10.1073/pnas.0503610102](https://doi.org/10.1073/pnas.0503610102)
- Kemp, L. et al. (2022). Climate Endgame: Exploring catastrophic climate change scenarios. *Proceedings of the National Academy of Sciences* 119, e2108146119. [doi:10.1073/pnas.2108146119](https://doi.org/10.1073/pnas.2108146119)
- Kirschner, J. W. (2003). The Gaia Hypothesis: Conjectures and Refutations. *Climatic Change* 58, 21-45. [doi:10.1023/A:1023494111532](https://doi.org/10.1023/A:1023494111532)

- Kitcher, P. (1981). Explanatory Unification. *Philosophy of Science* 48, 507-531. [doi:10.1086/289019](https://doi.org/10.1086/289019)
- Kleiber, M. (1932). Body size and metabolism. *Hilgardia* 6, 315-353. [doi:10.3733/hilg.v06n11p315](https://doi.org/10.3733/hilg.v06n11p315)
- Kleidon, A. (2010). Life, hierarchy, and the thermodynamic machinery of planet Earth. *Physics of Life Reviews* 7, 424-460. [doi:10.1016/j.plev.2010.10.002](https://doi.org/10.1016/j.plev.2010.10.002)
- Kolchinsky, A. & Wolpert, D. H. (2018). Semantic information, autonomous agency and non-equilibrium statistical physics. *Interface Focus* 8, 20180041. [doi:10.1098/rsfs.2018.0041](https://doi.org/10.1098/rsfs.2018.0041)
- Kolokotronis, T. et al. (2010). Curvature in metabolic scaling. *Nature* 464, 753-756. [doi:10.1038/nature08920](https://doi.org/10.1038/nature08920)
- Kéfi, S. et al. (2007). Spatial vegetation patterns and imminent desertification in Mediterranean arid ecosystems. *Nature* 449, 213-217. [doi:10.1038/nature06111](https://doi.org/10.1038/nature06111)
- Landauer, R. (1961). Irreversibility and Heat Generation in the Computing Process. *IBM Journal of Research and Development* 5, 183-191. [doi:10.1147/rd.53.0183](https://doi.org/10.1147/rd.53.0183)
- Lane, N. & Martin, W. (2010). The energetics of genome complexity. *Nature* 467, 929-934. [doi:10.1038/nature09486](https://doi.org/10.1038/nature09486)
- Laughlin, S. B. & Sejnowski, T. J. (2003). Communication in Neuronal Networks. *Science* 301, 1870-1874. [doi:10.1126/science.1089662](https://doi.org/10.1126/science.1089662)
- LeCun, Y. et al. (2015). Deep learning. *Nature* 521, 436-444. [doi:10.1038/nature14539](https://doi.org/10.1038/nature14539)
- Lenton, T. M. et al. (2008). Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences* 105, 1786-1793. [doi:10.1073/pnas.0705414105](https://doi.org/10.1073/pnas.0705414105)
- Lenton, T. M. et al. (2018). Selection for Gaia across Multiple Scales. *Trends in Ecology & Evolution* 33, 633-645. [doi:10.1016/j.tree.2018.05.006](https://doi.org/10.1016/j.tree.2018.05.006)
- Lenton, T. M. & Latour, B. (2018). Gaia 2.0. *Science* 361, 1066-1068. [doi:10.1126/science.aau0427](https://doi.org/10.1126/science.aau0427)
- Lineweaver, C. H. & Egan, C. A. (2008). Life, gravity and the second law of thermodynamics. *Physics of Life Reviews* 5, 225-242. [doi:10.1016/j.plev.2008.08.002](https://doi.org/10.1016/j.plev.2008.08.002)
- Lotka, A. J. (1922). Contribution to the Energetics of Evolution. *Proceedings of the National Academy of Sciences* 8, 147-151. [doi:10.1073/pnas.8.6.147](https://doi.org/10.1073/pnas.8.6.147)
- Lyons, T. W. et al. (2014). The rise of oxygen in Earth's early ocean and atmosphere. *Nature* 506, 307-315. [doi:10.1038/nature13068](https://doi.org/10.1038/nature13068)
- López-Ruiz, R. et al. (1995). A statistical measure of complexity. *Physics Letters A* 209, 321-326. [doi:10.1016/0375-9601\(95\)00867-5](https://doi.org/10.1016/0375-9601(95)00867-5)
- Machta, B. B. et al. (2013). Parameter Space Compression Underlies Emergent Theories and Predictive Models. *Science* 342, 604-607. [doi:10.1126/science.1238723](https://doi.org/10.1126/science.1238723)
- Martyushev, L. & Seleznev, V. (2006). Maximum entropy production principle in physics, chemistry and biology. *Physics Reports* 426, 1-45. [doi:10.1016/j.physrep.2005.12.001](https://doi.org/10.1016/j.physrep.2005.12.001)
- May, R. M. (1972). Will a Large Complex System be Stable? *Nature* 238, 413-414. [doi:10.1038/238413a0](https://doi.org/10.1038/238413a0)
- May, R. M. (1976). Simple mathematical models with very complicated dynamics. *Nature* 261, 459-467. [doi:10.1038/261459a0](https://doi.org/10.1038/261459a0)
- May, R. M. et al. (2008). Ecology for bankers. *Nature* 451, 893-894. [doi:10.1038/451893a](https://doi.org/10.1038/451893a)
- McCann, K. S. (2000). The diversity–stability debate. *Nature* 405, 228-233. [doi:10.1038/35012234](https://doi.org/10.1038/35012234)
- Milo, R. et al. (2002). Network Motifs: Simple Building Blocks of Complex Networks. *Science* 298, 824-827. [doi:10.1126/science.298.5594.824](https://doi.org/10.1126/science.298.5594.824)
- Mitzenmacher, M. (2004). A Brief History of Generative Models for Power Law and Lognormal Distributions. *Internet Mathematics* 1, 226-251. [doi:10.1080/15427951.2004.10129088](https://doi.org/10.1080/15427951.2004.10129088)
- Mora, T. & Bialek, W. (2011). Are Biological Systems Poised at Criticality? *Journal of Statistical Physics* 144, 268-302. [doi:10.1007/s10955-011-0229-4](https://doi.org/10.1007/s10955-011-0229-4)
- Murray, C. D. (1926). The Physiological Principle of Minimum Work. *Proceedings of the National Academy of Sciences* 12, 207-214. [doi:10.1073/pnas.12.3.207](https://doi.org/10.1073/pnas.12.3.207)
- Nagy, B. et al. (2013). Statistical Basis for Predicting Technological Progress. *PLoS ONE* 8, e52669. [doi:10.1371/journal.pone.0052669](https://doi.org/10.1371/journal.pone.0052669)
- Newman, M. E. J. (2003). The Structure and Function of Complex Networks. *SIAM Review* 45, 167-256. [doi:10.1137/S003614450342480](https://doi.org/10.1137/S003614450342480)
- Newman, M. (2005). Power laws, Pareto distributions and Zipf's law. *Contemporary Physics* 46, 323-351. [doi:10.1080/00107510500052444](https://doi.org/10.1080/00107510500052444)

- Newman, M. E. J. (2006). Modularity and community structure in networks. *Proceedings of the National Academy of Sciences* 103, 8577-8582. [doi:10.1073/pnas.0601602103](https://doi.org/10.1073/pnas.0601602103)
- Odum, E. P. (1969). The Strategy of Ecosystem Development. *Science* 164, 262-270. [doi:10.1126/science.164.3877.262](https://doi.org/10.1126/science.164.3877.262)
- Ostrom, E. (2009). A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science* 325, 419-422. [doi:10.1126/science.1172133](https://doi.org/10.1126/science.1172133)
- Parrondo, J. M. R. et al. (2015). Thermodynamics of information. *Nature Physics* 11, 131-139. [doi:10.1038/nphys3230](https://doi.org/10.1038/nphys3230)
- Pastor-Satorras, R. & Vespignani, A. (2001). Epidemic Spreading in Scale-Free Networks. *Physical Review Letters* 86, 3200-3203. [doi:10.1103/PhysRevLett.86.3200](https://doi.org/10.1103/PhysRevLett.86.3200)
- Planck Collaboration et al. (2020). Planck 2018 results. VI. Cosmological parameters. *Astronomy & Astrophysics* 641, A6. [doi:10.1051/0004-6361/201833910](https://doi.org/10.1051/0004-6361/201833910)
- Prigogine, I. (1978). Time, Structure, and Fluctuations. *Science* 201, 777-785. [doi:10.1126/science.201.4358.777](https://doi.org/10.1126/science.201.4358.777)
- Richardson, K. et al. (2023). Earth beyond six of nine planetary boundaries. *Science Advances* 9, eadh2458. [doi:10.1126/sciadv.adh2458](https://doi.org/10.1126/sciadv.adh2458)
- Rietkerk, M. et al. (2004). Self-Organized Patchiness and Catastrophic Shifts in Ecosystems. *Science* 305, 1926-1929. [doi:10.1126/science.1101867](https://doi.org/10.1126/science.1101867)
- Rockström, J. et al. (2009). A safe operating space for humanity. *Nature* 461, 472-475. [doi:10.1038/461472a](https://doi.org/10.1038/461472a)
- Rosas, F. E. et al. (2020). Reconciling emergences: An information-theoretic approach to identify causal emergence in multivariate data. *PLOS Computational Biology* 16, e1008289. [doi:10.1371/journal.pcbi.1008289](https://doi.org/10.1371/journal.pcbi.1008289)
- Savage, V. M. et al. (2004). The predominance of quarter-power scaling in biology. *Functional Ecology* 18, 257-282. [doi:10.1111/j.0269-8463.2004.00856.x](https://doi.org/10.1111/j.0269-8463.2004.00856.x)
- Scheffer, M. et al. (2001). Catastrophic shifts in ecosystems. *Nature* 413, 591-596. [doi:10.1038/35098000](https://doi.org/10.1038/35098000)
- Scheffer, M. et al. (2009). Early-warning signals for critical transitions. *Nature* 461, 53-59. [doi:10.1038/nature08227](https://doi.org/10.1038/nature08227)
- Scheffer, M. et al. (2012). Anticipating Critical Transitions. *Science* 338, 344-348. [doi:10.1126/science.1225244](https://doi.org/10.1126/science.1225244)
- Schläpfer, M. et al. (2014). The scaling of human interactions with city size. *Journal of The Royal Society Interface* 11, 20130789. [doi:10.1098/rsif.2013.0789](https://doi.org/10.1098/rsif.2013.0789)
- Schneider, E. & Kay, J. (1994). Life as a manifestation of the second law of thermodynamics. *Mathematical and Computer Modelling* 19, 25-48. [doi:10.1016/0895-7177\(94\)90188-0](https://doi.org/10.1016/0895-7177(94)90188-0)
- Seifert, U. (2012). Stochastic thermodynamics, fluctuation theorems and molecular machines. *Reports on Progress in Physics* 75, 126001. [doi:10.1088/0034-4885/75/12/126001](https://doi.org/10.1088/0034-4885/75/12/126001)
- Shannon, C. E. (1948). A Mathematical Theory of Communication. *Bell System Technical Journal* 27, 379-423. [doi:10.1002/j.1538-7305.1948.tb01338.x](https://doi.org/10.1002/j.1538-7305.1948.tb01338.x)
- Sharma, A. et al. (2023). Assembly theory explains and quantifies selection and evolution. *Nature* 622, 321-328. [doi:10.1038/s41586-023-06600-9](https://doi.org/10.1038/s41586-023-06600-9)
- Simon, H. A. (1955). On a class of skew distribution functions. *Biometrika* 42, 425-440. [doi:10.1093/biomet/42.3-4.425](https://doi.org/10.1093/biomet/42.3-4.425)
- Springel, V. et al. (2005). Simulations of the formation, evolution and clustering of galaxies and quasars. *Nature* 435, 629-636. [doi:10.1038/nature03597](https://doi.org/10.1038/nature03597)
- Steffen, W. et al. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science* 347, 1259855. [doi:10.1126/science.1259855](https://doi.org/10.1126/science.1259855)
- Steffen, W. et al. (2015). The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review* 2, 81-98. [doi:10.1177/2053019614564785](https://doi.org/10.1177/2053019614564785)
- Stumpf, M. P. H. & Porter, M. A. (2012). Critical Truths About Power Laws. *Science* 335, 665-666. [doi:10.1126/science.1216142](https://doi.org/10.1126/science.1216142)
- Szathmáry, E. & Smith, J. M. (1995). The major evolutionary transitions. *Nature* 374, 227-232. [doi:10.1038/374227a0](https://doi.org/10.1038/374227a0)
- Szathmáry, E. (2015). Toward major evolutionary transitions theory 2.0. *Proceedings of the National Academy of Sciences* 112, 10104-10111. [doi:10.1073/pnas.1421398112](https://doi.org/10.1073/pnas.1421398112)
- Tainter, J. A. (2006). Archaeology of Overshoot and Collapse. *Annual Review of Anthropology* 35, 59-74. [doi:10.1146/annurev.anthro.35.081705.123136](https://doi.org/10.1146/annurev.anthro.35.081705.123136)
- Tegmark, M. (2008). The Mathematical Universe. *Foundations of Physics* 38, 101-150. [doi:10.1007/s10701-007-9186-9](https://doi.org/10.1007/s10701-007-9186-9)
- Turchin, P. et al. (2018). Quantitative historical analysis uncovers a single dimension of complexity that structures global variation in human social organization. *Proceedings of the National Academy of Sciences* 115. [doi:10.1073/pnas.1708800115](https://doi.org/10.1073/pnas.1708800115)

- Turing, A. M. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* 237, 37-72. [doi:10.1098/rstb.1952.0012](https://doi.org/10.1098/rstb.1952.0012)
- Vicsek, T. et al. (1995). Novel Type of Phase Transition in a System of Self-Driven Particles. *Physical Review Letters* 75, 1226-1229. [doi:10.1103/PhysRevLett.75.1226](https://doi.org/10.1103/PhysRevLett.75.1226)
- Wagner, G. P. & Altenberg, L. (1996). Perspective: complex adaptations and the evolution of evolvability. *Evolution* 50, 967-976. [doi:10.1111/j.1558-5646.1996.tb02339.x](https://doi.org/10.1111/j.1558-5646.1996.tb02339.x)
- Walker, J. C. G. et al. (1981). A negative feedback mechanism for the long-term stabilization of Earth's surface temperature. *Journal of Geophysical Research: Oceans* 86, 9776-9782. [doi:10.1029/JC086iC10p09776](https://doi.org/10.1029/JC086iC10p09776)
- Watson, A. J. & Lovelock, J. E. (1983). Biological homeostasis of the global environment: the parable of Daisyworld. *Tellus B* 35B, 284-289. [doi:10.1111/j.1600-0889.1983.tb00031.x](https://doi.org/10.1111/j.1600-0889.1983.tb00031.x)
- Watts, D. J. & Strogatz, S. H. (1998). Collective dynamics of 'small-world' networks. *Nature* 393, 440-442. [doi:10.1038/30918](https://doi.org/10.1038/30918)
- Way, R. et al. (2022). Empirically grounded technology forecasts and the energy transition. *Joule* 6, 2057-2082. [doi:10.1016/j.joule.2022.08.009](https://doi.org/10.1016/j.joule.2022.08.009)
- West, G. B. et al. (1997). A General Model for the Origin of Allometric Scaling Laws in Biology. *Science* 276, 122-126. [doi:10.1126/science.276.5309.122](https://doi.org/10.1126/science.276.5309.122)
- Wilson, K. G. (1975). The renormalization group: Critical phenomena and the Kondo problem. *Reviews of Modern Physics* 47, 773-840. [doi:10.1103/RevModPhys.47.773](https://doi.org/10.1103/RevModPhys.47.773)
- Witten, T. A. & Sander, L. M. (1981). Diffusion-Limited Aggregation, a Kinetic Critical Phenomenon. *Physical Review Letters* 47, 1400-1403. [doi:10.1103/PhysRevLett.47.1400](https://doi.org/10.1103/PhysRevLett.47.1400)
- Wong, M. L. et al. (2023). On the roles of function and selection in evolving systems. *Proceedings of the National Academy of Sciences* 120, e2310223120. [doi:10.1073/pnas.2310223120](https://doi.org/10.1073/pnas.2310223120)
- Wright, T. P. (1936). Factors Affecting the Cost of Airplanes. *Journal of the Aeronautical Sciences* 3, 122-128. [doi:10.2514/8.155](https://doi.org/10.2514/8.155)