

H HEURISTICS

RESEARCH REPORT · OCTOBER 2026

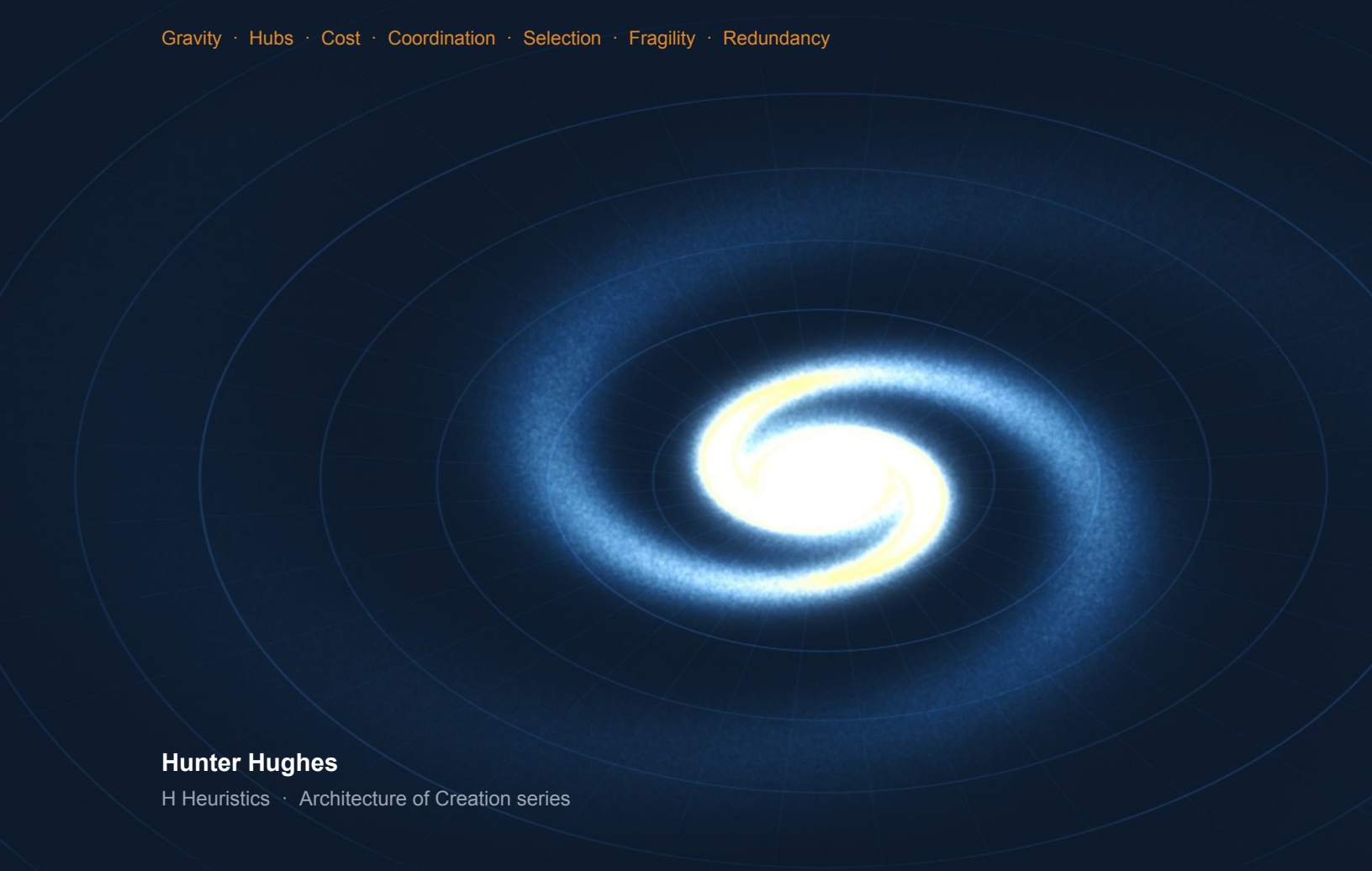
The Architecture of Centrality

Why Creation, Nature, and Human Systems
Repeatedly Organize Around One

Gravity · Hubs · Cost · Coordination · Selection · Fragility · Redundancy

Hunter Hughes

H Heuristics · Architecture of Creation series



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About This Report

This report asks why so many systems, from atoms and planetary systems to cities, brains, networks and states, organize around a single dominant center, and whether that recurring pattern reflects a shared architecture or a shared illusion. It belongs to the H Heuristics [Architecture of Creation](#) series. The foundational report argued that reality produces recurring forms because matter, energy, information and development operate within a constrained set of physical and mathematical relationships. Later reports applied that model to the cosmos in [The Architecture of Creation in the Universe](#), to biology in [The Architecture of Life](#), to a coupled planet in [The Architecture of Earth](#), to thermodynamics in [The Architecture of Entropy](#) and to human societies in [The Architecture of Civilization](#). [The Mathematical Architecture of Reality](#) asked why mathematics describes the world at all, [The Architecture of Fractals](#) examined self-similarity across scales, and [A Unified Architecture of Reality](#) compared every domain.

Centers appeared in almost all of those reports: stars at the middle of planetary systems, nuclei in cells, hubs in networks, primate cities in urban systems, capitals in states. None of them examined centrality in its own right. This report does. It matters because centrality raises two questions at once. The first is scientific: do very different systems share a small set of processes that generate centers? The second is practical: centers make systems efficient and fragile at the same time, and the world is currently building more of them in finance, computing, logistics and energy than at any time in history. If the pattern is understood, it can be designed with; if it is only an artefact of how people look at systems, much current thinking about concentration and resilience rests on sand.

The objective is therefore not to claim that everything revolves around one thing. It is to investigate where centers appear, what generates them, why they persist, what they cost, and where the pattern fails. The report is written for researchers, students and general readers. It assumes no mathematics beyond logarithms, and every calculation is explained in words.

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 3 set out the question, define what a center is and is not, and build a framework: five generators of centers and a ladder for grading claims. Sections 4 to 7 survey four domains: the physical world, life, cities and networks, and mind and power. Sections 8 to 11 ask why centers form, why they persist, what they cost and where the pattern breaks. Sections 12 to 14 test the central hypothesis with nine original calculations, state ten testable propositions, draw out implications and give a verdict.

FOUNDATIONS

**1. Introduction**

The pattern, the question and what is not claimed

Section 1

**2. Defining Centrality**

Four meanings, one word, and the literature

Section 2

**3. The Theoretical Framework**

Five generators of centers and a ladder of claims

Section 3

WHERE CENTERS APPEAR

**4. The Physical World**

Atoms, stars, galaxies, Earth and the universe

Section 4

**5. Life**

Nuclei, pacemakers, brains, hubs and keystones

Section 5

**6. Cities, Economies and Networks**

Primate cities, airline hubs and firms

Section 6

**7. Mind, Culture and Power**

Attention, sacred centers, capitals and rulers

Section 7

EXPLANATION

**8. Hubs Without Designers**

Growth, cumulative advantage and attack

Section 8

**9. Why Centers Persist**

The cost of distance and the value of one clock

Section 9

**10. The Price of One**

Fragility, capture and cascading failure

Section 10

**11. Where Centrality Fails**

Counterexamples, statistics and polycentric order

Section 11

TESTS AND VERDICT

**12. Testing the Hypothesis**

Nine calculations and a scorecard

Section 12

**13. Hypotheses and Implications**

Ten propositions and what follows from them

Section 13

**14. Conclusion**

An architecture of centers, not a law of one

Section 14

Figure 1. The structure of the report. Three foundational sections establish the question and framework, four survey the domains where centers appear, four explain, price and bound the pattern, and three test the hypothesis and draw conclusions.

Source: *H Heuristics*.

Blue underlined text is a hyperlink. Where a specific result is cited, links go to the DOI record of the primary literature. Where a concept is introduced, links go to a reference article, usually Wikipedia, and for datasets and incident reports to the publisher or official source. Every DOI was checked against its registered title before publication, and a full reference list follows Section 14.

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	Example from this report
A: Established	Proven mathematically, observed directly, or confirmed repeatedly by independent measurements.	The Sun holds 99.86% of the mass of the Solar System; the universe shows no center above the scale of homogeneity
B: Well supported	Strong evidence from several lines of work, with unresolved detail or some dissent.	Growth with cumulative advantage produces hubs; targeted removal of hubs fragments networks much faster than random failure
C: Plausible or contested	A credible argument and partial evidence; specialists actively disagree.	City sizes follow Zipf's law; complex societies need a central authority
D: Speculative	A hypothesis or interpretation offered for evaluation, labeled as such wherever it appears.	Reality as a whole is organized around a single principle or source

The grade describes the state of knowledge, not the importance of a claim. The same system can be graded A for 'has a dominant node' and C for 'has a power-law distribution'; the report grades the specific claim being made.

A note on the figures and calculations

The report contains 15 figures and 10 tables. Nine calculations were made for this report, in Python, using public data where real systems are examined. They collapse a cloud of 1,200 gravitating particles into a cluster; grow networks by preferential attachment and by random wiring and compare their hubs; remove nodes at random and by degree to measure fragility; compare seven network topologies for efficiency and robustness; simulate a trade-off between the cost of distance and the cost of steps that turns a single hub into a web; measure the concentration of the world airport network from the [OpenFlights](#) route data; measure rank-size regularity and primacy in twenty national city systems from [GeoNames](#) populations; compute four centrality measures on a real social network; and tabulate the share of mass held by the center of six systems. Each caption states what was computed, with what assumptions, and every number quoted from the models can be regenerated from the code and data named in Appendix A. The other figures are diagrams drawn for this report.

How to cite

Hughes, H. (2026). *The Architecture of Centrality: Why Creation, Nature, and Human Systems Repeatedly Organize Around One*. H Heuristics Research Report, Architecture of Creation series. The report synthesizes published research and presents original calculations and propositions, which are labeled as such.

Executive Summary

The question. Do creation, nature and human systems repeatedly organize around a single dominant center, and if so, is that a deep architecture or a shared illusion? The report answers in three layers. At the descriptive layer the pattern is real and widespread. At the explanatory layer a small number of processes generate it, and those processes are understood. At the metaphysical layer, the claim that reality as a whole is organized around One, the evidence does not reach, and parts of it point the other way.

Eight findings

1. **Centers are real, common and of different kinds (Grade A).** The word covers at least four things: a position, a concentration of mass or flow, a place in a network, and a locus of control or meaning. These measures do not coincide. On a real 34-person social network, rankings by betweenness and by eigenvector centrality agree with a rank correlation of only 0.69 (Figure 3).
2. **Five generators account for nearly every case (Grade B).** Attraction toward a potential well, cumulative advantage, cost minimization, coordination and selection each produce centers on their own, and often together (Figure 5).
3. **In the physical world, centrality ranges from total to trivial to absent (Grade A).** The proton holds 99.9% of a hydrogen atom's mass and the Sun 99.9% of the Solar System's, Earth's core 32.5% of the planet's, and the Milky Way's central black hole about 0.00033% of the Galaxy's. The universe as a whole shows no center at all (Figure 6). Centrality is a property of subsystems, not of everything.
4. **Most centers are not designed (Grade B).** In the report's model, networks grown by cumulative advantage developed a best-connected node with 212 links, against 13 for random wiring with the same number of links. The best-connected 1% held 11.7% of all link endpoints, against 2.6%. In the real airport network, the busiest 1% of 3,257 airports hold 14.8% of route endpoints (Figure 10, Figure 9).
5. **Centers are cheap in wiring and fast in travel (Grade B).** In a model where each new node trades the cost of distance against the cost of steps from the center, a single hub needed 14 times more total link length than a spanning web but put every node one step from the center instead of 6.4 (Figure 12).
6. **Centers carry a price that grows with their importance (Grade A for networks, B elsewhere).** Removing the best-connected 20% of nodes from the hub-rich model left 1.2% of the network connected; removing 20% at random left 78.4%. Real incidents from the Suez Canal to a single cloud region show the same pattern (Figure 11).
7. **Popular claims about hubs and Zipf laws are weaker than their reputation (Grade A).** A statistical test did not support a pure power law in the tail of the airport network; an exponential and a lognormal fitted better. City-size slopes in twenty countries had a median of 1.36, not 1, and the ratio of largest to second-largest city ran from 1.04 to 13.1 (Figure 8).
8. **The robust form is few and redundant, not one (Grade B).** Systems that last combine a small, interlinked core with a diverse periphery and lateral links: bow-tie architectures in metabolism and the Internet, polycentric governance, degenerate neural circuits. Designs with one irreplaceable center score highest on efficiency and lowest on survival (Figure 13, Figure 14).

The verdict

Centrality is a genuine architecture of processes, not a law of reality. The same few generators operate in galaxies, cells, markets and states, and wherever they operate they produce concentrations of mass, links, flow or authority around a small number of nodes. That is a real discovery about how structure forms, and the report grades it B. But the unity is of mechanisms, not of outcomes. The share of a system held by its center runs across more than five orders of magnitude; city systems range from nearly flat to dominated more than ten to one; the largest scale of the universe has no center; and the networks that survive longest are those that refuse to depend on one node. The stronger claim, that creation as a whole is organized around One, is a philosophical interpretation that these data neither establish nor refute. The report grades it D and treats it as a question for other disciplines.

In one sentence. Centers recur because a few simple processes build them, and they persist because they are efficient, but the systems that endure are those that keep a center without depending on only one.

01

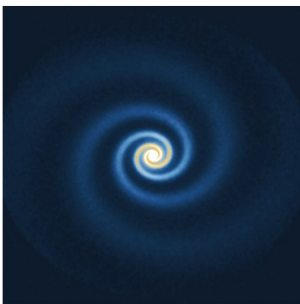
INTRODUCTION

1. Introduction

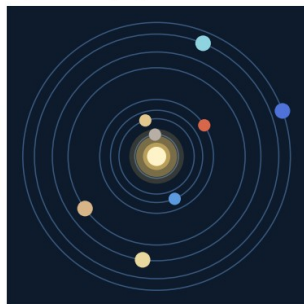
1.1 Four pictures

Look at four images side by side (Figure 2). A spiral galaxy is brightest at its core, and its arms wind inward toward it. A planetary system is a star surrounded by small bodies that carry almost none of its mass. A network drawn from airline routes, or from citations, or from links between web pages, has a few nodes with enormous numbers of connections and a great many with one or two. A city's streets run in rings and radials toward a dense core. They are different objects, made of different materials by different processes, at scales that differ by twenty orders of magnitude. Yet each invites the same description: *there is a middle, and the middle matters more than the rest.*

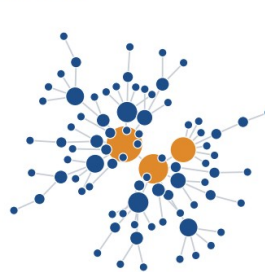
A galaxy



A planetary system



A network



A city

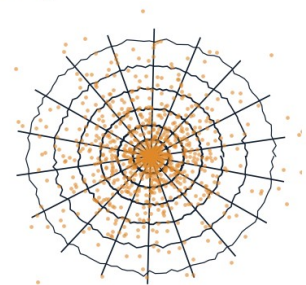


Figure 2. Four systems that invite the same description. From left: a spiral galaxy generated from logarithmic spiral arms around a dense bulge; a planetary system with orbits spaced logarithmically around a central star; a network grown by cumulative advantage, with its best-connected nodes in orange; a city plan with ring roads and radial avenues around a dense core. All four were generated for this report.

Source: H Heuristics calculations. Galaxy: 500,000 stars on two logarithmic spiral arms plus a Gaussian bulge. Planetary system: orbital distances of the eight planets, log-scaled. Network: 85 nodes, preferential attachment with one link per new node. City: concentric rings, radial avenues and a Gaussian density of buildings.

The intuition is old. Humans have organized their astronomy, their cities, their religions and their politics around centers for as long as there are records. What is new is that the sciences now have measurements. Astronomers can weigh the black hole at the middle of the Milky Way. Network scientists can count the links of every airport. Economists can rank every city in a country by population. Neuroscientists can map the hubs of the human brain. The question can finally be asked as a question about evidence rather than as a matter of taste: how often do real systems concentrate around one place, and why?

1.2 The central question

Central question. Why do creation, nature and human systems repeatedly organize around a center, and does that recurrence reveal a shared architecture or a shared illusion?

The question has three layers, and the report treats them separately because the evidence differs at each. The **descriptive layer** asks whether centers are in fact common once they are measured against honest null models. The **explanatory layer** asks whether a small number of processes generate them, so that similar centers in different domains share a cause. The **metaphysical layer** asks whether the recurrence points to something about reality as a whole, a principle or source that things are organized around. The first two are empirical and can be tested. The third is an interpretation, and the report offers it only as one.

1.3 What is not claimed

Centrality is a subject that attracts overreach, so the boundaries are stated plainly. The report does not claim that every system has a center; that centers are good, natural or inevitable; that the universe has a center, which it demonstrably does not; that every heavy-tailed distribution implies a hub; or that the recurrence of centers supports any particular theology or political order. It treats a center as a measurable property of a system at a stated scale, and it counts counterexamples as seriously as examples.

- **A center is always a center of something.** Mass, links, flow, control and meaning are different quantities, and a node can be central in one and peripheral in another.
- **Resemblance is not mechanism.** Two systems that both have hubs may have them for unrelated reasons. The report asks for matched numbers and a shared generating process before it calls two centers the same.
- **Absence matters.** A theory of centrality that cannot explain why the largest scale of the universe, ant colonies and the Internet's routing layer have no single center is not yet a theory.

02

DEFINING CENTRALITY



2. Defining Centrality

2.1 One word, four meanings

In ordinary speech a center is the middle. In science the word does four different jobs, and most confusion about centrality comes from sliding between them (Table 2).

Table 2. Four meanings of *center*, with the question each answers

Meaning	Question it answers	How it is measured	Example
Geometric and dynamical	Where is the middle, and what is drawn toward it?	Center of mass, density peak, potential minimum	The Sun in the Solar System; the density peak of a galaxy cluster
Structural (network)	How well connected or how strategically placed is this node?	Degree, closeness, betweenness, eigenvector centrality, PageRank	Amsterdam Schiphol in the airline network; a protein with many partners
Functional (control)	What happens to the system if this element is removed or silent?	Lesion, knockout, outage and cascade studies	The sinoatrial node of the heart; a keystone species; a payment network
Symbolic (meaning)	What does the system treat as its middle?	Ethnography, history, attention and eye-tracking studies	An axis mundi; a capital city; the central fixation of the eye

The four meanings often coincide, which is why they are confused. They can also come apart: the Milky Way's black hole is geometrically central, dynamically influential and carries a few millionths of the Galaxy's mass.

The structural meaning has the most developed mathematics. [Freeman \(1978\)](#) separated three intuitions that social scientists had been mixing: a node is central if it has many ties (*degree*), if it is close to everyone (*closeness*), or if it lies on the paths between others (*betweenness*). [Bonacich \(1972\)](#) added a recursive version, in which a node is central if it is tied to other central nodes, now called [eigenvector centrality](#), and the idea underlies Google's [PageRank](#). [Borgatti \(2005\)](#) argued that no measure is correct in general: each assumes a particular way that things flow through the network, and applying a measure to the wrong flow gives a confident wrong answer.

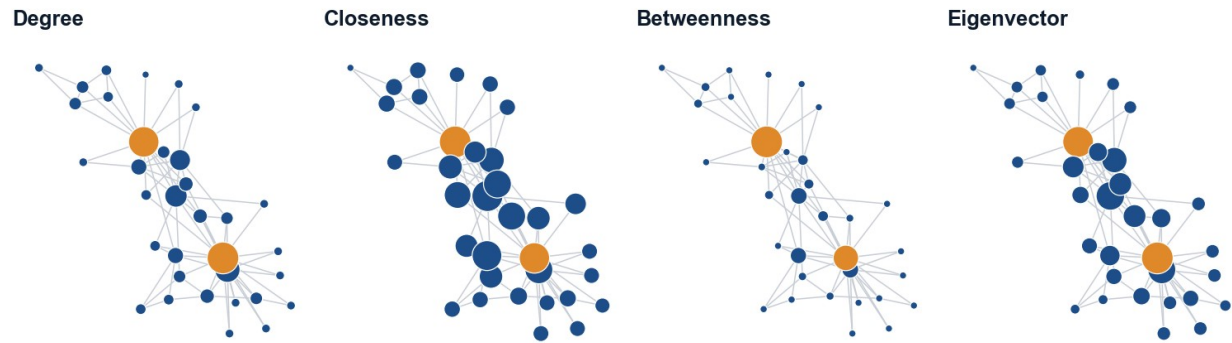


Figure 3. Four measures of centrality on one real network. The network records friendships among 34 members of a university karate club in the 1970s, which later split around two leaders (orange). Node size shows each measure. The two leaders rank highest on every measure, but the ordering of everyone else changes, and the measures agree only partly (rank correlations from 0.69 to 0.90).

Source: [Zachary \(1977\)](#), network of 34 nodes and 78 ties; H Heuristics calculations with NetworkX. Spearman rank correlations between measures computed over all 34 nodes.

Figure 3 makes the point on a network small enough to see. Everyone agrees that the club's two leaders are central. Few agree on who comes next. One member with only three ties, two of them to the leaders, ranks 19th on degree but 9th on betweenness, because it is tied directly to both leaders and so shortens many paths between the factions. The practical lesson is that a statement such as “this system has a center” is incomplete until it says which kind, and a claim of *universal* centrality is a claim that four different measures all point the same way.

2.2 A short intellectual history

The ideas in this report have been developed in separate literatures that rarely meet (Figure 4). In astronomy, the history of centers is largely a history of removing them. [Copernicus](#) moved the Sun to the middle of the planets and, by implication, removed Earth from it. [Shapley \(1918\)](#) used the distribution of globular clusters to show that the center of the Galaxy lies far from the Sun, in the direction of Sagittarius. Modern cosmology went further: surveys of luminous red galaxies show that the universe is statistically [homogeneous](#) above a scale of roughly a hundred megaparsecs, so no place is special at that scale. The [cosmological principle](#) is, in effect, a statement that the largest scale has no center.

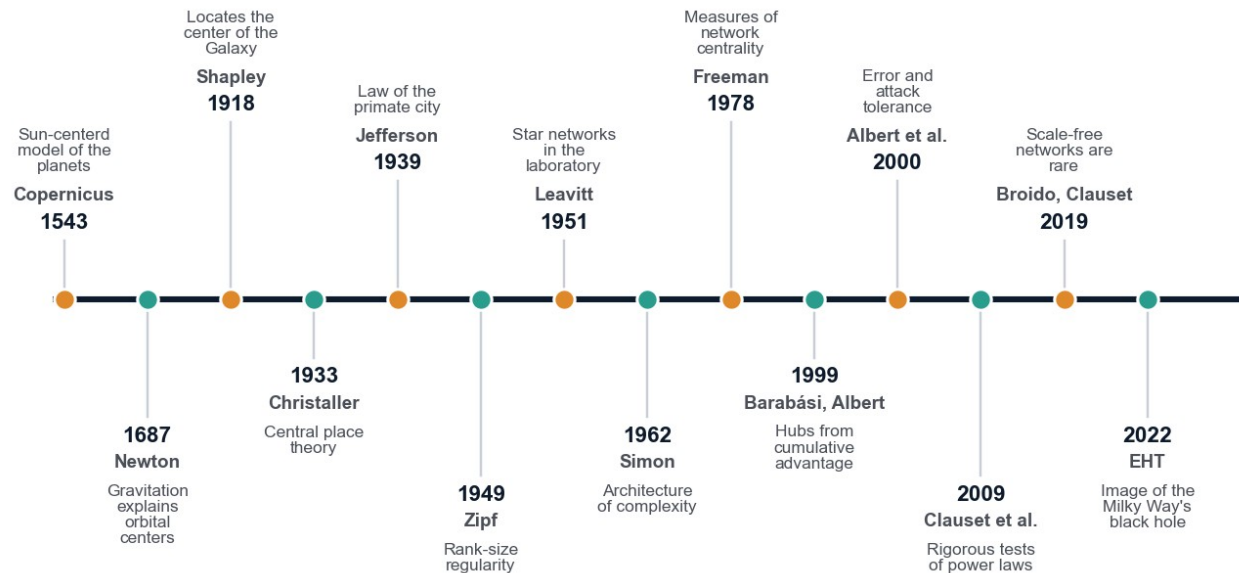


Figure 4. Fourteen steps in the study of centers, from the Sun-centered planetary model to the statistical critique of scale-free networks. Orange markers are discoveries that found or built a center; teal markers are measurements, theories or critiques that explained or limited one.

Source: *H Heuristics*, from the primary literature cited in the text and the reference list.

In geography and economics, the study of centers began with [Christaller's central place theory](#) in 1933, which explained why towns of different rank are spaced in a hierarchy, and with [Jefferson's law of the primate city](#) in 1939, which noted that many countries have one city far larger than any other. [Zipf \(1949\)](#) described the regularity that the second city is about half the size of the first, the third a third, and so on. [Gabaix \(1999\)](#) showed that this follows if cities grow at the same average rate regardless of size, and [Krugman \(1996\)](#) wrote of the “mystery” of urban hierarchy, because few economic models of the time predicted it.

In network science, [Price \(1965\)](#) found that the number of citations to scientific papers is heavily skewed and proposed in [1976](#) that cumulative advantage explains it; [Simon \(1955\)](#) had already derived the same mathematics for word frequencies and city sizes; [Merton \(1968\)](#) named the sociological version the Matthew effect. [Barabási and Albert \(1999\)](#) rediscovered the mechanism for networks, called it *preferential attachment*, and set off a field. [Albert, Jeong and Barabási \(2000\)](#) showed that hub-dominated networks tolerate random failure but not targeted attack, and [Newman \(2003\)](#) and [Albert and Barabási \(2002\)](#) reviewed the field.

In organization science, [Bavelas \(1950\)](#) and [Leavitt \(1951\)](#) put small groups into artificial communication networks, star, chain and circle, and measured how well they solved problems. [Simon \(1962\)](#) argued in *The Architecture of Complexity* that complex systems that survive are nearly decomposable hierarchies, because modules can be built and repaired independently.

Finally, a critical literature asks how much of this is real. [Clauset, Shalizi and Newman \(2009\)](#) showed that many claimed power laws cannot be distinguished from other heavy-tailed distributions without rigorous tests. [Broido and Clauset \(2019\)](#) applied those tests to nearly a thousand real networks and found strongly scale-free structure to be rare. [Arcaute and colleagues \(2015\)](#) and [Rozenfeld and colleagues \(2011\)](#) showed that urban regularities depend on how a city is defined. This report builds on both sides of that debate: it takes the mechanisms seriously and the statistics seriously.

03

THE THEORETICAL FRAMEWORK



3. The Theoretical Framework

3.1 Five generators of centers

The report's central proposal is that a small number of processes generate centers, and that most cases in the literature are produced by one or more of them (Figure 5). The five are distinct, which matters: if centers had a single cause, similar centers in different domains would be unsurprising; because they have several, finding the *same* quantitative signature in unrelated systems is informative.

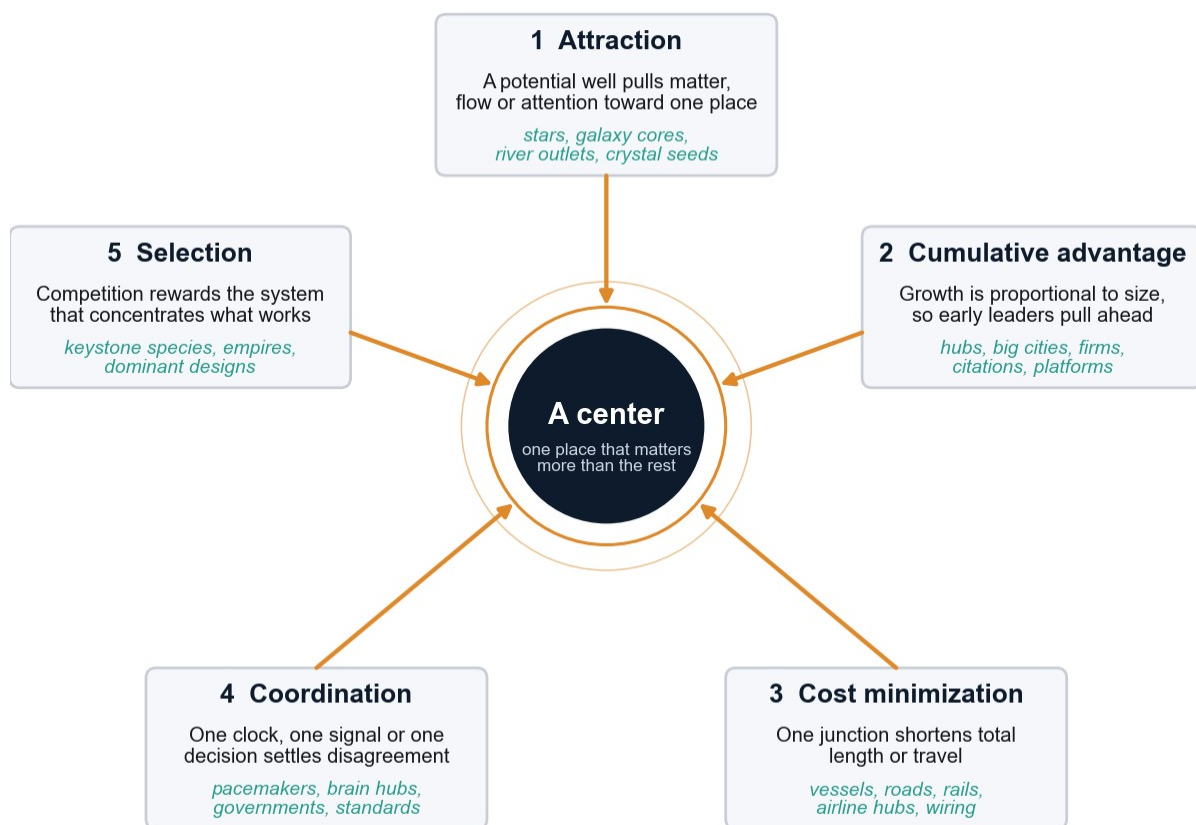


Figure 5. Five generators of centers. Attraction, cumulative advantage, cost minimization, coordination and selection each produce centers on their own, and in real systems usually act together.

Source: H Heuristics synthesis. Examples are developed in Sections 4 to 7.

1. **Attraction toward a potential well.** Where a force draws things toward one place, matter, flow or attention collects there. Gravity builds stars and galaxy cores, a drainage basin funnels water to one outlet, and a freezing liquid gathers atoms at a seed crystal. The center is simply where the potential is lowest.
2. **Cumulative advantage.** Where growth is proportional to size, early leaders pull ahead. This process, rediscovered under the names [preferential attachment](#), the [Matthew effect](#) and [network effects](#), produces hubs without any plan. It needs no force, only feedback.
3. **Cost minimization.** Where moving things or building links is costly, a shared junction shortens total length or travel. [Fabrikant, Koutsoupias and Papadimitriou \(2002\)](#) showed that a simple trade-off between link length and distance from a root produces hub-and-branch structures. Blood vessels, road systems and airline schedules are solutions of the same family of problems.
4. **Coordination.** Where many parts must act together, one clock, one signal or one decision settles disagreement more cheaply than negotiation. Pacemakers, standard times, standards bodies and governments are coordination centers.
5. **Selection.** Where systems compete, those that concentrate what works outcompete those that do not, and the concentration persists. Dominant technologies, empires and keystone species are partly the survivors of such contests, as [Arthur \(1989\)](#) showed for technologies that lock in through increasing returns.

The five can be told apart by what they predict. Attraction predicts a center at the minimum of a measurable potential. Cumulative advantage predicts a skewed distribution whose leaders are, on average, the earliest. Cost minimization predicts that centers shift as the relative cost of distance changes. Coordination predicts centers at the points where timing or decisions must be shared. Selection predicts that centers disappear when the environment that favored them changes.

3.2 A ladder of claims

Statements about centrality range from obvious to extravagant, and they should not all be held to the same standard. The report grades them on a five-rung ladder, adapted from the one used for fractal claims in the series (Table 3). A claim is only as strong as the highest rung it has reached.

Table 3. A ladder for grading claims about centers

Rung	Claim	What it requires	Typical failure
1	This system has a dominant node	A defined quantity and a count	Choosing the quantity after seeing the data
2	The dominance exceeds chance	Comparison with a null model of the same size	No null model, or the wrong one
3	A mechanism produces it	A model that reproduces the distribution, not just the picture	A plausible story that was never simulated
4	The center has a function	A measurable outcome that depends on the center	Confusing what a center does with why it exists
5	The same signature recurs across domains	Matching numbers, not matching shapes, from independent systems	Matching vocabulary in place of matching measurement

Rung 5 is the hardest and the one most often asserted without evidence. A hub in an airline network and a king in an empire share a word, not necessarily a mechanism.

Four tests accompany the ladder. **Null model:** would a random system of the same size show the same concentration? **Scale:** does the center survive when the system is redrawn at a different resolution, for

instance when a city is defined by its legal boundary or by its built-up area? **Mechanism:** can a rule, run forward, reproduce the observed numbers? **Counterexample:** which systems of the same class lack the center, and why?

3.3 The hypothesis

The report tests a hypothesis at three levels, graded separately.

1. **Descriptive.** Concentration around a small number of dominant nodes is common across physical, biological, technological and social systems, well beyond what random organization would produce.
2. **Explanatory.** Five generators, acting singly or together, account for most observed centers, and wherever the same generator operates the same quantitative signature appears.
3. **Metaphysical.** The recurrence of centers is evidence that reality as a whole is organized around a single principle, source or order.

The report evaluates the first two with calculation and evidence. The third is not testable with the methods used here; it is a way of reading the first two, and the report says plainly where the reading goes beyond the data.

04

DOMAIN I · THE PHYSICAL WORLD



4. The Physical World

4.1 Atoms, stars and planetary systems

The strongest centers in nature are the oldest. In a hydrogen atom the nucleus is a single proton, and it holds 99.9% of the atom's mass, because a proton is about 1,836 times heavier than an electron. In the Solar System the Sun holds about 99.86% of the mass, according to [NASA's fact sheet](#); summing the eight planets from the [NASA planetary fact sheet](#) gives 99.9% for the Sun against the planets alone, and Jupiter accounts for 71% of what the planets hold. These are cases of the first generator, attraction, at its limit. When a cloud of gas collapses under its own gravity, the central region gains mass fastest and becomes the star; what is left in the disk forms the planets.

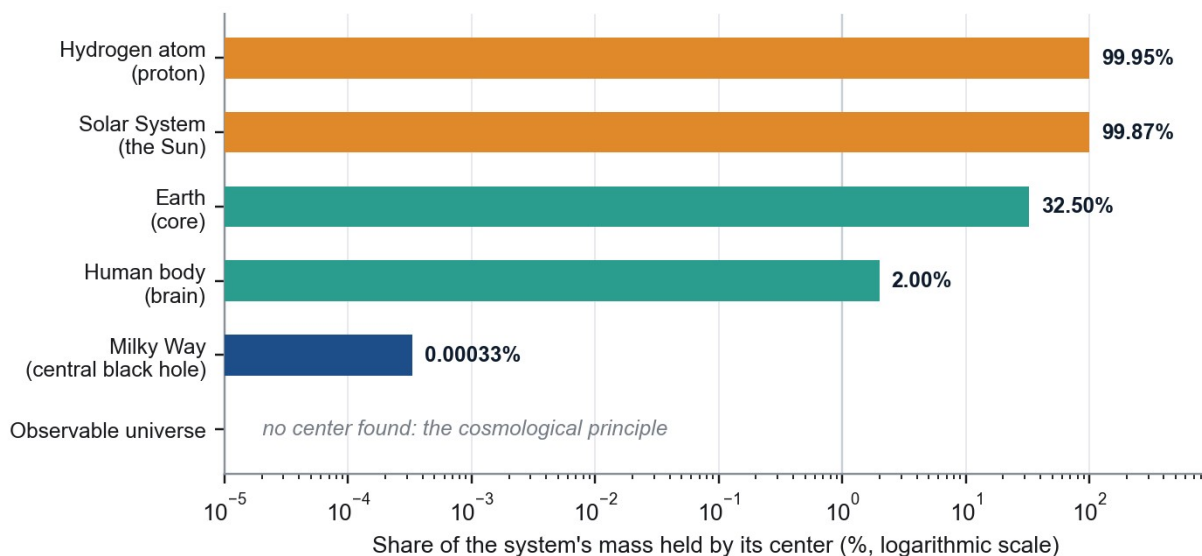


Figure 6. The center's share of the system's mass varies by more than five orders of magnitude. Atoms and planetary systems are almost all center; the Earth is one-third core; a human body is about 2% brain, which uses roughly a fifth of resting energy; the Milky Way's central black hole holds about three millionths of the Galaxy's mass. The observable universe has no center that can be identified.

Source: H Heuristics calculations from [CODATA](#) proton–electron mass ratio; NASA planetary fact sheets; [Dziewonski and Anderson \(1981\)](#) for Earth's core; [Raichle and Gusnard \(2002\)](#) for the brain; [Ghez et al. \(2008\)](#) and [Bland-Hawthorn and Gerhard \(2016\)](#) for Sagittarius A* (4.3×10^6 solar masses) and the Galaxy (1.3×10^{12}).

Figure 6 sets out the spectrum on a logarithmic axis, and the spread is the main finding. A center can hold nearly everything, a third, a few percent, or almost nothing, and it is called a center in every case. The word therefore cannot mean *where the mass is*. It has to mean something about *influence*: what the rest of the system's behavior depends on. That is the functional meaning from Section 2, and it is why the body's brain and the Galaxy's black hole qualify despite their small shares.

4.2 Collapse makes centers

Is a center the inevitable result of gravity acting on matter? A simple calculation says yes. The report evolved 1,200 equal-mass particles, initially spread uniformly through a sphere with small random velocities, under their mutual gravity with a standard leapfrog integrator. Total energy was conserved to 0.012% over the run (Figure 7). The cloud fell together and rebounded into a dense core inside a diffuse halo. A sphere of radius 0.1 around the density peak, which holds 0.1% of the mass in a uniform cloud, held 22% by the end; a sphere of radius 0.25 held 56%, up from 1.7%.

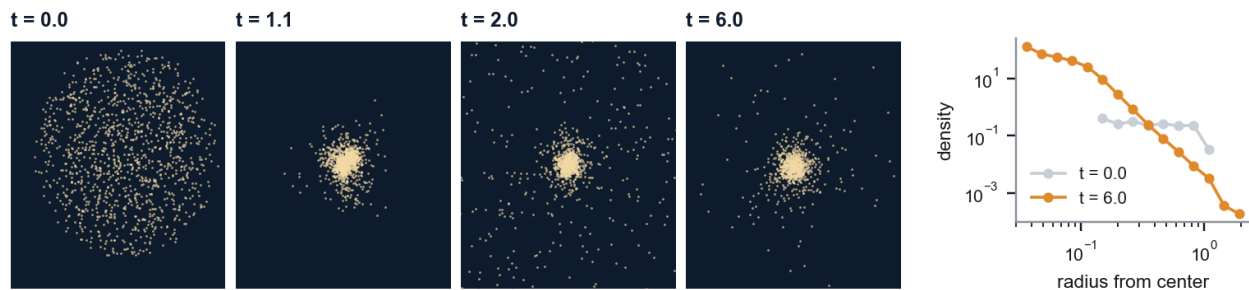


Figure 7. A uniform cloud of 1,200 particles collapses under gravity into a dense center inside a halo. Left four panels: positions at four times, centered on the density peak. Right: density against radius at the start and the end. The center is a thousand times denser than the average at the start of the run.

Source: H Heuristics calculation. Direct summation, Plummer softening 0.04, time step 0.004, $G = M = R = 1$, initial velocity dispersion 0.12; energy conserved to 0.012%. A toy model with no gas, dark matter or expansion.

The toy model is far from a galaxy, but its outcome is robust, and large simulations show the same thing at scale. Dark-matter halos in cosmological simulations have a [universal density profile](#) that rises steeply toward the center, whatever their mass. In the [Millennium Simulation](#) matter gathers into nodes joined by filaments, the [cosmic web](#), and the nodes are where clusters form. Centers in the physical world are, to a good approximation, what gravity does to a lumpy distribution of matter. This is Grade A.

4.3 Galaxies and their black holes

Most large galaxies contain a supermassive black hole at the center. The one in the Milky Way, [Sagittarius A*](#), was weighed from the orbits of stars around it: its mass is about four million times the Sun's ([Ghez et al., 2008](#); [Genzel, Eisenhauer and Gillessen, 2010](#)), and the [Event Horizon Telescope](#) imaged its shadow in 2022. Yet that is only about 0.00033% of the Galaxy's mass, and about 0.009% of its stellar mass. The black hole is geometrically central but gravitationally minor for the Galaxy as a whole.

Why call it central, then? Because its mass correlates with the properties of the whole galaxy. Two groups showed in 2000 that black-hole mass tracks the velocity dispersion of the surrounding stellar bulge ([Ferrarese and Merritt, 2000](#); [Gebhardt et al., 2000](#)). That implies a link between a region many orders of magnitude smaller than the galaxy and the galaxy itself. Whether the link reflects feedback, in which accretion onto the black hole regulates star formation, or merely a statistical effect of mergers is still debated; [Kormendy and Ho \(2013\)](#) review the evidence that bulges and black holes coevolve while disks and dwarf galaxies mostly do not. The honest summary: the center of a galaxy is influential out of all proportion to its mass, in some galaxies, for reasons that are partly understood. Grade B.

4.4 Earth and fluid systems

Centers form wherever matter or flow has a preferred place to accumulate. Earth's core holds about a third of the planet's mass ([Dziewonski and Anderson, 1981](#)), and the motion of its liquid outer shell generates the magnetic field that shields the surface ([Roberts and King, 2013](#)). A tropical cyclone organizes the atmosphere around an eye, and [Emanuel \(1986\)](#) explained how the storm is maintained as a heat engine fed by the warm sea. Freezing starts from a seed: [crystal nucleation](#) is the case in which one small cluster of atoms, by growing past a critical size, decides where the solid will form. River basins converge on one outlet, and the optimal-channel models of [Rinaldo and colleagues \(1993\)](#) show how branching networks that minimize energy dissipation develop a trunk.

These examples span three of the five generators: attraction (the core and the river outlet), cost minimization (the river network) and cumulative advantage (the nucleus that outgrows its competitors). Each is understood quantitatively. Together they make the physical world the cleanest case for the hypothesis at the descriptive and explanatory levels.

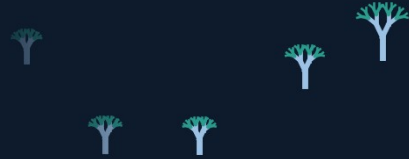
4.5 The universe has no center

At the largest scale the picture reverses. The [cosmological principle](#) states that the universe is homogeneous and isotropic on large scales, and the evidence supports it: [Hogg and colleagues \(2005\)](#) found that the distribution of luminous red galaxies becomes homogeneous above scales of roughly 70 megaparsecs per unit of the Hubble parameter, and the [Planck mission](#) measured a cosmic microwave background that is uniform to about one part in a hundred thousand. The expansion of space has no center; every observer sees the others receding.

Finding. Centers are properties of subsystems, not of the whole. Gravity builds a center everywhere it can, at every scale from planets to clusters, and the sum of all those centers has none. A theory that treats centrality as a feature of reality as a whole must reckon with this: the universe is made of centers and has no center.

05

DOMAIN II · LIFE



5. Life

5.1 Centers in living systems

Life repeatedly builds centers, and at each level of organization biologists have asked what happens when the center is removed. The answers form a gradient from strict dependence to graceful redundancy (Table 4).

Table 4. Centers at six levels of biological organization

Level	Center	What it does	What happens without it
Cell	Nucleus	Stores the genome and transcribes it; most protein-coding information	An enucleated cell can survive for a time but cannot transcribe new genes
Organ	Sinoatrial node	A small cluster of cells sets the heart rate	Other tissue can take over, at a slower and less flexible rhythm
Rhythm	Suprachiasmatic nucleus	Master clock that synchronizes the body's circadian clocks	Clocks in other tissues keep running, but drift out of step
Nervous system	Hubs and rich club	A set of interlinked brain regions carries a disproportionate share of communication	Damage to hubs has larger effects than damage to peripheral regions
Molecular network	Hub proteins	A few proteins have many interaction partners	Deleting highly connected proteins is more often lethal
Ecosystem	Keystone species	A species whose effect on the community is large relative to its abundance	Community composition shifts, sometimes sharply

Sources in the links and in the text. The rightmost column describes the type of evidence available; effect sizes differ widely between cases and are not comparable across rows.

The pattern at the top of the table is control: one structure holds the instruction or sets the beat. At the bottom it becomes influence: a hub or a species matters because many things connect through it. In between are brains, where a small set of strongly interconnected hubs forms what [van den Heuvel and Sporns \(2011\)](#) call a rich club, and where [Sporns, Honey and Kötter \(2007\)](#) classify hubs by their roles; the brain as a whole is about 2% of body mass and uses about 20% of resting energy ([Raichle and Gusnard, 2002](#)). [Bullmore and Sporns \(2009\)](#) review the case that brain networks are neither random nor regular, but organized around hubs and modules at low wiring cost.

5.2 Hubs in molecular and plant networks

Cells are networks. In the metabolic networks of forty-three organisms, [Jeong and colleagues \(2000\)](#) found a few highly connected metabolites and many with few links; in yeast, [Jeong and colleagues \(2001\)](#)

found that the more interactions a protein has, the more likely its deletion is lethal. That is a functional meaning of centrality verified by experiment: hubs are not just well connected, they matter more. Csete and Doyle (2002, 2004) argued that this structure is better described as a bow tie, a diverse set of inputs funneled into a narrow, conserved core of common currencies such as ATP and then fanned out again into diverse products. The core is shared and robust because it is the one component that cannot be allowed to fail.

Plants use a coordination center that is easy to see. In [apical dominance](#) the growing tip of a shoot suppresses the growth of buds below it, a phenomenon first measured by [Thimann and Skoog \(1934\)](#) and now understood as signaling through the hormone auxin and its competitors ([Domagalska and Leyser, 2011](#)). Remove the tip and a lower bud takes over. The center is real but replaceable, which is the design principle that recurs in Section 11.

5.3 Rhythm, rank and the limits of command

Rhythm is the cleanest case of coordination. A [central pattern generator](#) is a small circuit that produces the repeated pattern behind walking, swimming or breathing without needing a rhythmic input, and the heart's pacemaker is its cardiac equivalent. In animal groups, [dominance hierarchies](#) concentrate access to resources in a few individuals, and [Sapolsky \(2005\)](#) reviews how rank affects health in primates in both directions, with low rank costly in some species and high rank costly in others. [Dunbar \(1992\)](#) linked group size in primates to brain size, which suggests that the capacity of a coordinator limits how large a group can be managed directly.

The limits of command are equally instructive. Social-insect colonies look centrally ruled, and the word “queen” invites the reading. But in harvester ants, [Gordon and Mehdiabadi \(1999\)](#) showed that task allocation emerges from the rate at which workers meet one another, and the queen does not direct the work. The same pattern holds across many biological systems: where speed or precision of timing is at stake, evolution builds a center; where adaptability under uncertain conditions is at stake, it builds a distributed system, often with overlapping parts. [Edelman and Gally \(2001\)](#) call that overlap *degeneracy* and argue it is a pervasive property of biological systems. Vascular networks, which branch from the heart, are a further case: [West, Brown and Enquist \(1997\)](#) derived allometric scaling laws from the geometry of branching supply networks, a claim that remains contested but that shows how cost-minimizing transport can fix the shape of a whole organism.

Finding. Life builds centers where timing and control are decisive and avoids sole dependence on them where survival is. The typical living system has a center, a deputy for it and a periphery that can operate, more slowly, without either. That is the opposite of a single point of failure, and the pattern anticipates Section 11.

06

DOMAIN III · CITIES AND NETWORKS

6. Cities, Economies and Networks

6.1 Primate cities and rank-size order

Human settlement is the domain where centers are most visible and most debated. [Christaller's central place theory](#) explains a hierarchy of towns by the distance people will travel for goods of different kinds. [Jefferson \(1939\)](#) observed that in many countries one city dominates, which he called the [primate city](#). [Zipf's law](#) describes a different regularity: when cities are ranked by population, size falls in proportion to rank, so that the largest is twice the second, three times the third, and so on. The two are not the same. A country can obey Zipf's law with a modest ratio of largest to second city near 2, or it can have a primate city ten times larger than the next.

The report measured both in twenty national city systems, using city populations from the [GeoNames](#) database for all places with at least 15,000 inhabitants (Figure 8). The rank-size slope, estimated for the largest 100 cities with the [Gabaix–Ibragimov](#) correction, had a median of 1.36 and ran from 0.83 in Australia to 1.68 in Thailand; a slope of 1 is Zipf's law. In 12 of the 20 systems a slope of 1 lay within two standard errors, but the standard errors are wide, about 0.2, because only 100 cities are fitted. The ratio of the largest city to the second varied far more: from 1.04 in Australia, where Sydney and Melbourne are nearly equal, to 13.1 in Thailand, where Bangkok towers.

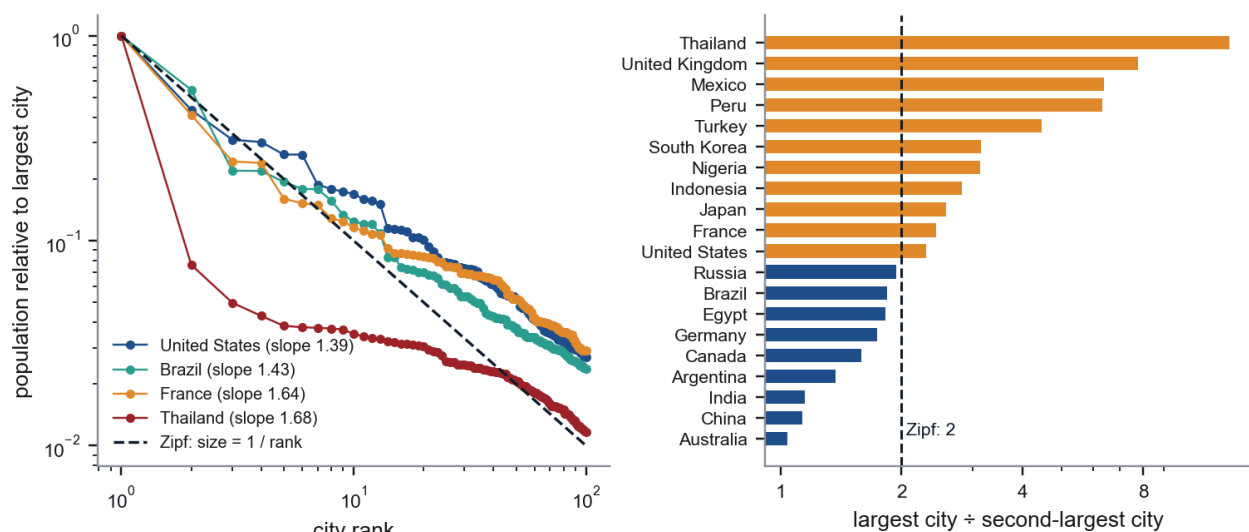


Figure 8. City systems are not all alike. Left: population against rank for four countries, relative to the largest city; the dashed line is Zipf's law. Right: the ratio of the largest to the second-largest city in twenty countries; orange bars exceed the ratio of 2 that Zipf's law implies. Primacy ranges from near equality to more than a factor of ten.

Source: H Heuristics calculations from GeoNames city populations (places of 15,000 or more; 'city proper' populations, which depend on national definitions). Slope: Gabaix–Ibragimov estimator on the largest 100 cities. The second city in some countries is an administrative neighbor of the first (for example Samut Prakan near Bangkok), so primacy ratios are upper bounds.

Table 5. The five most centralized and the five least centralized national city systems in the sample

Country	Largest city	Second city	Ratio	Slope
Thailand	Bangkok (5.1 million)	Samut Prakan (0.4 million)	13.1	1.68
United Kingdom	London (9.0 million)	Birmingham (1.2 million)	7.7	1.53
Mexico	Mexico City (12.3 million)	Tijuana (1.9 million)	6.4	1.39
Peru	Lima (7.7 million)	Callao (1.2 million)	6.3	0.92
Turkey	Istanbul (15.7 million)	Ankara (3.5 million)	4.5	1.09
Canada	Toronto (2.8 million)	Montréal (1.8 million)	1.6	1.30
Argentina	Buenos Aires (2.9 million)	Córdoba (2.1 million)	1.4	1.34
India	Mumbai (12.7 million)	Delhi (11.0 million)	1.2	1.43
China	Shanghai (24.9 million)	Chongqing (22.0 million)	1.1	1.32
Australia	Sydney (5.6 million)	Melbourne (5.4 million)	1.0	0.83

Populations in the GeoNames database; the slope is the rank-size exponent for the largest 100 cities (all fitted cities if fewer). The five rows at the top are the highest ratios in the sample, the five at the bottom among the lowest. Definitions of the urban unit differ between countries and affect both columns.

Two conclusions follow. The first is that centered urban systems are common: in 11 of 20 countries the largest city is more than twice the second, and in five it is at least four times larger. The second is that the strict form of Zipf's law is a good first approximation for some systems and not for others, and that the answer depends on how a city is defined. [Rozenfeld and colleagues \(2011\)](#) obtained exponents close to 1 by building cities from clusters of built-up land rather than from administrative boundaries, and [Arcaute and colleagues \(2015\)](#) showed that other urban regularities shift with the definition. Cities are also not always monocentric: [Fujita and Ogawa \(1982\)](#) modeled the shift from one center to several as commuting costs rise, and [Louf and Barthélemy \(2013\)](#) reproduced a transition to polycentric structure as cities grow. [Krugman \(1991\)](#) showed how increasing returns and transport costs alone can split an economy into a core and a periphery. Urban centers are thus generated by cumulative advantage (Zipf's law), by cost minimization (the monocentric model) and by selection (the core-periphery economy), and they are neither universal nor fixed.

6.2 Airline hubs

The airport network is an unusually clean test because its center is an engineering choice and the data are public. After deregulation of US airlines in 1978, carriers reorganized their routes around [hubs](#): rather than flying every pair of cities, a carrier flies each city to a hub and connects passengers there. [Guimerà and Amaral \(2004\)](#) modeled the world airport network as a small-world network with heavy-tailed degrees, and [Guimerà and colleagues \(2005\)](#) found “anomalous centrality”: some airports are far more important to the network than their number of connections suggests, because political geography as well as passenger demand shapes where airlines choose to link.

The report analyzed the [OpenFlights](#) route data, which cover 3,257 airports with scheduled service and 18,930 distinct pairs of airports joined by a route (the data are a snapshot from about 2014 and a sample, not a complete schedule). The mean airport serves 11.6 destinations; the median serves 3, and 23% serve only one. The best-connected, Amsterdam Schiphol, serves 248 destinations, against 25 for a random network of the same size. The busiest 1% of airports hold 14.8% of all route endpoints and the

busiest 5% hold 44.0% (Figure 9). Concentration of this kind is large and real. It is not, however, a clean power law, a point taken up in Section 11.

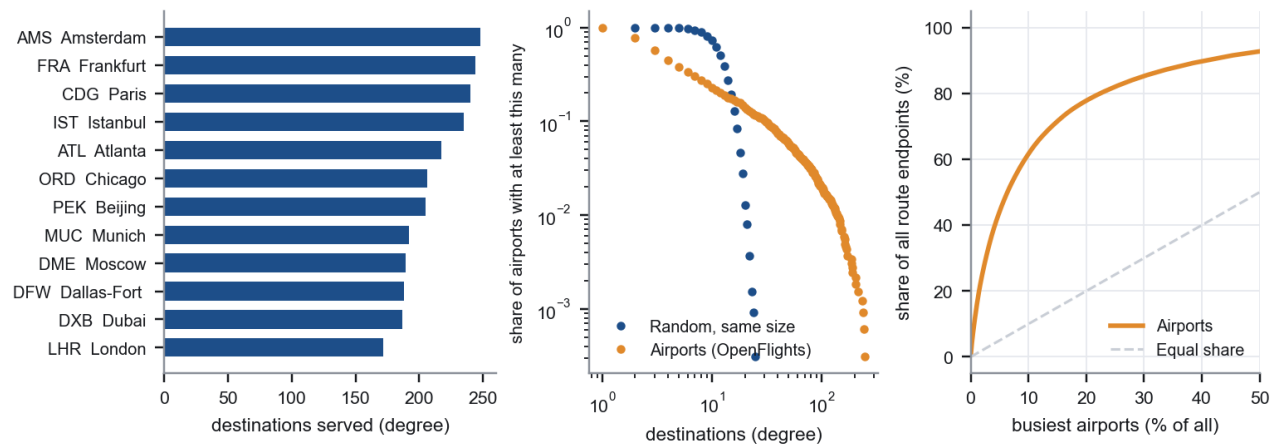


Figure 9. The world airport network is strongly centralized. Left: the twelve airports serving the most destinations. Middle: share of airports with at least a given number of destinations, compared with a random network of the same size and number of routes. Right: cumulative share of route endpoints held by the busiest airports; the dashed line would be equal shares.

Source: H Heuristics calculations from OpenFlights route and airport data (about 2014; [data page](#)). The ranking is by number of destinations, not passengers.

6.3 Economies and technologies

Firms and platforms show the same signature. [Axtell \(2001\)](#) found that the sizes of all US firms follow Zipf's law closely. [Vitali, Glattfelder and Battiston \(2011\)](#) mapped ownership links among 43,060 transnational corporations and found a small, densely connected core of financial institutions that control a large part of the network's value. Technologies lock in when early adoption makes later adoption cheaper, a mechanism formalized by [Arthur \(1989\)](#) and common in [network-effect](#) industries. At the scale of cities, [Bettencourt and colleagues \(2007\)](#) found that wages, patents and other outputs grow faster than population, while infrastructure grows more slowly, a pattern [Bettencourt \(2013\)](#) derives from the geometry of social interaction in dense places. Large centers pay their way, which helps explain why cumulative advantage can be sustained.

The Internet is a subtler case. [Faloutsos and colleagues \(1999\)](#) reported power laws in the degrees of Internet routers and domains, which many read as a signature of preferential attachment. [Doyle and colleagues \(2005\)](#) argued that the router-level Internet is better explained as the output of engineering trade-offs among bandwidth, cost and technology, which produce a core of fast links and a periphery of slow ones, and that its robustness to random failure and fragility to targeted attack are a design consequence, not a statistical accident. The same measured degree distribution can come from two different mechanisms, which is why the report insists on rung 3 of the ladder before it equates similar curves.

Finding. In human settlement and exchange, centers are generated by cumulative advantage, cost minimization and selection at once. They are common and often large, they vary between countries by more than a factor of ten, and the strict statistical laws attached to them are better approximations in some places than in others.

07

DOMAIN IV · MIND AND POWER



7. Mind, Culture and Power

7.1 Why minds look for centers

Any survey of centrality has to consider that the observers are human. Perception is centered. Viewers of a scene look first at its middle, a regularity called the [central fixation bias](#) that persists after image content and eye movements are controlled. Categories are centered: [Rosch \(1975\)](#) showed that people organize concepts around [prototypes](#), and judge some members as better examples than others. Judgment is centered: estimates start from an anchor and adjust away from it, an insufficiency of adjustment that [Tversky and Kahneman \(1974\)](#) documented in a series of experiments. Each is a form of reference point, a way of making a complex field tractable by choosing a middle.

This matters for the report because it gives a reason to suspect that some perceived centrality is contributed by the observer. A person asked to describe a network will describe its hubs; a person asked to summarize an empire will begin with its capital. The corrective is the one used throughout: a null model, a defined quantity and a count. It does not follow that perceived centers are illusory; the physical and technological examples above are measured. It follows that where the measurement is weaker, as in culture and history, the claim should be graded lower.

7.2 Sacred centers

Many cultures locate the world's middle at a particular place. The [axis mundi](#) is the pillar, mountain, tree or temple that connects heaven, earth and the underworld in the cosmologies of many traditions, and the term was taken into the study of religion by the historian Mircea Eliade. The Greek shrine at [Delphi](#) housed an [omphalos](#), a stone marking the navel of the world. Such centers organize pilgrimage, orientation and calendar. They are a clear case of the symbolic meaning of center, and an equally clear case that the symbolic center need not coincide with a geometric or functional one.

How common they are, and whether they arise from universal features of cognition or from particular histories, is an open question that this report does not attempt to answer. Their relevance here is narrower. Societies build symbolic centers because centers solve a coordination problem: a place and a time that everyone shares make it easier to act together. That places sacred centers within the fourth generator, coordination, and ties the symbolic meaning to the functional one.

7.3 States, rulers and the limits of the central story

The state is the largest human institution built around a center. [Carneiro \(1970\)](#) proposed that states arise where land is circumscribed, so that defeated groups cannot leave and are subordinated, a theory in which centralization comes from selection under conflict. Cultural evolutionists have argued that moralizing, prosocial religions helped societies grow ([Norenzayan et al., 2016](#)), and whether such beliefs

drove or followed social complexity has been disputed; a re-analysis of the historical data concluded that [the way missing data were treated determined the conclusion](#). That dispute is a useful warning. The story in which complex societies need a single central authority is attractive, widely told and not secure; the dataset that would settle it is incomplete.

Leadership itself is subject to attribution bias. [Meindl, Ehrlich and Dukerich \(1985\)](#) argued that observers credit organizational outcomes to leaders more readily than the evidence warrants, a tendency they called the romance of leadership, and the [great man theory](#) of history is its popular form. Laboratory work points the same way. In the small-group experiments of [Bavelas \(1950\)](#) and [Leavitt \(1951\)](#), centralized communication patterns solved simple problems quickly, the person in the central position emerged as leader, and members of the decentralized circle reported higher satisfaction. Speed, leadership and morale did not move together. The pattern recurs in organizations: a center buys speed and costs adaptability.

Finding. In mind and culture, centrality is real as perception and as organization, but its causes are harder to isolate and its claims are weaker. The evidence graded B at best for the existence of centers and C for their necessity. This domain tells us more about why people see centers than about whether the world requires them.

08

HUBS WITHOUT DESIGNERS

8. Hubs Without Designers

8.1 Growth with cumulative advantage

The previous four sections found centers in the physical, biological, urban and cultural worlds. This section and the next ask how they arise, starting with the most counterintuitive answer: nobody has to build them. Take a network that grows one node at a time. Each newcomer links to existing nodes, and the probability of linking to a given node is proportional to the number of links it already has. This rule, [preferential attachment](#), was proposed for networks by [Barabási and Albert \(1999\)](#), after [Price \(1976\)](#) and [Simon \(1955\)](#) had derived it for citations, words and cities. It requires no force, no plan and no intelligence. It requires only that being well connected makes further connection easier.

The report grew a network of 20,000 nodes by this rule, adding two links per node, and compared it with a random network that has the same number of nodes and links but wires them without regard to degree (Figure 10). The average node has about 4 links in both. The best-connected node in the random network has 13. In the grown network it has 212, which is 53 times the average against 3.3 times for the random network. The best-connected 1% of nodes hold 11.7% of all link endpoints against 2.6%. The degree distribution of the grown network follows a straight line on logarithmic axes with exponent 2.92, close to the theoretical value of 3 for this model.

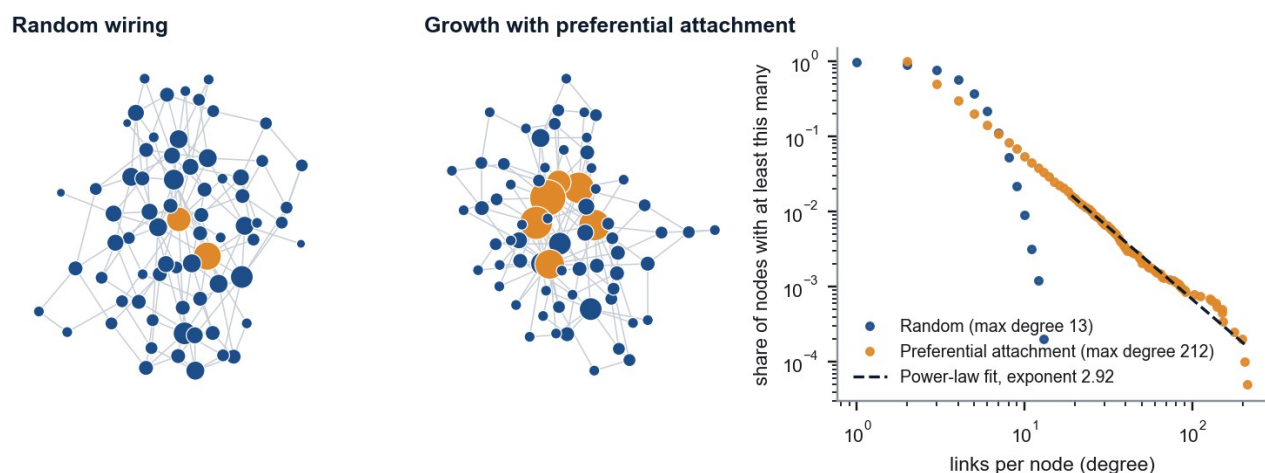


Figure 10. Growth with preferential attachment produces hubs; random wiring does not. Left: two networks of 70 nodes and about the same number of links, one wired at random and one grown by cumulative advantage, with the best-connected nodes (nine or more links) in orange. Right: share of nodes with at least a given number of links, for two networks of 20,000 nodes. The random network's distribution ends near 13 links; the grown network's reaches more than 200.

Source: H Heuristics calculations. Preferential attachment: two links per new node. Random: same number of nodes and links, wired uniformly at random. Exponent fitted by maximum likelihood with a Kolmogorov–Smirnov selection of the lower bound (Clauset et al., 2009).

This is the strongest evidence in the report for the second layer of the hypothesis. It shows that heavily skewed outcomes can be produced by a rule that contains no reference to centers at all, and that the outcome is far from what random organization would give (rung 2 and rung 3 of the ladder). It also shows why similar centers in unrelated systems may share a cause: the rule applies to citations, firms, web pages and cities alike, as [Newman \(2005\)](#) reviews. Grade B, because evidence that the rule is *the* cause in any particular real system is usually indirect.

8.2 Error and attack

Hubs change how a network behaves under stress. [Albert, Jeong and Barabási \(2000\)](#) showed that networks with a heavy-tailed degree distribution are extremely tolerant of random failure, because most nodes are peripheral and their loss changes little, and extremely vulnerable to targeted removal of the best-connected nodes. The report reproduced the effect on its model networks of 3,000 nodes (Figure 11). Removing 10% of nodes at random left 90% of the grown network connected in one piece. Removing the best-connected 10% left 62%, and removing the best-connected 20% left 1.2%, essentially nothing. The random network showed little difference between the two kinds of removal: 76% against 69% at 20%.

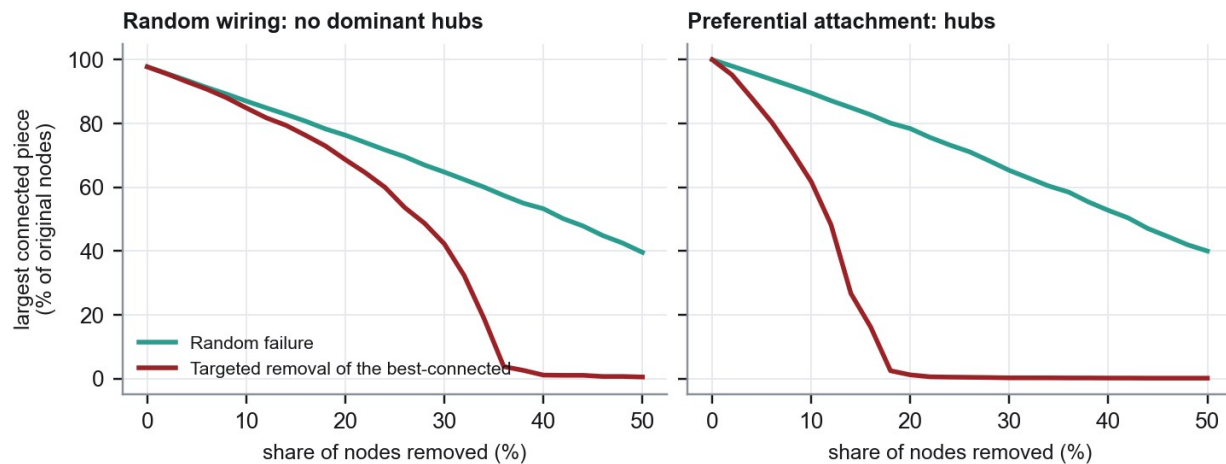


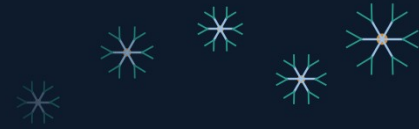
Figure 11. Hubs make a network robust to accident and fragile to attack. Share of the network that remains connected in one piece as nodes are removed at random (teal) or best-connected first (red). The random network, which has no hubs, loses connection gradually either way. The network grown with cumulative advantage survives random loss as well as the random network does and collapses when its hubs are removed.

Source: H Heuristics calculations. 3,000 nodes, 2 links per node (average degree 4). Random removal averaged over 5 runs; targeted removal by initial degree.

The same asymmetry appears when failure spreads. In the cascade model of [Mottet and Lai \(2002\)](#), the failure of one heavily loaded node sends its traffic to others, which may overload in turn; the more heterogeneous the loads, the larger the cascade. In interdependent networks, such as a power grid coupled to its communications network, [Buldyrev and colleagues \(2010\)](#) showed that the failure of a few nodes in one can trigger a catastrophic cascade across both. Section 10 turns from model to evidence.

09

WHY CENTERS PERSIST



9. Why Centers Persist

9.1 The cost of distance

Cumulative advantage explains how hubs form. It does not explain why systems that *can* avoid them, because someone designs them or selection weeds out the poor ones, so often keep them. The answer lies in cost. A center shortens the number of steps between any two nodes, which makes travel and signaling fast, but it lengthens the physical distance traveled when nodes are spread out. Which effect dominates depends on the relative cost of the two.

The report simulated this trade-off using the model of [Fabrikant, Koutsoupias and Papadimitriou \(2002\)](#). Points are scattered in a square, with a root at the middle. Each new point links to the existing point that minimizes a combination of two costs: the distance to that point, weighted by a parameter α , and the number of steps from that point to the root. Summed over all nodes the objective is:

$$C = \alpha \sum_i d_{i,p(i)} + \sum_i h_i \quad (1)$$

where d is the length of the link from node i to its chosen parent $p(i)$, and h is the number of steps from i to the root. When α is small, distance is cheap and steps are dear, so every node connects directly to the root. When α is large, distance is dear and steps are cheap, so each node connects to its nearest neighbor, giving a spanning web. The result is a transition between the two (Figure 12). With 1,500 nodes, every node linked directly to the root for α up to about 1; at $\alpha = 2$ the root still held 83% of the links, at 3.4 it held 33%, at 5.8 it held 14%, and by $\alpha = 10$ it held 6% and other hubs had emerged to share the load.

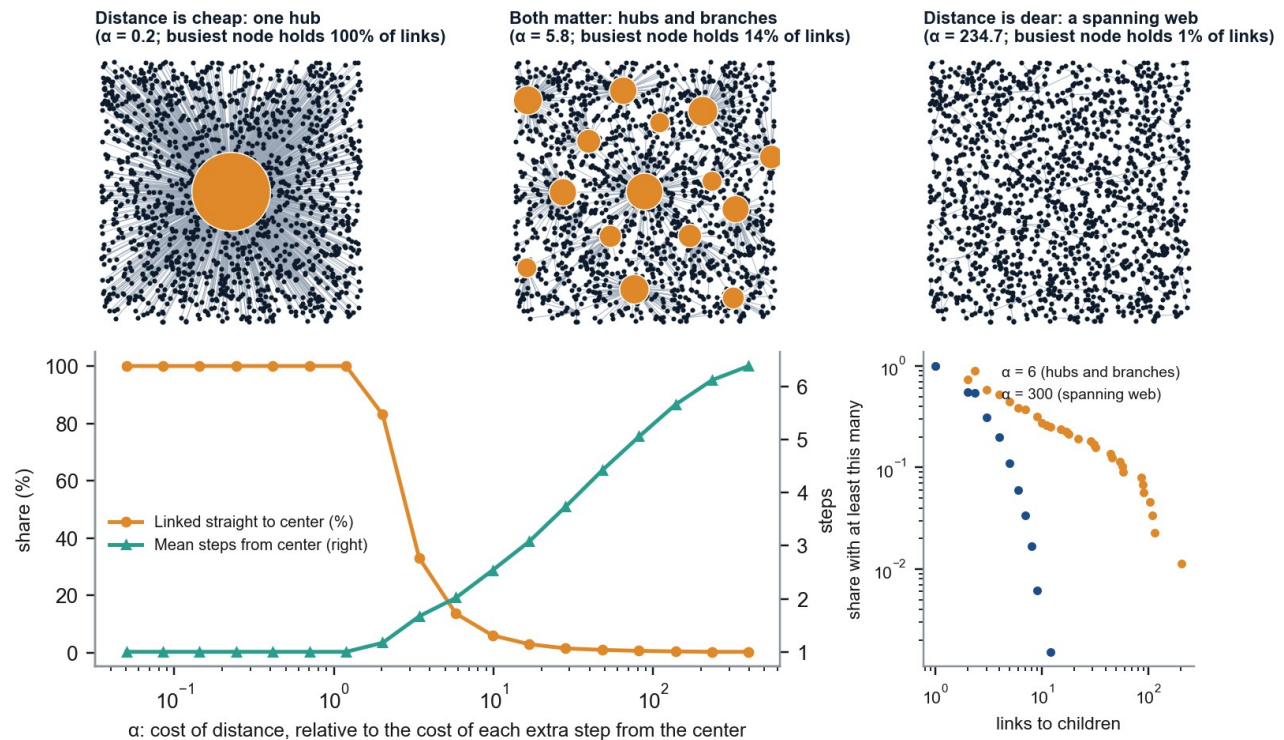


Figure 12. Centralization is a response to the cost of distance. Top: networks of 1,500 nodes built when distance is cheap (left), when distance and steps both matter (middle) and when distance is dear (right); the busiest nodes are in orange. Bottom left: as α rises, the share of nodes linked straight to the center falls, while the average number of steps from the center rises. Bottom right: degree distribution at two values of α ; the middle regime has a heavy tail of hubs.

Source: H Heuristics calculation of the heuristically optimized trade-off model (Fabrikant et al., 2002). Nodes arrive in random order in the unit square; root at the center. At $\alpha = 0.2$ one node holds 100% of links.

The cost of this arrangement is in total wiring. In the report's run the single-hub network needed 569 units of link length and the spanning web 40, a ratio of 14 to 1. But the hub network placed every node one step from the center and the web placed the average node 6.4 steps away. Neither is better in the abstract. The intermediate regime, where hubs coexist with local branches, is the one that most resembles airline networks, river basins and vascular trees, which pay some distance to save some steps. When the economics change, as when air travel became cheaper relative to time, the optimum moves, and the centers move with it.

9.2 One clock, one signal

The second reason is coordination. Parts that must act together need a shared reference, and a single reference is cheaper than negotiating many. [Simon \(1962\)](#) argued that complex systems that last are built from nearly decomposable modules, each internally dense and loosely connected to the others, because modules can be assembled and repaired independently. Hierarchies are the commonest way of building such systems, and a hierarchy has a top. The laboratory finding of [Leavitt \(1951\)](#) is the human version: groups with a central member solved simple problems faster and with fewer messages. The biological version is the pacemaker and the clock of Section 5, and the physical version is the single fixed point about which all else orbits.

A center that coordinates need not be large. The suprachiasmatic nucleus has tens of thousands of neurons in a rodent, a tiny fraction of the brain. The central point is that a small structure, correctly

placed, can set the state of a large one. That is cheap in resources and powerful in effect, which is why selection favors it.

9.3 Lock-in and selection

The third reason is that centers, once present, are hard to dislodge. Technologies and institutions that gather adopters become more attractive to the next adopter, and alternatives that were better at the start may never get the chance to prove it ([Arthur, 1989](#)). In economic geography, [Krugman \(1991\)](#) showed how increasing returns and transport costs let an initially symmetric economy tip into a core and a periphery, and stay there. Selection works at the system level as well: where an empire, a firm or an ecosystem that concentrates its resources outcompetes one that does not, centralized forms spread. Cumulative advantage forms centers, cost makes them efficient, coordination makes them useful and lock-in makes them last. The same forces that build centers keep them in place after the conditions that justified them change.

Finding. Centers persist because they are cheap in steps, quick to coordinate and difficult to displace. The same properties make them risky. The conditions that justify a center are not permanent, but the center usually outlives them.

10

THE PRICE OF ONE



10. The Price of One

10.1 Single points of failure

A system with one irreplaceable center has a [single point of failure](#), and the cost of concentration is paid when the point fails. The history of recent systemic disruptions is, to a striking degree, a history of centers failing (Table 6). In each case below a very large system depended on one component, one provider, one route or one record, and the failure of that component set the scale of the outage.

Table 6. Five recent disruptions in which a single concentrated element set the scale of the failure

Event	Date	The concentrated element	Effect
Northeast blackout	14 Aug 2003	An alarm system in one utility's control room	A manageable local fault cascaded across the Northeast and Ontario, affecting an estimated 55 million people
Suez Canal obstruction	23–29 Mar 2021	One grounded ship in a single-channel section of one canal	Traffic stopped for six days; goods worth an estimated US\$9.6 billion a day delayed
Colonial Pipeline attack	7 May 2021	One pipeline operator's control systems; see also the CISA advisory	The operator halted all pipeline operations to contain the attack
CrowdStrike update	19 Jul 2024	One faulty software update distributed to a dominant operating system	Roughly 8.5 million Windows systems crashed
AWS us-east-1 outage	19–20 Oct 2025	A single empty DNS record for one regional database endpoint, from a latent race condition	Service disruption lasting about 14.5 hours for customers and dependent services

Sources: linked reports. The table records what was concentrated and the immediate effect; it does not estimate economic losses, which are contested in every case. Five incidents are illustrations, not a statistical sample.

Five incidents do not prove a trend, and each had its own immediate cause. What they share is structure: in each case a failure at a central element propagated to a population of dependents far larger than the element itself. That is what Section 8's attack curve predicts, and it is the sense in which modern concentration risk is a network property rather than a series of unrelated accidents. [Doyle and colleagues \(2005\)](#) described the general pattern as “robust yet fragile”: systems optimized to tolerate the failures their designers expected become, as a consequence, exposed to the ones they did not.

10.2 The efficiency–fragility frontier

How steep is the trade? The report compared seven network designs of about 200 nodes each on two measures: efficiency, as the average distance between two nodes, and robustness, as the share of the network that stays connected after the best-connected nodes are removed (Figure 13). The star, the

purest center, has the shortest average distance, 2.0 steps, and is destroyed by the loss of its hub, leaving 0.5% of nodes connected. The ring is robust to any single failure and slow, with an average of 49 steps. Between them lie hub-rich growth, 3.3 steps with 99% connected after the worst single failure, and a design built for the purpose: five interlinked hubs, each node tied to two of them, with some lateral links. It averages 2.35 steps and survives the loss of any one hub, but only 25% stays connected when all five hubs are removed together, because the periphery has too few links of its own.

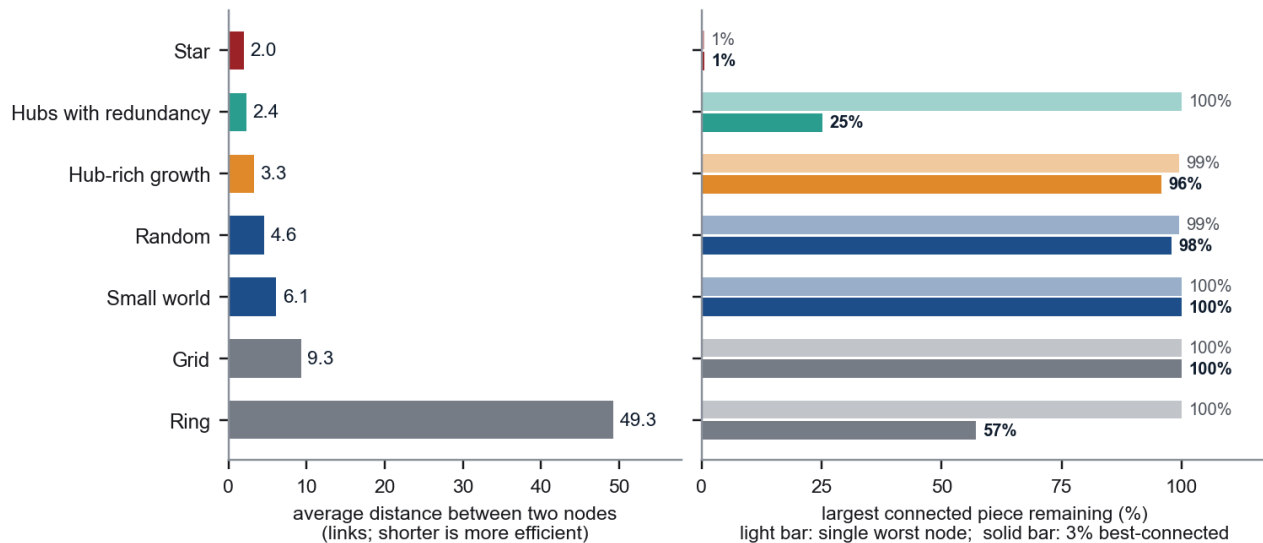


Figure 13. Seven network designs compared. Left: average distance between two nodes (shorter is more efficient). Right: largest connected piece remaining after the single worst-placed node is removed (light bar) and after the 3% best-connected nodes are removed (solid bar). The star is the most efficient and the most fragile; the ring is the reverse. A small interlinked core with redundancy keeps most of the efficiency and survives a single failure, but not the loss of the whole core.

Source: H Heuristics calculations. 196–200 nodes per design; star, ring, 14×14 grid, random graph, small-world, preferential attachment (2 links per node), and a five-hub core with each periphery node linked to two hubs plus lateral links. Ties in degree are broken at random.

The lesson is not that centers should be avoided. It is that the cost of a center depends on its redundancy, and that the usual policy of adding capacity to the center, which looks like resilience, can make the system more efficient and more dependent at the same time. A design with five hubs is more robust than a design with one, but the hubs, if few, remain a target.

10.3 Capture

Fragility is a risk from accident and attack. A related cost is capture. A center that controls a resource everyone needs can charge for it, delay it or withhold it, so centers attract those who want to control them. This is an interpretive claim of the report, not a measurement, and it is graded C: the economic literature on market power and the political-science literature on state capture are large and are outside what the report calculates. It suggests only that the structural features that make a center useful, that everything passes through it, also make it valuable to control, and that where such centers exist, rules on access and ownership matter as much as the engineering.

11

WHERE CENTRALITY FAILS



11. Where Centrality Fails

11.1 Systems that work without a center

The strongest argument against a universal architecture of centrality is that many successful systems do not have one. Section 4 already supplied the largest example, the universe. Others are smaller and closer. A colony of harvester ants allocates its workers without a ruler, as shown in Section 5. The slime mold *Physarum polycephalum*, a single cell with no brain, [solves mazes](#) by retracting from dead ends, and a model of its tube-building rules, applied to a map of the towns around Tokyo, produced a [network with efficiency and fault tolerance comparable to the real rail system](#). The nervous system relies on [degeneracy](#), different structures that can perform the same function. Some woodland ecosystems are linked below ground by [mycorrhizal networks](#) whose functions, and whether they are organized around “hub trees”, are active subjects of research and debate that this report does not adjudicate.

11.2 Polycentric order

In human institutions, the leading alternative is *polycentric* organization, in which many centers of decision-making have overlapping jurisdictions and none is supreme. [Ostrom, Tiebout and Warren \(1961\)](#) argued that the many small governments of a metropolitan area were better described as a system than as a mess, and [Ostrom \(2010\)](#) summarized a research programme showing that polycentric arrangements can manage shared resources, from fisheries to groundwater, without a single central authority, with the benefit of local knowledge and of redundancy when a unit fails. A recognized risk is that polycentric systems may be slow to coordinate where coordination is essential, for example in a pandemic or a financial crisis. The choice is a design problem, not an ideological one.

11.3 The statistics of hubs

A second kind of failure is statistical. Many claims of centrality rest on distributions that look like straight lines on logarithmic axes. [Clauset, Shalizi and Newman \(2009\)](#) showed that a straight-looking line is not enough: lognormal and exponential distributions can mimic a power law over the range of most datasets, and a rigorous test needs a fitted lower bound and a likelihood comparison. [Broido and Clauset \(2019\)](#) applied it to nearly a thousand real networks and found that strongly scale-free structure is empirically rare, while hubs of some kind are common.

The report applied the same method to its own data. The grown network, as it should, was not distinguishable from a power law (the likelihood comparison with a lognormal was inconclusive, $p = 0.64$) and fitted far better than an exponential. The airport network told a different story. It is strongly concentrated, with the busiest 1% of airports holding 14.8% of endpoints. But in the tail, from 37 destinations upward, a power law with exponent 2.53 fitted worse than both an exponential ($z = -2.9$, $p = 0.004$) and a lognormal ($z = -3.5$, $p = 0.0005$). Real airports cannot grow without limit, because gates,

runways and slots are finite, so the largest hubs plateau. Concentration is real; the power law is an approximation that fails at the top. For cities, as Section 6 reported, the rank-size slope depended on definitions and the median was 1.36, not 1.

11.4 The robust form

Taken together the counterexamples point to a pattern rather than a refutation. Systems that last for a long time keep a center and refuse to depend on only one, and the form that results is repeated across domains (Figure 14). In the bow tie of [Csete and Doyle \(2004\)](#), a narrow core of interchangeable standards, such as ATP in cells or the Internet Protocol online, joins a wide variety of sources to a wide variety of uses. The core is small, interlinked and redundant; the periphery is varied, local and replaceable; and lateral connections let the periphery bypass the core when necessary. The airlines, the brain's rich club and polycentric governance are all, in different ways, variations on it.

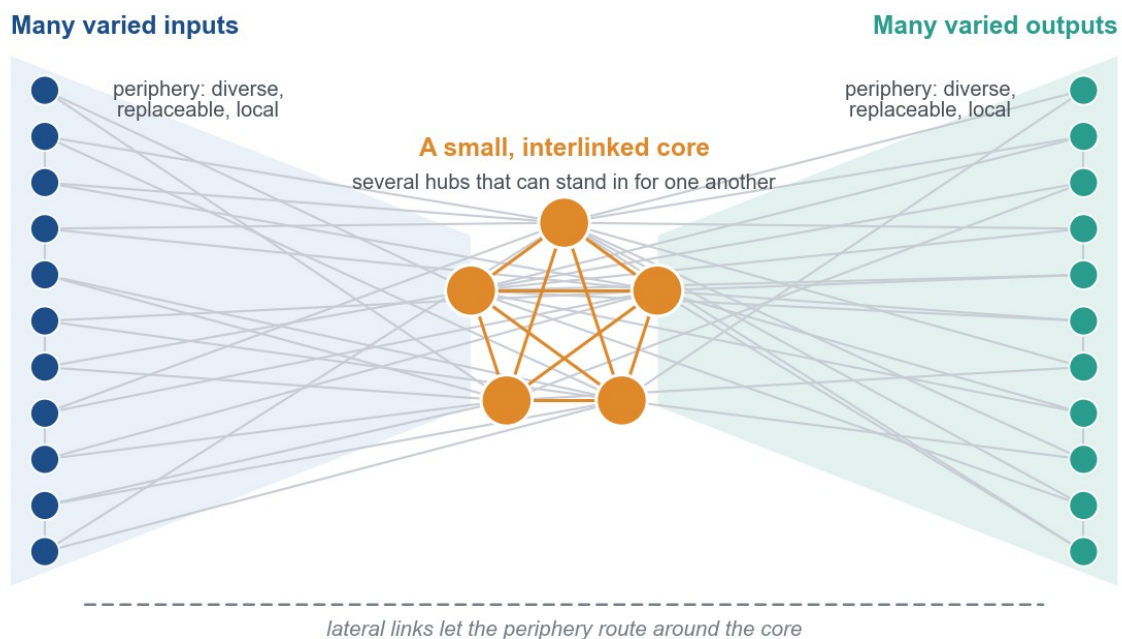


Figure 14. The robust form of centrality. A small, interlinked core of hubs that can stand in for one another joins a diverse periphery of inputs to a diverse periphery of outputs, and lateral links let the periphery route around the core. The pattern is found in metabolism, in the Internet and in polycentric institutions.

Source: *H Heuristics schematic, after Csete and Doyle (2004) and the robust-yet-fragile analysis of Doyle et al. (2005).*

Finding. The architecture that evidence supports is not one center but a few, joined to each other and to a periphery that can operate without them. Where a system seems to depend on exactly one center, it is either young, small, short-lived or lucky.

12

TESTING THE HYPOTHESIS

12. Testing the Hypothesis

12.1 Nine calculations

The report's descriptive and explanatory hypotheses make predictions, and nine of them could be tested with the models and data described in Sections 4 to 11 (Table 7). Each calculation was designed so that it could have come out against the hypothesis. Two came out against the universal form of the hypothesis and two were mixed. That is the intended outcome of a test, and the results from the failures shape the verdict as much as those from the successes.

Table 7. Nine calculations and what each shows

Test	Question	Result	Verdict
T1 Collapse	Does gravity alone build a center from a uniform cloud?	A sphere of radius 0.1 around the density peak went from 0.1% to 22% of the mass	Supports
T2 Mass share	Is the center's share of mass universal?	From 99.9% (atom) to 0.00033% (Galaxy); none for the universe	Rejects a universal share
T3 Growth rule	Does cumulative advantage produce hubs?	Largest hub 212 links against 13; top 1% hold 11.7% against 2.6%	Supports
T4 Failure and attack	Are hubs fragile to targeted removal?	At 20% removed: 1.2% connected when targeted, 78% when random	Supports
T5 Topologies	Is the most efficient design the most fragile?	Star: 2.0 steps and 0.5% connected after hub loss; ring: 49 steps and fully connected	Supports
T6 Trade-off	Does the cost of distance move a system from hub to web?	Direct links to the center: 100% ($\alpha \leq 1$) to 0.3% ($\alpha = 400$); wiring 14 to 1	Supports
T7 Airports	Is a real hub network a clean power law?	Top 1% hold 14.8% of endpoints; tail fits exponential and lognormal better	Mixed
T8 City systems	Is Zipf's law universal?	Median slope 1.36; largest-to-second ratio 1.04 to 13.1	Rejects universality
T9 Measures	Do centrality measures agree?	Rank correlations 0.69 to 0.90 on a real 34-node network	Partly

Calculations T1 to T9 are described in Appendix A. The verdict column states whether the result supports the hypothesis that centers are produced by shared generators, or limits it.

The tests show a consistent shape. Where the question is whether a mechanism can produce a center (T1, T3, T6), the answer is yes, and from very simple rules. Where the question is what a center costs (T4, T5), the answer is a fragility that grows with the center's importance. Where the question is whether centers are *alike* (T2, T7, T8, T9), the answer is no: the mass share, the statistical form, the degree of primacy and even the identity of the central node depend on what is measured. The generators are shared; the outcomes are not.

12.2 The scorecard

Figure 15 grades nine classes of system on four properties: whether a center is observed, whether a mechanism is understood, whether the center is found in every member of the class, and whether the cost or fragility of the center has been documented. The grades reflect the evidence in Sections 4 to 11. They are the report's judgment, not an objective score, and are open to challenge.

	A center is observed	A mechanism is understood	Found in all cases of the class	Cost or fragility is documented
Stars, planetary systems, atoms	A	A	A	—
Galaxy cores	A	B	B	—
The universe as a whole	None	A	A	—
Earth and fluid systems	A	A	B	—
Organisms and ecosystems	A	B	B	B
Cities and economies	A	B	C	B
Technological networks	A	A	C	A
Minds and cultures	B	C	C	C
States and institutions	A	B	C	B

Established
 Well supported
 Plausible or contested
 Not applicable or absent

Figure 15. Scorecard by class of system. Grades A to C follow the evidence scale in the About section. Centers are well observed in the physical and technological worlds and rest on weaker evidence in minds, cultures and institutions. Universality is graded C wherever counterexamples are documented. For the universe as a whole the finding is that no center exists.

Source: H Heuristics assessment. A dash marks a property that does not apply or has not been established as a cost; "None" marks the observed absence of a center.

- **Stars, planetary systems, atoms, galaxy cores and Earth (A, A–B, A–B).** The center is observed directly, gravity or electromagnetism explains it, and it occurs in nearly every member of the class; dwarf and disk galaxies are weaker cases, and why black-hole mass tracks the host galaxy is only partly understood.
- **The universe as a whole (none, A, A).** Homogeneity is among the best-established facts in cosmology. It is also the clearest counterexample in the report.
- **Organisms and ecosystems (A, B, B, B).** Centers are everywhere and mechanisms are partly understood; redundant backups are common, so universality is B, and the cost of removing a center has been measured in many cases.
- **Cities, economies and technological networks (A, A–B, C, A–B).** Concentration is large and documented and the mechanisms are modeled, but statistical forms are not universal; fragility is documented in detail for technological networks.
- **Minds, cultures, states and institutions (A–B, B–C, C, B–C).** Centers are real as perception and as organization, but their causes are contested and claims of necessity are graded lower.

12.3 Verdict at three levels

Table 8. Verdict on the hypothesis at three levels

Level	Claim	Grade	Basis
Descriptive	Centers are common across domains, beyond what random organization gives	A–B	T1, T3, T7 and Sections 4 to 6; measured concentration well above null models
Explanatory	Five generators account for most centers, and shared generators give shared signatures	B	T1, T3, T6 reproduce centers from simple rules; T2, T7, T8 show that signatures differ
Metaphysical	Reality as a whole is organized around One	D	Not testable with these methods; the universe shows no center (Section 4.5)

A grade describes the state of knowledge about the claim, not the importance of the claim.

13

HYPOTHESES AND IMPLICATIONS



13. Hypotheses and Implications

13.1 Ten testable propositions

The report closes with ten propositions that follow from its findings and that data could confirm or reject. They are original to this report; each states what would falsify it.

Table 9. Ten testable propositions

Proposition	Falsified if
P1 In networks grown by cumulative advantage, the largest hub scales as $N^{1/(y-1)}$; real networks with hard capacity limits fall below this line at large N .	Capacity-limited networks keep following the unconstrained scaling
P2 Hub tails in capacity-limited systems (airports, ports, data centers) are better fitted by exponential or lognormal forms than by power laws; systems without capacity limits (citations, links) are not.	Both kinds are fitted equally well by power laws
P3 A system moves from hub-and-spoke to a web when the cost of distance rises relative to the cost of each step; the transition occurs near the ratio at which the star stops being cost-optimal.	Observed restructurings do not track the cost ratio
P4 Robustness of an infrastructure network to targeted attack depends more on the number and interconnection of its top hubs than on the exponent of its degree distribution.	The exponent predicts robustness better than hub redundancy does
P5 A country's primacy ratio is higher where transport and fiscal systems are more radial.	Primacy and centralization indices are uncorrelated across countries
P6 Zipf slopes estimated from built-up-area clusters are closer to 1 than slopes from administrative boundaries in every country sampled.	Any country shows the reverse
P7 The more essential a central structure is to an organism's survival, the more often a documented compensatory mechanism exists.	Essential centers lack fallbacks as often as non-essential ones
P8 Outage size in large digital services scales with the number of dependents of the failed component, not the severity of the fault.	Fault severity explains outage size better than dependence
P9 Descriptions of complex systems mention central nodes more often than their share of flow warrants.	Descriptions match flow-weighted shares
P10 A dominant node's share falls whenever a system's boundary is widened; centers are properties of bounded subsystems.	A nested sequence of boundaries is found in which the share rises

P1 uses the exponent y of the degree distribution and N , the number of nodes; for the Barabási–Albert model, $y = 3$.

13.2 Implications

For system design. The question is seldom whether to have a center but how many, how interconnected, and with what backup. The evidence favors a small number of interlinked hubs with lateral links in the periphery, the bow-tie form in Figure 14. Designs that put capacity in a single node raise average performance and lower survival. The test is that the periphery should be able to run, more slowly, without the core.

For risk and policy. Concentration is a systemic risk because its costs are paid by the dependents of the center, not by the center. H Heuristics' work on compound and cascading risk, such as [The Cascading Risk Atlas](#) and [The Polycrisis Apocalypse](#), treats the interdependence of infrastructure, finance and ecosystems as a central feature of twenty-first-century danger. The findings here add a structural prediction: the most damaging failures are those at the hubs, and the most useful interventions identify hubs and add redundancy to them before failure, not after. Where a center cannot be duplicated, as with a canal or a grid, the policy question is the cost of slack.

For organizations. Centralize what must be consistent, such as standards, timing and identity, and decentralize what must adapt, such as local decisions, because the first is cheap to coordinate through a center and the second is costly to coordinate through one. The experiments of Bavelas and Leavitt, the polycentric governance work of Ostrom and the biology of degeneracy converge on this division.

For science. Any claim of centrality should name the quantity, the scale and the null model. Several popular statements about hubs, scale-free networks and Zipf laws fail when tested against those standards, and the failures are informative: capacity limits, definitions of the unit and finite samples produce departures that tell us how real systems differ from the models.

For the series. Centrality joins fractal geometry, entropy and network structure as one of the recurring structural motifs of the Architecture of Creation. It is a motif of *process* rather than shape: a handful of generators, applied in different domains, produce related but not identical results. The unification the series seeks is the unification of those processes, not a claim that everything is a hub.

14

CONCLUSION



14. Conclusion

The question was why creation, nature and human systems repeatedly organize around one. The report's answer has three parts, and each part has a different strength.

First, the pattern is real. Gravity builds centers wherever matter can fall together; growth by cumulative advantage builds hubs wherever size attracts size; cost of distance builds junctions wherever things must move; coordination builds clocks, hubs and capitals wherever parts must act as one; and selection preserves the concentrations that work. From a hydrogen atom to the world airport network, concentration around a few dominant nodes is far more common than random organization would produce, and in the physical and technological worlds it is measured, modeled and, in the case of the Milky Way's black hole, photographed.

Second, the pattern is plural, not universal. The center's share of its system runs from nearly all to nearly nothing. City systems range from two near-equal cities to one city more than ten times the size of the second. The best tests of statistical law, such as scale-free degree distributions and Zipf's rank-size rule, are met in some systems and not in others. The largest scale of the universe has no center at all. Wherever a theory of One has to say *which* One, *of what* and *at what scale*, it turns into a theory of many.

Third, the form that endures is a center that is not alone. Systems that last for long periods combine a small, interlinked core with a varied periphery and with ways round the core. The single point of failure is not an exception to the architecture but its cost, and recent disruptions of canals, pipelines, grids and clouds are examples. The designers who learn this from biology and from engineering build systems with centers and without sole dependence on any one.

What the report cannot say is whether the recurrence of centers means anything about reality as a whole. That is a question for philosophy and theology as much as for science, and the evidence here neither establishes it nor excludes it. What it can say is that if the world is organized around anything, the organizing is done by processes that are understood, that produce centers in many places and not in one, and that reward systems which keep their centers plural.

In one sentence. Nature and human systems repeatedly organize around centers, but not around a single One: a few processes build many centers, and the structures that last keep a center without depending on only one.

References

- Albert, R. & Barabási, A. L. (2002). Statistical mechanics of complex networks. *Reviews of Modern Physics* 74, 47-97. [doi:10.1103/RevModPhys.74.47](https://doi.org/10.1103/RevModPhys.74.47)
- 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)
- Arcaute, E. et al. (2015). Constructing cities, deconstructing scaling laws. *Journal of The Royal Society Interface* 12, 20140745. [doi:10.1098/rsif.2014.0745](https://doi.org/10.1098/rsif.2014.0745)
- 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)
- Axtell, R. L. (2001). Zipf Distribution of U.S. Firm Sizes. *Science* 293, 1818-1820. [doi:10.1126/science.1062081](https://doi.org/10.1126/science.1062081)
- 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)
- Bavelas, A. (1950). Communication Patterns in Task-Oriented Groups. *The Journal of the Acoustical Society of America* 22, 725-730. [doi:10.1121/1.1906679](https://doi.org/10.1121/1.1906679)
- Beheim, B. et al. (2021). Treatment of missing data determined conclusions regarding moralizing gods. *Nature* 595, E29-E34. [doi:10.1038/s41586-021-03655-4](https://doi.org/10.1038/s41586-021-03655-4)
- 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)
- 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)
- Bland-Hawthorn, J. & Gerhard, O. (2016). The Galaxy in Context: Structural, Kinematic, and Integrated Properties. *Annual Review of Astronomy and Astrophysics* 54, 529-596. [doi:10.1146/annurev-astro-081915-023441](https://doi.org/10.1146/annurev-astro-081915-023441)
- Bonacich, P. (1972). Factoring and weighting approaches to status scores and clique identification. *The Journal of Mathematical Sociology* 2, 113-120. [doi:10.1080/0022250X.1972.9989806](https://doi.org/10.1080/0022250X.1972.9989806)
- 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)
- Borgatti, S. P. (2005). Centrality and network flow. *Social Networks* 27, 55-71. [doi:10.1016/j.socnet.2004.11.008](https://doi.org/10.1016/j.socnet.2004.11.008)
- Brin, S. & Page, L. (1998). The anatomy of a large-scale hypertextual Web search engine. *Computer Networks and ISDN Systems* 30, 107-117. [doi:10.1016/S0169-7552\(98\)00110-X](https://doi.org/10.1016/S0169-7552(98)00110-X)
- 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)
- 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)
- Carneiro, R. L. (1970). A Theory of the Origin of the State. *Science* 169, 733-738. [doi:10.1126/science.169.3947.733](https://doi.org/10.1126/science.169.3947.733)
- 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)
- Csete, M. & Doyle, J. (2004). Bow ties, metabolism and disease. *Trends in Biotechnology* 22, 446-450. [doi:10.1016/j.tibtech.2004.07.007](https://doi.org/10.1016/j.tibtech.2004.07.007)
- Csete, M. E. & Doyle, J. C. (2002). Reverse Engineering of Biological Complexity. *Science* 295, 1664-1669. [doi:10.1126/science.1069981](https://doi.org/10.1126/science.1069981)
- Domagalska, M. A. & Leyser, O. (2011). Signal integration in the control of shoot branching. *Nature Reviews Molecular Cell Biology* 12, 211-221. [doi:10.1038/nrm3088](https://doi.org/10.1038/nrm3088)
- Doyle, J. C. et al. (2005). The "robust yet fragile" nature of the Internet. *Proceedings of the National Academy of Sciences* 102, 14497-14502. [doi:10.1073/pnas.0501426102](https://doi.org/10.1073/pnas.0501426102)
- Dunbar, R. (1992). Neocortex size as a constraint on group size in primates. *Journal of Human Evolution* 22, 469-493. [doi:10.1016/0047-2484\(92\)90081-J](https://doi.org/10.1016/0047-2484(92)90081-J)
- Dziewonski, A. M. & Anderson, D. L. (1981). Preliminary reference Earth model. *Physics of the Earth and Planetary Interiors* 25, 297-356. [doi:10.1016/0031-9201\(81\)90046-7](https://doi.org/10.1016/0031-9201(81)90046-7)
- Edelman, G. M. & Gally, J. A. (2001). Degeneracy and complexity in biological systems. *Proceedings of the National Academy of Sciences* 98, 13763-13768. [doi:10.1073/pnas.231499798](https://doi.org/10.1073/pnas.231499798)

- Emanuel, K. A. (1986). An Air-Sea Interaction Theory for Tropical Cyclones. Part I: Steady-State Maintenance. *Journal of the Atmospheric Sciences* 43, 585-605. [doi:10.1175/1520-0469\(1986\)043<0585:AASITF>2.0.CO;2](https://doi.org/10.1175/1520-0469(1986)043<0585:AASITF>2.0.CO;2)
- Event Horizon Telescope Collaboration et al. (2022). First Sagittarius A Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole in the Center of the Milky Way. *The Astrophysical Journal Letters* 930, L12*. [doi:10.3847/2041-8213/ac6674](https://doi.org/10.3847/2041-8213/ac6674)
- Fabrikant, A. et al. (2002). Heuristically Optimized Trade-Offs: A New Paradigm for Power Laws in the Internet. *Lecture Notes in Computer Science*, 110-122. [doi:10.1007/3-540-45465-9_11](https://doi.org/10.1007/3-540-45465-9_11)
- Faloutsos, M. et al. (1999). On power-law relationships of the Internet topology. *ACM SIGCOMM Computer Communication Review* 29, 251-262. [doi:10.1145/316194.316229](https://doi.org/10.1145/316194.316229)
- Ferrarese, L. & Merritt, D. (2000). A Fundamental Relation between Supermassive Black Holes and Their Host Galaxies. *The Astrophysical Journal* 539, L9-L12. [doi:10.1086/312838](https://doi.org/10.1086/312838)
- Freeman, L. C. (1978). Centrality in social networks conceptual clarification. *Social Networks* 1, 215-239. [doi:10.1016/0378-8733\(78\)90021-7](https://doi.org/10.1016/0378-8733(78)90021-7)
- Fujita, M. & Ogawa, H. (1982). Multiple equilibria and structural transition of non-monocentric urban configurations. *Regional Science and Urban Economics* 12, 161-196. [doi:10.1016/0166-0462\(82\)90031-X](https://doi.org/10.1016/0166-0462(82)90031-X)
- 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)
- Gebhardt, K. et al. (2000). A Relationship between Nuclear Black Hole Mass and Galaxy Velocity Dispersion. *The Astrophysical Journal* 539, L13-L16. [doi:10.1086/312840](https://doi.org/10.1086/312840)
- Genzel, R. et al. (2010). The Galactic Center massive black hole and nuclear star cluster. *Reviews of Modern Physics* 82, 3121-3195. [doi:10.1103/RevModPhys.82.3121](https://doi.org/10.1103/RevModPhys.82.3121)
- Ghez, A. M. et al. (2008). Measuring Distance and Properties of the Milky Way's Central Supermassive Black Hole with Stellar Orbits. *The Astrophysical Journal* 689, 1044-1062. [doi:10.1086/592738](https://doi.org/10.1086/592738)
- Gordon, D. M. & Mehdiabadi, N. J. (1999). Encounter rate and task allocation in harvester ants. *Behavioral Ecology and Sociobiology* 45, 370-377. [doi:10.1007/s002650050573](https://doi.org/10.1007/s002650050573)
- Guimerà, R. et al. (2005). The worldwide air transportation network: Anomalous centrality, community structure, and cities' global roles. *Proceedings of the National Academy of Sciences* 102, 7794-7799. [doi:10.1073/pnas.0407994102](https://doi.org/10.1073/pnas.0407994102)
- Guimerà, R. & Amaral, L. A. N. (2004). Modeling the world-wide airport network. *The European Physical Journal B* 38, 381-385. [doi:10.1140/epjb/e2004-00131-0](https://doi.org/10.1140/epjb/e2004-00131-0)
- Hogg, D. W. et al. (2005). Cosmic Homogeneity Demonstrated with Luminous Red Galaxies. *The Astrophysical Journal* 624, 54-58. [doi:10.1086/429084](https://doi.org/10.1086/429084)
- Jefferson, M. (1939). The Law of the Primate City. *Geographical Review* 29, 226. [doi:10.2307/209944](https://doi.org/10.2307/209944)
- Jeong, H. et al. (2000). The large-scale organization of metabolic networks. *Nature* 407, 651-654. [doi:10.1038/35036627](https://doi.org/10.1038/35036627)
- Jeong, H. et al. (2001). Lethality and centrality in protein networks. *Nature* 411, 41-42. [doi:10.1038/35075138](https://doi.org/10.1038/35075138)
- Kormendy, J. & Ho, L. C. (2013). Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. *Annual Review of Astronomy and Astrophysics* 51, 511-653. [doi:10.1146/annurev-astro-082708-101811](https://doi.org/10.1146/annurev-astro-082708-101811)
- Krugman, P. (1991). Increasing Returns and Economic Geography. *Journal of Political Economy* 99, 483-499. [doi:10.1086/261763](https://doi.org/10.1086/261763)
- Krugman, P. (1996). Confronting the Mystery of Urban Hierarchy. *Journal of the Japanese and International Economies* 10, 399-418. [doi:10.1006/jjie.1996.0023](https://doi.org/10.1006/jjie.1996.0023)
- Leavitt, H. J. (1951). Some effects of certain communication patterns on group performance. *The Journal of Abnormal and Social Psychology* 46, 38-50. [doi:10.1037/h0057189](https://doi.org/10.1037/h0057189)
- Louf, R. & Barthelemy, M. (2013). Modeling the Polycentric Transition of Cities. *Physical Review Letters* 111, 198702. [doi:10.1103/PhysRevLett.111.198702](https://doi.org/10.1103/PhysRevLett.111.198702)
- Mangoni, M. E. & Nargeot, J. (2008). Genesis and Regulation of the Heart Automaticity. *Physiological Reviews* 88, 919-982. [doi:10.1152/physrev.00018.2007](https://doi.org/10.1152/physrev.00018.2007)
- Marder, E. & Bucher, D. (2001). Central pattern generators and the control of rhythmic movements. *Current Biology* 11, R986-R996. [doi:10.1016/S0960-9822\(01\)00581-4](https://doi.org/10.1016/S0960-9822(01)00581-4)
- Meindl, J. R. et al. (1985). The Romance of Leadership. *Administrative Science Quarterly* 30, 78. [doi:10.2307/2392813](https://doi.org/10.2307/2392813)
- Merton, R. K. (1968). The Matthew Effect in Science. *Science* 159, 56-63. [doi:10.1126/science.159.3810.56](https://doi.org/10.1126/science.159.3810.56)
- Motter, A. E. & Lai, Y. C. (2002). Cascade-based attacks on complex networks. *Physical Review E* 66, 065102. [doi:10.1103/PhysRevE.66.065102](https://doi.org/10.1103/PhysRevE.66.065102)
- Nakagaki, T. et al. (2000). Maze-solving by an amoeboid organism. *Nature* 407, 470-470. [doi:10.1038/35035159](https://doi.org/10.1038/35035159)

- Navarro, J. F. et al. (1997). A Universal Density Profile from Hierarchical Clustering. *The Astrophysical Journal* 490, 493-508. [doi:10.1086/304888](https://doi.org/10.1086/304888)
- 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. (2003). The Structure and Function of Complex Networks. *SIAM Review* 45, 167-256. [doi:10.1137/S003614450342480](https://doi.org/10.1137/S003614450342480)
- Norenzayan, A. et al. (2016). The cultural evolution of prosocial religions. *Behavioral and Brain Sciences* 39, e1. [doi:10.1017/S0140525X14001356](https://doi.org/10.1017/S0140525X14001356)
- Ostrom, E. (2010). Beyond Markets and States: Polycentric Governance of Complex Economic Systems. *American Economic Review* 100, 641-672. [doi:10.1257/aer.100.3.641](https://doi.org/10.1257/aer.100.3.641)
- Ostrom, V. et al. (1961). The Organization of Government in Metropolitan Areas: A Theoretical Inquiry. *American Political Science Review* 55, 831-842. [doi:10.2307/1952530](https://doi.org/10.2307/1952530)
- Paine, R. T. (1966). Food Web Complexity and Species Diversity. *The American Naturalist* 100, 65-75. [doi:10.1086/282400](https://doi.org/10.1086/282400)
- 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)
- Price, D. D. S. (1976). A general theory of bibliometric and other cumulative advantage processes. *Journal of the American Society for Information Science* 27, 292-306. [doi:10.1002/asi.4630270505](https://doi.org/10.1002/asi.4630270505)
- Price, D. J. d. S. (1965). Networks of Scientific Papers. *Science* 149, 510-515. [doi:10.1126/science.149.3683.510](https://doi.org/10.1126/science.149.3683.510)
- Raichle, M. E. & Gusnard, D. A. (2002). Appraising the brain's energy budget. *Proceedings of the National Academy of Sciences* 99, 10237-10239. [doi:10.1073/pnas.172399499](https://doi.org/10.1073/pnas.172399499)
- Reppert, S. M. & Weaver, D. R. (2002). Coordination of circadian timing in mammals. *Nature* 418, 935-941. [doi:10.1038/nature00965](https://doi.org/10.1038/nature00965)
- Rinaldo, A. et al. (1993). Self-organized fractal river networks. *Physical Review Letters* 70, 822-825. [doi:10.1103/PhysRevLett.70.822](https://doi.org/10.1103/PhysRevLett.70.822)
- Roberts, P. H. & King, E. M. (2013). On the genesis of the Earth's magnetism. *Reports on Progress in Physics* 76, 096801. [doi:10.1088/0034-4885/76/9/096801](https://doi.org/10.1088/0034-4885/76/9/096801)
- Rosch, E. (1975). Cognitive representations of semantic categories. *Journal of Experimental Psychology: General* 104, 192-233. [doi:10.1037/0096-3445.104.3.192](https://doi.org/10.1037/0096-3445.104.3.192)
- Rozenfeld, H. D. et al. (2011). The Area and Population of Cities: New Insights from a Different Perspective on Cities. *American Economic Review* 101, 2205-2225. [doi:10.1257/aer.101.5.2205](https://doi.org/10.1257/aer.101.5.2205)
- Sapolsky, R. M. (2005). The Influence of Social Hierarchy on Primate Health. *Science* 308, 648-652. [doi:10.1126/science.1106477](https://doi.org/10.1126/science.1106477)
- Shapley, H. (1918). Globular clusters and the structure of the galactic system. *Publications of the Astronomical Society of the Pacific* 30, 42-42. [doi:10.1086/122686](https://doi.org/10.1086/122686)
- 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)
- Sosso, G. C. et al. (2016). Crystal Nucleation in Liquids: Open Questions and Future Challenges in Molecular Dynamics Simulations. *Chemical Reviews* 116, 7078-7116. [doi:10.1021/acs.chemrev.5b00744](https://doi.org/10.1021/acs.chemrev.5b00744)
- Sporns, O. et al. (2007). Identification and Classification of Hubs in Brain Networks. *PLoS ONE* 2, e1049. [doi:10.1371/journal.pone.0001049](https://doi.org/10.1371/journal.pone.0001049)
- 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)
- Tatler, B. W. (2007). The central fixation bias in scene viewing: Selecting an optimal viewing position independently of motor biases and image feature distributions. *Journal of Vision* 7, 4. [doi:10.1167/7.14.4](https://doi.org/10.1167/7.14.4)
- Tero, A. et al. (2010). Rules for Biologically Inspired Adaptive Network Design. *Science* 327, 439-442. [doi:10.1126/science.1177894](https://doi.org/10.1126/science.1177894)
- Thimann, K. V. et al. (1934). On the inhibition of bud development and other functions of growth substance in vicia faba. *Proceedings of the Royal Society of London. Series B, Containing Papers of a Biological Character* 114, 317-339. [doi:10.1098/rspb.1934.0010](https://doi.org/10.1098/rspb.1934.0010)
- Tversky, A. & Kahneman, D. (1974). Judgment under Uncertainty: Heuristics and Biases. *Science* 185, 1124-1131. [doi:10.1126/science.185.4157.1124](https://doi.org/10.1126/science.185.4157.1124)
- van den Heuvel, M. P. & Sporns, O. (2011). Rich-Club Organization of the Human Connectome. *The Journal of Neuroscience* 31, 15775-15786. [doi:10.1523/JNEUROSCI.3539-11.2011](https://doi.org/10.1523/JNEUROSCI.3539-11.2011)
- Vitali, S. et al. (2011). The Network of Global Corporate Control. *PLoS ONE* 6, e25995. [doi:10.1371/journal.pone.0025995](https://doi.org/10.1371/journal.pone.0025995)

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)

Zachary, W. W. (1977). An Information Flow Model for Conflict and Fission in Small Groups. *Journal of Anthropological Research* 33, 452-473. [doi:10.1086/jar.33.4.3629752](https://doi.org/10.1086/jar.33.4.3629752)

Data and web sources

GeoNames (2026). *GeoNames geographical database: cities with population above 15,000*. geonames.org/export; data used under the Creative Commons Attribution licence.

OpenFlights (n.d.). *Airport and airline route data*. openflights.org/data.php.

NASA Goddard Space Flight Center (n.d.). *Sun fact sheet* and *Planetary fact sheet*. nssdc.gsfc.nasa.gov/planetary/factsheet.

Amazon Web Services (2025). *Summary of the Amazon DynamoDB service disruption in the Northern Virginia (US-EAST-1) region*. aws.amazon.com/message/101925.

Cybersecurity and Infrastructure Security Agency (2021). *Joint advisory AA21-131A: DarkSide ransomware*. cisa.gov.

Simon, H. A. (1962). The architecture of complexity. *Proceedings of the American Philosophical Society* 106, 467-482. [jstor.org/stable/985254](https://www.jstor.org/stable/985254).

Zipf, G. K. (1949). *Human Behavior and the Principle of Least Effort*. Addison-Wesley; see [Zipf's law](#).

Christaller, W. (1933). *Die zentralen Orte in Süddeutschland*. Gustav Fischer; see [Central place theory](#).

Eliade, M. (1957). *Das Heilige und das Profane*. Rowohlt; English edition *The Sacred and the Profane* (1959); see [Axis mundi](#).

Wikipedia articles cited for concepts and event summaries, including [Centrality](#), [Central place theory](#), [Primate city](#), [Zipf's law](#), [Preferential attachment](#) and [Cosmological principle](#).

Appendix A. Methods and Data

All calculations were made in Python with NumPy, SciPy, NetworkX and Matplotlib. Random seeds are fixed in the code, and every number quoted in the text is regenerated by running the scripts. The table lists each calculation with its main parameters.

Table 10. Calculations, parameters and data

ID	Calculation	Main parameters and data
T1	Gravitational collapse	N = 1,200 equal-mass particles; uniform sphere of radius 1; $G = M = 1$; velocity dispersion 0.12; softening 0.04; leapfrog, step 0.004 to $t = 6$; density center from the 50 particles with the smallest 10th-neighbor distances; energy drift 0.012%
T2	Center's mass share	Proton-to-electron mass ratio 1836.15; NASA planetary masses; Earth core 32.5% of mass; brain 2% of mass and 20% of resting energy; Sagittarius A* 4.3×10^6 and Milky Way 1.3×10^{12} solar masses
T3	Growth rule	Barabási–Albert graph, N = 20,000, 2 links per node; random graph with the same numbers of nodes and edges; power-law fit by maximum likelihood with Kolmogorov–Smirnov selection of the lower bound; Vuong likelihood-ratio tests
T4	Failure and attack	N = 3,000, average degree 4; removal at random (5 runs) and by initial degree, in steps of 2% to 50%; largest connected component
T5	Topologies	Seven designs of 196–200 nodes: star, ring, 14×14 grid, random, small world ($k = 4$, $p = 0.1$), Barabási–Albert ($m = 2$), five-hub core with lateral links; removal of the single worst node among the top 10 by degree, and of the top 3% with random tie-breaking
T6	Distance trade-off	N = 1,500 points in the unit square with root at the center; each new point links to the existing point minimizing $\alpha \times \text{distance} + \text{steps to root}$; 18 values of α from 0.05 to 400
T7	Airport network	OpenFlights routes and airports (about 2014): 3,257 airports with IATA codes, 18,930 undirected airport pairs; degree, concentration, tail fit (lower bound 37, 271 tail airports) and attack
T8	City systems	GeoNames cities15000 file, places of class P with population above zero; 20 countries; largest 100 cities per country; rank-size slope by the Gabaix–Ibragimov regression, standard error $b\sqrt{(2/n)}$
T9	Centrality measures	Zachary karate club network (34 nodes, 78 edges) from NetworkX; degree, closeness, betweenness and eigenvector centrality; Spearman rank correlation

Limits: the collapse model omits gas, dark matter and expansion; the OpenFlights data are a sample from about 2014; GeoNames populations are city-proper counts and depend on national definitions; the network models use small samples relative to real systems.