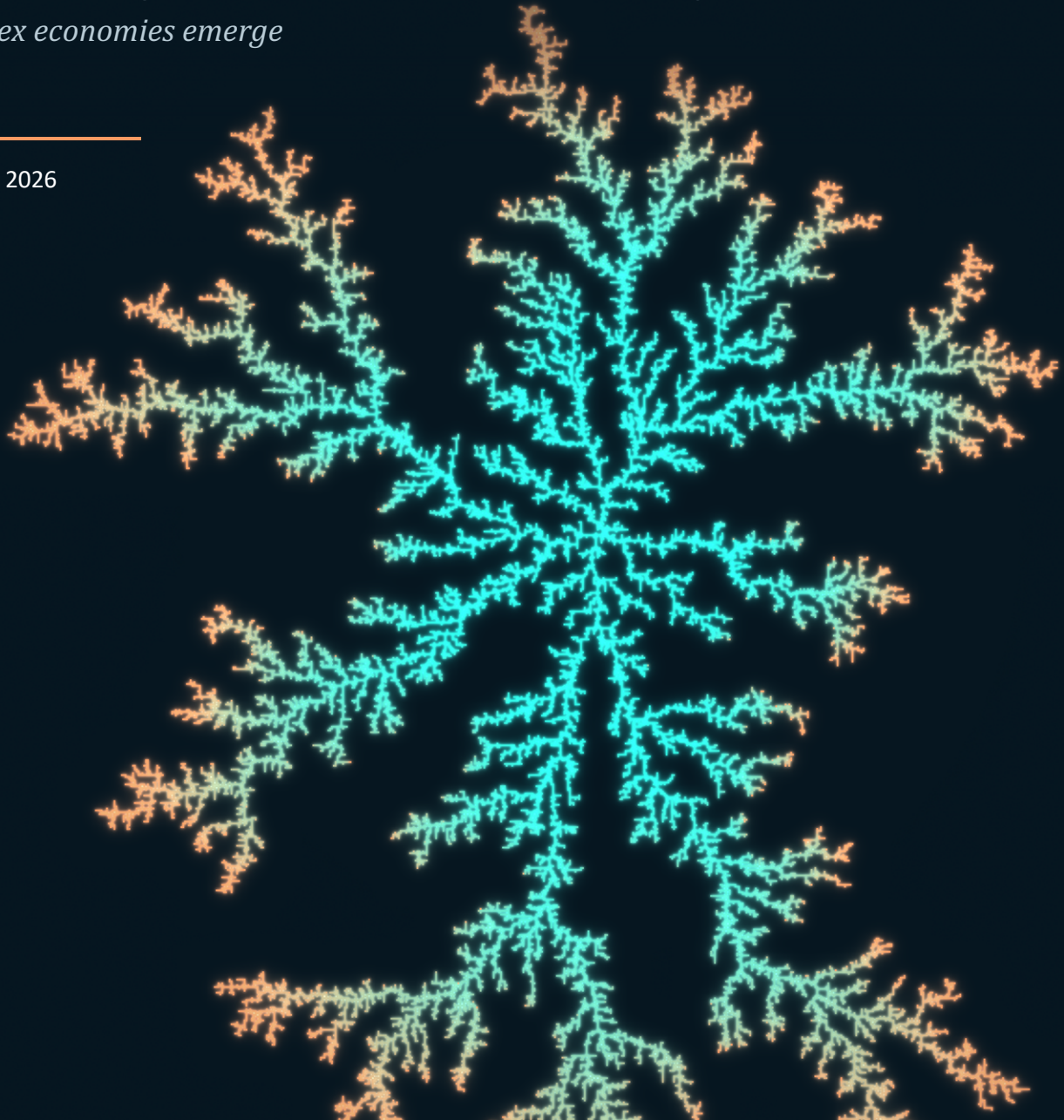


The Architecture of Creation and Development

Diffusion, convergence and the structural principles through which complex economies emerge

October 2026



ABOUT THIS REPORT

The Architecture of Creation and Development is a flagship research report by H Heuristics. It connects the structural principles through which complex forms emerge in natural systems with the economics of technology diffusion, productivity convergence and development, using the mathematics of diffusion as a bridge between physical processes and socioeconomic change.

HOW TO READ THIS REPORT

Sections 1 and 2 build the conceptual and mathematical foundations. Section 3 assembles the mathematics of innovation spread. Section 4 turns to convergence between economies, and Section 5 to the constraints that slow it. Section 6 integrates these elements into a unified architecture of development, and Section 7 converts that architecture into testable hypotheses and a research agenda. Technical derivations appear in Appendix A; data sources and methods in Appendix B. All citations are hyperlinked to their published source, and entries in the Contents link to their sections.

SUGGESTED CITATION

H Heuristics. 2026. *The Architecture of Creation and Development: Diffusion, Convergence and the Structural Principles through which Complex Economies Emerge*. Flagship Research Report. October 2026.

DATA

Empirical figures draw on public data from the [World Bank World Development Indicators](#), the [Maddison Project Database](#), the [International Telecommunication Union](#) and [Our World in Data](#), retrieved in October 2026. Simulations and illustrative figures are identified in their source notes. Appendix B documents all sources and methods.

DISCLAIMER

This report presents a research framework and an analysis of publicly available evidence. Its findings, interpretations and conclusions are those of H Heuristics. Illustrative models and simulations are intended to clarify mechanisms and are not forecasts for any specific economy. Nothing in this report constitutes investment advice.

CONTENTS

Contents

Executive Summary	5
01 The Architecture of Creation	7
1.1 Structure from rules	7
1.2 Layer I: Generative constraints	8
1.3 Layer II: Flows down gradients	9
1.4 Layer III: Emergence and structural change	9
1.5 Layer IV: Development and convergence	11
1.6 What transfers across domains, and what does not	11
02 From Physical Diffusion to Economic Diffusion	13
2.1 Fick's laws	13
2.2 One equation, many substrates	14
2.3 The microfoundations: random walks	15
2.4 Why pure diffusion is not enough	15
2.5 Conditions for a valid transfer	16
2.6 From geographic to effective distance	17
03 The Mathematics of Innovation Spread	18
3.1 The S-curve as a signature	18
3.2 Innovators and imitators: the Bass model	20
3.3 Diffusion on networks	21
3.4 Learning, costs and heterogeneity	22
3.5 Why adoption accelerates and then slows	23
3.6 Leapfrogging and the digital wave	23
04 The Architecture of Economic Convergence	25
4.1 The convergence hypothesis	25
4.2 The long view: divergence, big time	25
4.3 A new era of convergence, and its fading	26
4.4 Technology diffusion as the engine of catch-up	28
4.5 Arrival versus intensity	29
4.6 Ideas, meetings and the global diffusion of knowledge	30
4.7 Structural transformation and the escalator of manufacturing	30
05 The Bottlenecks of Development	31
5.1 Resistances in series	31
5.2 Weak links and complementarity	32
5.3 Electricity: the foundational conductance	32
5.4 Skills and management	33

5.5 Finance and the cost of adoption	34
5.6 Infrastructure, connectivity and logistics	34
5.7 State capacity, institutions and allocation	34
5.8 Diagnosing the binding constraint	34
06 A Unified Architecture of Development	36
6.1 The core equation	36
6.2 Six propositions	37
6.3 Thresholds, lock-in and the case for coordinated pushes	38
6.4 Resilience and continuity	38
6.5 From diagnosis to intervention	39
07 Testable Hypotheses and Research Agenda	41
7.1 Six hypotheses	41
7.2 Measuring the key quantities	41
7.3 Identification	42
7.4 A research programme	42
7.5 Limits of the framework	43
08 Conclusion	44
Mathematical Notes	45
Data and Methods	47
References	48

EXECUTIVE SUMMARY

Executive Summary

Development is the process by which societies create structure: by accumulating capabilities, linking them through networks, and channelling flows of knowledge, energy and capital toward places where they are scarce. This report argues that the mathematics of diffusion, first written down for salt dissolving in water, offers a disciplined way to see that process whole.

Across physical, biological, technological and economic systems, recurring structures emerge from a small set of generative rules. Matter and energy flow down gradients; local interactions assemble into networks and hierarchies; those structures in turn reshape the flows that created them. We call this recurring logic the **architecture of creation**: the structural principles through which complex forms emerge from simpler parts.

Development economics can be read as the study of how these generative processes operate within societies: how innovations diffuse, how productivity converges, how capabilities accumulate, and how initially uneven systems reorganise toward new states of development. The bridge we use is a single, well-tested relationship. In 1855 the physiologist Adolf Fick proposed that the flux of a substance is proportional to its concentration gradient ([Fick, 1855](#)). The same form, $flux = conductance \times gradient$, governs heat, electric current and groundwater. We show that it also organises a large body of evidence on technology adoption and economic catch-up, provided it is extended in specific, testable ways.

The report has three aims. First, to set out a unifying framework (constraints, flows, emergence, development) that is precise enough to generate hypotheses rather than metaphors. Second, to establish when concepts from physical diffusion legitimately transfer to economic diffusion, and when they do not. Third, to translate the framework into a diagnostic for policy: a way of identifying which constraints most slow the movement of productive knowledge into an economy, and where intervention would yield the greatest return.

Key findings

01 One equation, many substrates.

Fick's law, Fourier's law of heat conduction, Ohm's law and Darcy's law share one structure: a flow driven by a gradient and limited by a resistance. In development, the gradient is the gap between frontier and local practice; the conductance is the set of capabilities (skills, power, finance, connectivity, institutions) that lets knowledge move. The central policy question becomes: *what sets the conductance?*

02 Pure diffusion is too slow; development behaves like reaction–diffusion.

Pure diffusion spreads with the square root of time. Technologies spread far faster, because adoption also reproduces locally through imitation and learning. Reaction–diffusion models, first used for the spread of advantageous genes ([Fisher, 1937](#)), produce the travelling waves and S-curves observed in adoption data.

03 Network architecture governs speed.

In our simulations, random networks spread simple information fastest, while ideas that require social reinforcement spread reliably only through clustered networks with a few long-range bridges. This matches experimental evidence ([Centola, 2010](#)) and implies that *who adopts first* matters as much as *how many*.

04 Arrival has converged; intensity has not.

Mobile subscriptions in Sub-Saharan Africa rose from about 2 to 90 per 100 people between 2000 and 2025. Fixed broadband, which needs complementary infrastructure, remains near 1 per 100 against roughly 39 in high-income economies. Technologies now reach poor countries quickly; they are used far less intensively once they arrive ([Comin & Mestieri, 2018](#)).

05 Convergence is real but slow, and it has weakened.

Across 191 economies, poorer countries grew faster between 2000 and 2023 ($\beta = -0.43$), an implied convergence speed of about 0.45 percent a year, a half-life of roughly 150 years. Our rolling ten-year estimates peak for windows beginning in 2006–2007 and fade to statistical insignificance for windows beginning in 2012–2014.

06 Bottlenecks behave like resistances in series and weak links in a chain.

When capabilities are complements, the weakest one binds. In 2024 about 657 million people still lacked electricity, roughly 88 percent of them in Sub-Saharan Africa. In low-income countries access was 49 percent. No amount of digital ambition substitutes for a missing power supply.

07 Resilience is part of the architecture.

Shocks erase accumulated stock, and recoveries are frequently incomplete ([Cerra & Saxena, 2008](#)). A development strategy that raises conductance without protecting the accumulated stock will leak much of what it builds.

IMPLICATION FOR DECISION-MAKERS**Diagnose the binding resistance before adding force**

Development strategies often push harder on the gradient: more technology, more capital, more pilots. The framework in this report suggests a different first question: which resistance is binding? Because resistances add in series, lowering a small one achieves little, while lowering the largest one can multiply the effective rate of diffusion. Section 5 sets out the diagnostic; Section 6 maps it to interventions; Section 7 specifies how to test it.

SECTION 01

The Architecture of Creation

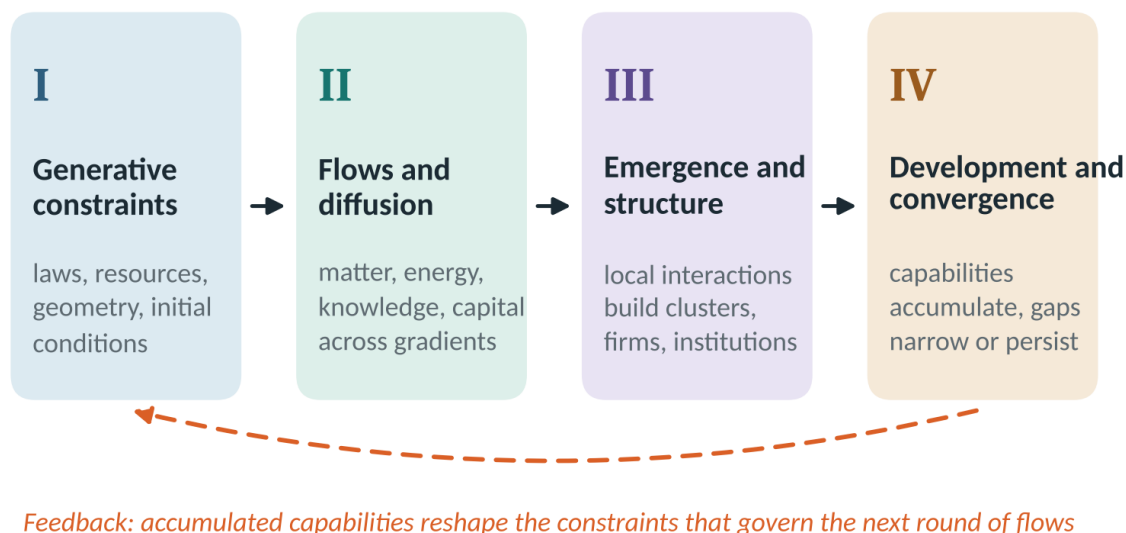
Complex forms rarely arise from complex instructions. They emerge when simple rules, operating under constraint, channel flows through space and time. This section sets out four layers of that generative logic and the conditions under which they illuminate economic development.

1.1 Structure from rules

A river delta, a bronchial tree, a lightning strike and a city's road network look strikingly alike. None was designed from a blueprint. Each emerged because something had to move (water, air, charge, people) through a medium that resisted it, and because the paths that moved it best were reinforced over time. The resulting forms are not accidents. They are solutions, discovered by repeated local interactions, to the problem of moving flows across a landscape of constraints.

This observation has a long scientific pedigree. Alan Turing showed that two chemicals diffusing at different rates and reacting with each other can spontaneously generate stripes, spots and spirals from an initially uniform state ([Turing, 1952](#)). Ilya Prigogine's work on dissipative structures demonstrated that systems held far from equilibrium by a continuous throughput of energy can organise themselves into stable, ordered patterns ([Prigogine, 1978](#)). Herbert Simon argued that complex systems, whether organisms, organisations or economies, are overwhelmingly built as hierarchies of nearly independent modules, because such architectures are far more likely to be assembled and to survive ([Simon, 1962](#)).

We use the phrase **architecture of creation** to describe the common structural principles behind such cases. The phrase is descriptive, not metaphysical: it names the recurring way in which constraints, flows and local interactions combine to produce structure. Our claim is not that all natural and economic systems obey one identical law. It is narrower and, we believe, more useful: a small number of structural principles recur across domains, and identifying which of them genuinely transfer to economic development, and under what conditions, yields concrete hypotheses and policy diagnostics.

Figure 1.1 The four layers of the generative architecture

Source: H Heuristics. The four layers form a conceptual sequence with feedback: accumulated capabilities alter the constraints that govern subsequent flows.

Figure 1.1 summarises the four layers. They are not stages that a society passes through once. They form a loop in which each round of development alters the constraints that shape the next.

1.2 Layer I: Generative constraints

Constraints are usually thought of as limits. In generative systems they are also the source of form. Conservation laws, geometry and initial conditions do not merely restrict which structures are possible; they select among them. A tree's branching follows from the need to distribute water and capture light within the mechanical limits of wood. The fractal geometry of mammalian circulatory systems follows from the need to supply every cell while minimising the energy lost to pumping; this single constraint generates the quarter-power scaling of metabolic rate with body size ([West, Brown & Enquist, 1997](#)).

Economies are shaped by constraints of the same kind. Physical geography fixes transport costs and disease environments. Resource endowments influence early specialisation. Demography determines the supply of labour and the dependency burden. Initial institutions, often inherited from historical events, condition which contracts can be enforced and which investments are safe ([Acemoglu, Johnson & Robinson, 2001](#)). These are the generative constraints of development: they do not dictate outcomes, but they define the option space within which flows and interactions operate.

Two properties of constraints matter for what follows. First, constraints can be **binding** or **slack**. A constraint that does not bind can be relaxed without effect; one that binds governs the entire system. Second, constraints **interact**. When they are complements, the tightest one determines outcomes, an idea we formalise in Section 5 as the weak-link principle.

1.3 Layer II: Flows down gradients

Wherever there is a difference (in concentration, temperature, pressure, price or knowledge), there is a potential for flow. Physical systems relax toward equilibrium by moving matter and energy from regions of abundance to regions of scarcity. The rate of that movement depends on two things: the size of the difference and the ease with which the medium lets the flow pass. This is the content of Fick's law, discussed in detail in Section 2.

Flows do more than equalise. In open systems sustained by continuous throughput, flows **build structure**. Water carving a channel deepens the channel, which attracts more water. Adrian Bejan's constructal law formalises the idea that flow systems evolve toward configurations that provide progressively easier access for the currents that pass through them ([Bejan & Lorente, 2010](#)). The economic analogue is familiar: trade routes, once established, attract investment that lowers the cost of further trade; a cluster of skilled workers attracts firms that attract further skilled workers.

In development, the relevant flows are of five kinds: **knowledge** (techniques, designs, managerial practices), **technology** embodied in equipment, **capital** (finance and investment), **energy** and **people** (through migration, travel and education). Each moves across gradients in productivity, returns or wages. Each faces resistances. And each, once flowing, tends to reshape the channels through which it moves.

BOX 1.1

The cover image: a structure built by diffusion

The branching form on the cover of this report was generated by **diffusion-limited aggregation** (DLA), a process introduced by Witten and Sander ([1981](#)). Particles perform random walks (the microscopic process underlying Fick's law) until they touch a growing cluster, where they stick. Because the tips of the cluster intercept wandering particles before they can reach the interior, tips grow faster than hollows. A simple rule thus produces an intricate fractal with no designer.

The image was generated for this report using roughly 32,000 particles. Colour encodes the order of attachment, from the earliest (teal, at the core) to the latest (copper, at the tips). The lesson for development is direct: where growth occurs depends on access to incoming flows. Places already at the frontier capture the flow; places screened behind them receive little. Divergence can emerge from an entirely symmetric rule.

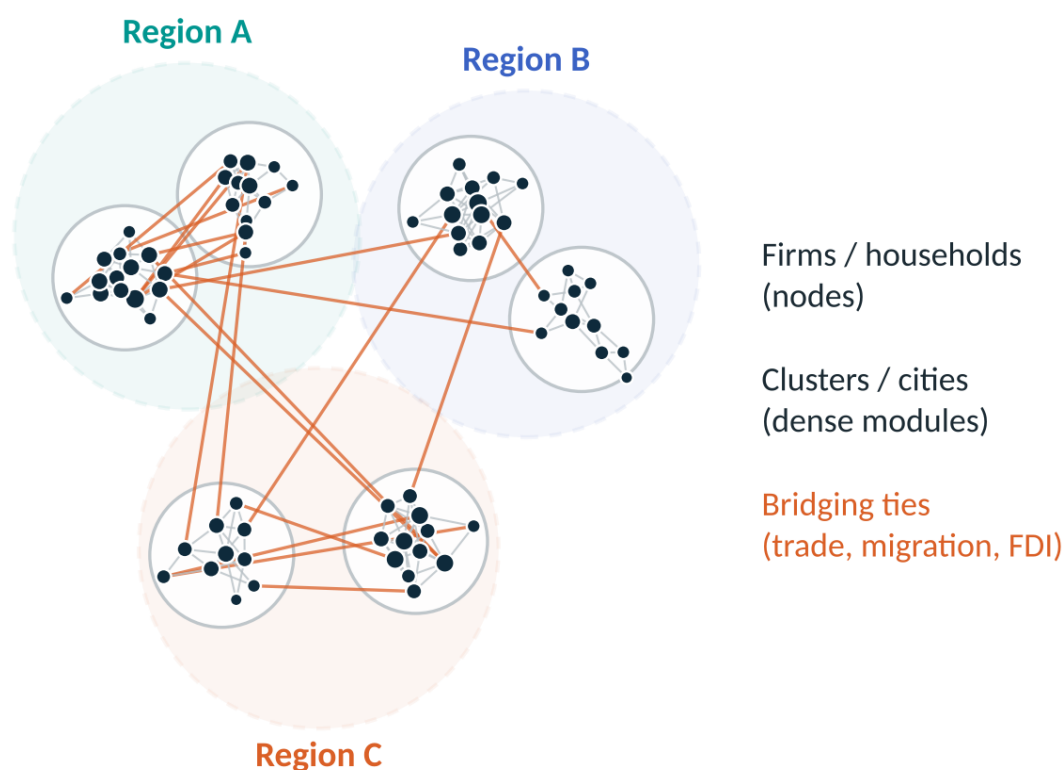
1.4 Layer III: Emergence and structural change

Emergence refers to patterns at one scale that arise from interactions at a smaller scale and cannot be read off from the properties of individual parts. A traffic jam is not a property of any single car. An industrial cluster is not a property of any single firm. In both cases, local rules (keep a safe distance; locate near suppliers and skilled workers) generate a structure that then constrains the individuals who created it.

Simon's insight about hierarchy is especially relevant. He showed that systems assembled from stable intermediate modules evolve far faster than systems that must be assembled all at once. His parable of two watchmakers makes the point: the watchmaker who builds from sub-assemblies loses only a small part of their work when interrupted, while the one who builds piece by piece must start over ([Simon, 1962](#)).

Economies are nested in this way. Households and firms form clusters; clusters form cities and regions; regions link through trade into national and global economies (Figure 1.2). Most interactions occur within modules, and a smaller number of bridging ties connect them.

Figure 1.2 Nested modules connected by bridging ties



Source: H Heuristics. Stylised stochastic block network: dense ties within clusters, sparse bridges between them. Node size reflects the number of connections.

This modular architecture has two consequences for diffusion. Within modules, ideas circulate quickly and reinforce one another. Between modules, the bridging ties (trade links, migrants, multinational firms, universities) act as the conduits through which new knowledge enters. The density of these bridges, and the absorptive capacity at each end, largely determine how fast a new practice moves from one part of the global economy to another. Empirically, knowledge spillovers are strongly localised, decaying with geographic distance ([Jaffe, Trajtenberg & Henderson, 1993](#); [Keller, 2002](#)).

Emergent structure also shows up in **scaling laws**. Across urban systems, socioeconomic outputs such as wages, patents and GDP tend to rise more than proportionally with city population, with exponents typically estimated between roughly 1.1 and 1.3, while infrastructure such as road surface scales less than proportionally ([Bettencourt et al., 2007](#)). Density concentrates interactions; interactions generate ideas. Cities are, in this sense, reactors in which the flows of Layer II are intensified to produce the structures of Layer III.

Structural change, the reallocation of labour and capital from low- to high-productivity activities, is the economic expression of emergence. Arthur Lewis described development as the transfer of workers from a traditional sector with low marginal productivity to a modern sector that accumulates capital ([Lewis, 1954](#)).

Large productivity gaps between agriculture and other sectors persist in many low-income economies ([Gollin, Lagakos & Waugh, 2014](#)), and the direction of labour reallocation has, in some periods and regions, reduced rather than raised aggregate productivity ([McMillan & Rodrik, 2011](#)).

1.5 Layer IV: Development and convergence

The fourth layer is the one that development economics measures most directly: the accumulation of capabilities, the rise of productivity and, potentially, the narrowing of gaps in living standards. Capabilities here include physical capital, human capital and the less tangible ‘know-how’ embedded in firms and networks. Hidalgo and Hausmann ([2009](#)) show that the diversity and sophistication of a country’s exports reveal the capabilities it possesses, and that countries tend to diversify into products that require capabilities close to those they already have ([Hidalgo et al., 2007](#)). Development, on this view, is a walk through a structured space in which adjacent possibilities are far easier to reach than distant ones.

Convergence is not guaranteed. Whether gaps narrow depends on whether flows into lagging economies exceed the rate at which leading economies continue to advance. That comparison is the subject of Section 4. What the architecture adds is a way to locate the sources of slow convergence: in constraints that bind (Layer I), in conductances that are low (Layer II), in network structures that isolate (Layer III), or in an inability to retain accumulated stock (Layer IV).

1.6 What transfers across domains, and what does not

Analogies between physical and social systems have a mixed record. They can clarify, but they can also mislead when the features that make a physical law work are absent in the social setting. We therefore distinguish structural correspondences, which can be specified mathematically and tested, from loose metaphors. Table 1.1 summarises the correspondences used in this report.

Table 1.1 Structural correspondences across domains

Concept	Physical systems	Biological systems	Economic development
Quantity that spreads	Concentration of a solute; heat	Allele frequency; population density	Adoption share; productivity level; know-how
Gradient	Difference in concentration or temperature	Fitness advantage; resource gradient	Gap between frontier and local practice; returns differential
Conductance	Diffusion coefficient; thermal conductivity	Dispersal rate; mobility	Absorptive capacity: skills, infrastructure, finance, institutions
Local reaction	Chemical reaction rate	Reproduction; growth rate	Imitation; learning by doing; network effects
Emergent structure	Turing patterns; fractal aggregates	Vascular trees; ecosystems	Industrial clusters; cities; production networks
Resistance	Viscosity; membrane barriers	Physical barriers; predation	Adoption costs; unreliable power; weak institutions

Source: H Heuristics.

Three differences between physical and economic diffusion recur throughout the report and should be kept in view.

- **Agents are purposive.** Molecules do not decide to move; firms and households do. Adoption depends on expected profitability, which means the economic “gradient” is a gradient in payoffs, not merely in presence. Griliches’s classic study of hybrid corn showed that both the timing and the ceiling of adoption across US states were explained by its profitability ([Griliches, 1957](#)).
- **Knowledge is non-rival.** In Fick’s world the source is depleted as solute moves away. When a technique is copied, the originator does not lose it. Knowledge diffusion is therefore not conservative, and total knowledge can grow through diffusion itself ([Romer, 1990](#)).
- **Conductance is endogenous.** A membrane’s permeability is fixed. An economy’s absorptive capacity rises as it adopts, learns and invests. This feedback, the loop in Figure 1.1, is what allows development to become self-reinforcing, and also what allows it to stall.

These differences do not invalidate the analogy. They specify how it must be extended: by adding payoffs to the gradient, local growth to the flow equation, and feedback to the conductance. Section 2 develops each extension formally.

SECTION 02

From Physical Diffusion to Economic Diffusion

Fick's law is among the most thoroughly validated relationships in science. This section explains what it says, why it holds, where its signature appears in economic data, and the precise conditions under which its logic can be carried over to the spread of technology.

2.1 Fick's laws

Adolf Fick, a physiologist studying the movement of salts across membranes, proposed in 1855 that the rate at which a substance diffuses is proportional to the gradient of its concentration (Fick, 1855). In one dimension, Fick's first law states:

$$J = -D \frac{\partial \varphi}{\partial x} \quad (2.1)$$

Here J is the flux (the amount crossing a unit area per unit time), φ is concentration, x is position and D is the diffusion coefficient, a property of both the substance and the medium. The negative sign indicates that flow runs from high to low concentration. The equation separates two very different things: the **driving force** (the gradient $\partial\varphi/\partial x$) and the **ease of movement** (D). A large gradient with a small D can produce the same flux as a small gradient with a large D .

Combining the first law with conservation of mass (what flows out of one region must flow into a neighbouring one) yields Fick's second law, the diffusion equation:

$$\frac{\partial \varphi}{\partial t} = D \frac{\partial^2 \varphi}{\partial x^2} \quad (2.2)$$

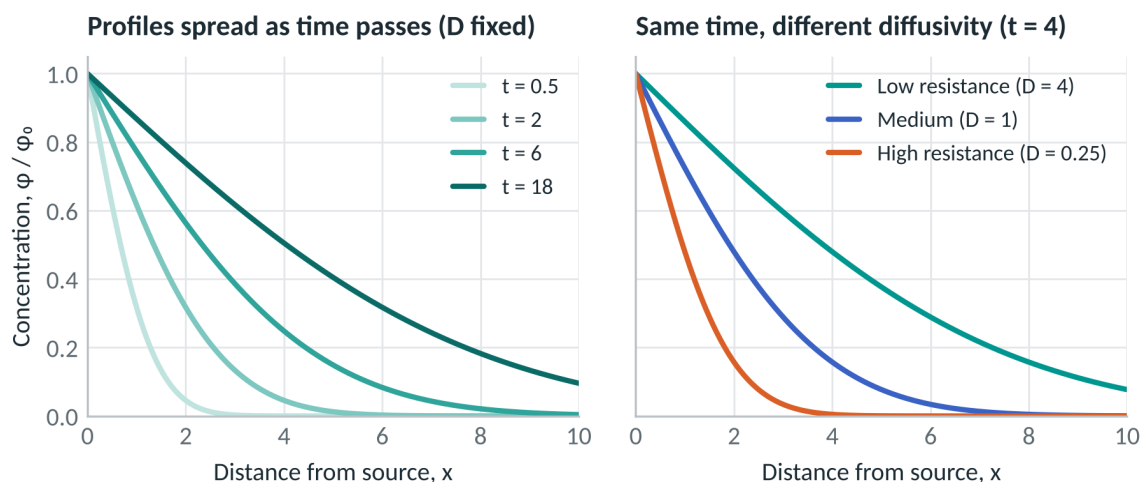
For a source held at constant concentration φ_0 at $x = 0$ and an initially empty medium, the solution is:

$$\varphi(x, t) = \varphi_0 \operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right) \quad (2.3)$$

where erfc is the complementary error function. The solution has a feature with large implications for economics: the characteristic distance the substance penetrates grows with the **square root** of time, not in proportion to it.

$$\ell(t) \sim \sqrt{Dt}, \quad t(\ell) \sim \frac{\ell^2}{D} \quad (2.4)$$

Doubling the distance quadruples the time required. Figure 2.1 shows both properties: profiles flatten and lengthen as time passes (left), and at any given moment the penetration depth depends on the diffusion coefficient (right). A medium with one-sixteenth of the conductance reaches only a quarter as far in the same time.

Figure 2.1 Diffusion from a constant source: time and conductance

Source: H Heuristics, analytical solution of equation 2.3 with $\phi_0 = 1$. Units are arbitrary. Left: $D = 1$ at four points in time. Right: three diffusion coefficients at $t = 4$.

2.2 One equation, many substrates

Fick's law belongs to a family of constitutive relations, each discovered independently, that share the same structure: a flux equals a conductance multiplied by a gradient. Fourier's law describes heat flowing down a temperature gradient. Ohm's law describes current flowing down a voltage gradient. Darcy's law describes fluid flowing through porous rock down a pressure gradient. The recurrence is not a coincidence. Each describes a system relaxing toward equilibrium through many small, local, random exchanges; at the macroscopic scale, such processes generically produce linear flux–gradient relations.

Table 2.1 The flux–gradient family and its economic counterpart

Law	Flux	Gradient	Conductance	Resistance
Fick (1855)	Solute per area per time	Concentration difference	Diffusion coefficient D	Medium viscosity; membranes
Fourier (1822)	Heat per area per time	Temperature difference	Thermal conductivity	Insulation
Ohm (1827)	Electric current	Voltage difference	Electrical conductance	Resistors, in series and parallel
Darcy (1856)	Fluid discharge	Pressure difference	Permeability	Tight rock; clogging
Economic catch-up	Rate of adoption or productivity growth	Gap to frontier, weighted by payoff	Absorptive capacity	Costs, power deficits, skill gaps, weak institutions

Source: H Heuristics.

The electrical analogy is especially useful because it carries a well-developed algebra of **resistances**. Resistances in series add: the total resistance of a chain is the sum of its links, and the largest dominates. Conductances in parallel add: opening a second channel increases total flow. Section 5 uses exactly this algebra to describe how multiple constraints combine to slow the movement of technology into an economy.

2.3 The microfoundations: random walks

Why should a macroscopic flux be proportional to a gradient? Einstein's 1905 analysis of Brownian motion supplied the answer ([Einstein, 1905](#)). If each particle moves randomly, with no preferred direction, then more particles cross a boundary from the crowded side than from the sparse side simply because there are more of them. Net flow arises from asymmetry in numbers, not from any particle "seeking" emptier space. Einstein showed that the mean squared displacement of a random walker grows linearly with time, $\langle x^2 \rangle = 2Dt$, which is the microscopic origin of the square-root law in equation 2.4.

The economic counterpart is the contact process. If firms or farmers learn about a technology through chance encounters with those who already use it, then regions with many users will "export" knowledge to regions with few, again without any intention on the part of the users. Torsten Hägerstrand's pioneering simulations of agricultural innovations in Sweden modelled adoption in exactly this way, as a sequence of local contacts governed by a distance-decaying "mean information field" (Hägerstrand, 1967). His central empirical finding, the **neighbourhood effect**, was that new adopters appear disproportionately close to existing ones.

2.4 Why pure diffusion is not enough

Taken literally, the square-root law implies that technologies would spread extraordinarily slowly over long distances: a practice that takes ten years to cross one district would need a thousand years to cross a hundred. Real innovations do not behave this way. They advance as **waves** that travel at roughly constant speed. The reason is that adoption is not only transported, it is also **reproduced**. Each adopter becomes a new source.

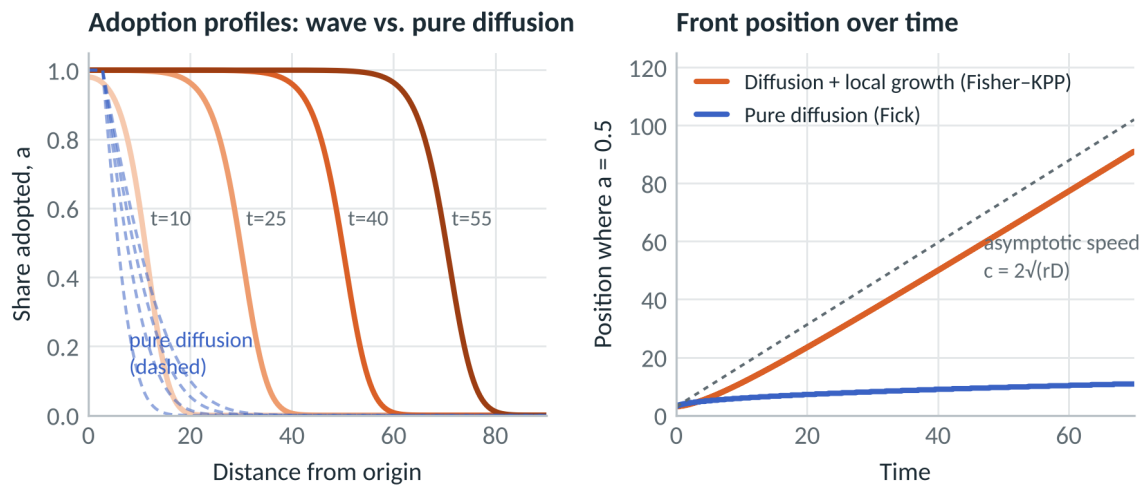
R. A. Fisher captured this in 1937 in a model of an advantageous gene spreading through a population distributed in space ([Fisher, 1937](#)). In the same year, Kolmogorov, Petrovsky and Piskunov analysed the same equation in greater mathematical generality. The Fisher–KPP equation adds a logistic growth term to diffusion:

$$\frac{\partial a}{\partial t} = D \frac{\partial^2 a}{\partial x^2} + r a (1 - a) \quad (2.5)$$

where a is the local adoption share and r the rate at which adoption reproduces locally through imitation or learning. Solutions starting from a localised introduction converge to a travelling wave of fixed shape that advances at a constant speed:

$$c = 2\sqrt{rD} \quad (2.6)$$

The speed depends on *both* the conductance D and the local reproduction rate r . A region where people rarely travel (low D) but imitate eagerly (high r) may see the same speed of advance as one with high mobility and slow uptake. Figure 2.2 contrasts the two regimes. Under pure diffusion the front decelerates indefinitely; under Fisher–KPP dynamics it settles into a constant velocity that converges to the theoretical value.

Figure 2.2 Pure diffusion versus a reaction–diffusion wave

Source: H Heuristics, numerical solution of equations 2.2 and 2.5 with $D = 1$ and $r = 0.5$. Left: adoption profiles at four times (solid: Fisher-KPP; dashed: pure diffusion). Right: position of the 50 percent adoption front over time.

This mathematics has a direct archaeological test. Skellam applied reaction–diffusion to the spread of populations (Skellam, 1951), and Ammerman and Cavalli-Sforza used radiocarbon dates to show that early farming spread across Europe as a wave advancing at a roughly constant average rate of about one kilometre per year (Ammerman & Cavalli-Sforza, 1971). The “wave of advance” has since become a standard model for the spread of populations, languages and practices.

2.5 Conditions for a valid transfer

When does it make sense to model technology adoption with diffusion equations? We propose five conditions. Where they hold, the physical concepts carry real explanatory weight; where they fail, the analogy should be modified or abandoned.

- 1. A measurable state variable.** There must be a quantity that varies across units and over time and plays the role of concentration: an adoption share, an intensity of use, or a productivity level relative to a frontier.
- 2. Transfer driven by local differences.** The rate of change in a unit must depend on the difference between that unit and the units it interacts with: its neighbours in space, or its partners in a network of trade, migration or communication.
- 3. A separable conductance.** It must be possible to distinguish the strength of the gradient from the ease of transmission, and to measure the latter through observable characteristics (skills, infrastructure, finance, institutions).
- 4. Payoffs enter the gradient.** Because adopters are purposive, the effective gradient must incorporate the expected profitability of adoption, which varies across adopters and over time.
- 5. Feedback is modelled, not assumed away.** Because adoption raises absorptive capacity and knowledge is non-rival, the conductance and the frontier must be allowed to evolve with the process itself.

BOX 2.1

Where the physical analogy breaks

- **Non-conservation.** A solute is conserved; knowledge is not. Diffusion of ideas increases the total stock, so economic diffusion models need a growth term, not just a transport term.
- **Strategic timing.** Firms may delay adoption to learn from others or to wait for a cheaper, better version. Waiting can be rational even when the gradient is large.
- **Coordination and thresholds.** Some technologies are valuable only when others adopt them (payment systems, communication standards). Such network goods can display tipping points and multiple equilibria that linear diffusion cannot capture.
- **Upstream diffusion.** In physics, flow never runs up a gradient. In economics, practices sometimes spread from poorer to richer places: mobile money spread from Kenya outward, and frugal innovations have travelled from emerging to advanced markets.

2.6 From geographic to effective distance

In Fick's setting, distance is physical. In a modern economy, the relevant distance is often a network distance: the number and strength of links separating a firm from the knowledge it needs. Brockmann and Helbing showed that the global spread of epidemics, which looks irregular on a geographic map, becomes a regular, wave-like process when distance is redefined in terms of the flows of the air-travel network ([Brockmann & Helbing, 2013](#)). Arrival times grow almost linearly with this **effective distance**.

The implication for development is that diffusion models should be estimated on the networks through which knowledge actually travels (trade, investment, migration, telecommunication, supply chains), not only on maps. A remote but well-connected port city may be "closer" to the technological frontier than a nearby but isolated rural district. Section 3 develops this idea; Section 7 proposes tests of it.

SECTION 03

The Mathematics of Innovation Spread

Adoption curves share a common signature: slow beginnings, rapid acceleration, and a long approach to saturation. This section assembles the models that explain that shape and shows how learning, costs, early adopters and network structure determine its timing and steepness.

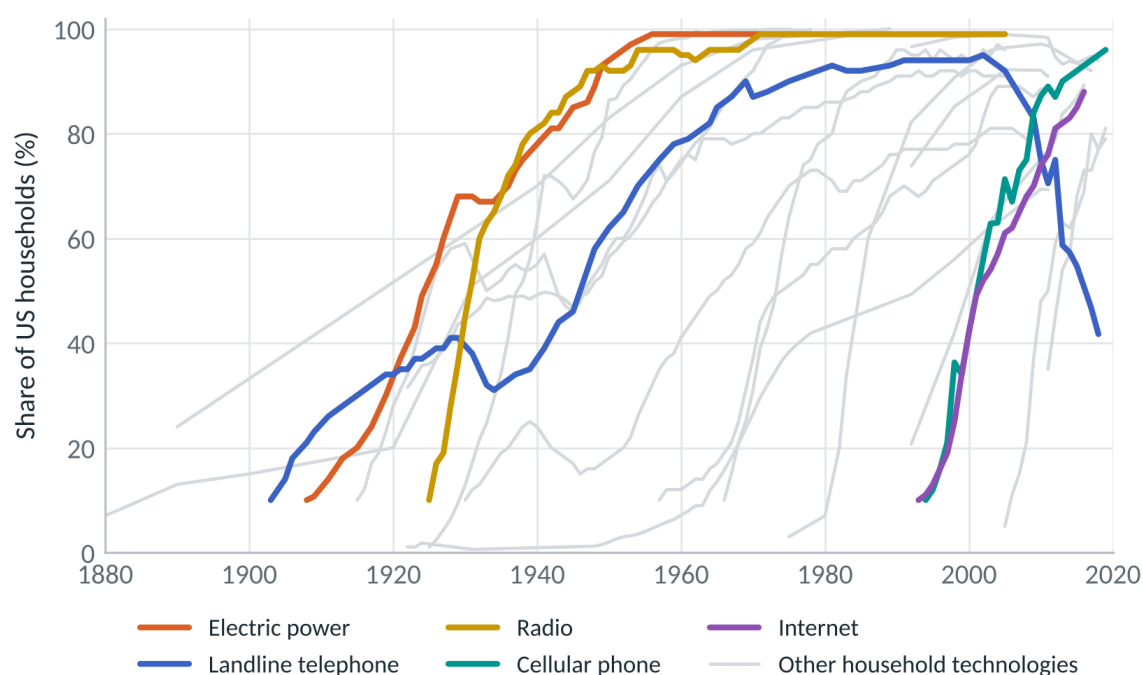
3.1 The S-curve as a signature

The simplest model of local reproduction ignores space altogether. If the rate of new adoption is proportional both to the share who have adopted (who spread the idea) and to the share who have not (who can still adopt), the adoption share follows the logistic equation:

$$\frac{da}{dt} = \beta a (1 - a) \Rightarrow a(t) = \frac{1}{1 + e^{-\beta(t-t_0)}} \quad (3.1)$$

The resulting S-curve has a natural interpretation: early on, few adopters exist to spread the innovation; in the middle, both adopters and potential adopters are plentiful and uptake accelerates; near saturation, few potential adopters remain. Griliches ([1957](#)) fitted logistic curves to the adoption of hybrid corn across US states and showed that differences in the timing and slope of adoption were explained by economic variables, notably the profitability of switching. Mansfield ([1961](#)) found similar patterns for industrial innovations, with faster imitation where the innovation was more profitable and required smaller investment.

Figure 3.1 shows the S-curve signature across a century of US household technologies. Two features stand out. First, the S-shape is pervasive. Second, the speed of adoption varies enormously and does not simply increase over time. Radio went from 10 to 75 percent of households in about 13 years in the 1920s and 1930s; the landline telephone took more than half a century, its progress interrupted by the Great Depression.

Figure 3.1 A century of S-curves: technology adoption in US households

Source: [Our World in Data](#), compiled from Comin and Hobijn (2004) and other sources. Share of US households using each technology. Five technologies highlighted; others shown for context.

Table 3.1 Years from 10 to 75 percent adoption, US households

Technology	Reached ~10%	Reached 75%	Years	Notes
Landline telephone	1903	1957	54	Interrupted by the Depression; later displaced by mobile
Automobile	1915	1960	45	Required roads, fuel networks and credit
Electric power	1908	1938	30	Earliest series observation is ~10%
Refrigerator	1930	1948	18	Complement to household electrification
Radio	1925	1938	13	Broadcast infrastructure already in place
Colour television	1966	1978	12	Built on existing TV networks
Cellular phone	1994	2008	14	Network effects; falling handset prices
Internet	1993	2011	18	Required computers and telecom lines
Microwave oven	1982	1992	10	Low complementarity requirements

Source: H Heuristics calculations from [Our World in Data](#) / Comin and Hobijn. First year in which each series reaches or exceeds the threshold.

The pattern in Table 3.1 anticipates a theme of Section 5. Technologies that rode on existing infrastructure (radio, colour television, the microwave oven) spread quickly. Those that required new complementary networks (roads for the automobile, wiring for the telephone, computers and phone lines for the internet) spread more slowly. The conductance of an economy is not a single number; it depends on the technology and on the complements it requires.

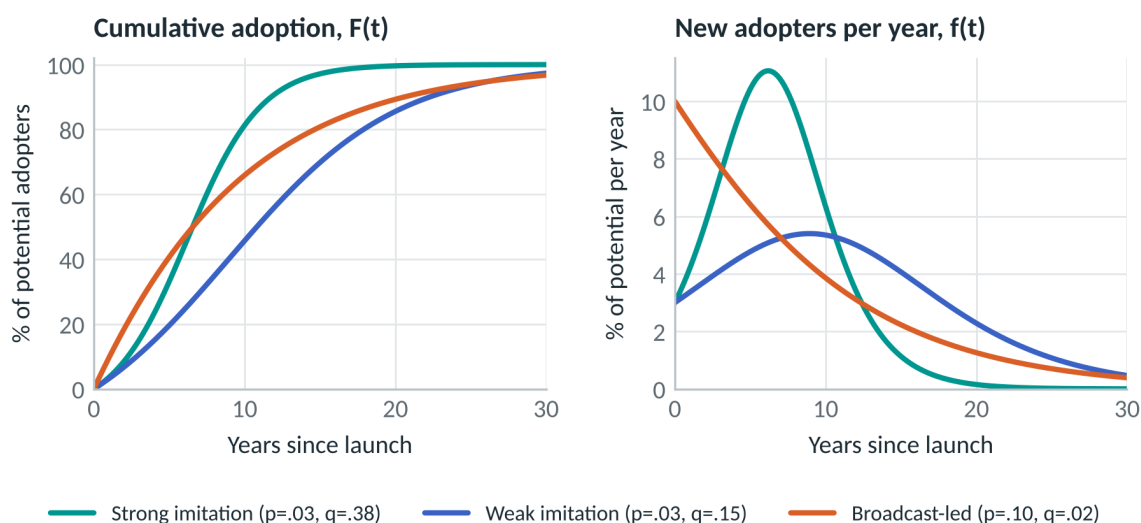
3.2 Innovators and imitators: the Bass model

The logistic model cannot explain how adoption starts, because with no initial adopters there is no one to imitate. Frank Bass resolved this by distinguishing two channels ([Bass, 1969](#)). A coefficient of **innovation**, p , captures adoption driven by external influences (advertising, extension services, information from outside the community), and a coefficient of **imitation**, q , captures adoption driven by contact with previous adopters. With F the cumulative share of the eventual market that has adopted:

$$\frac{dF}{dt} = (p + qF)(1 - F) \quad (3.2)$$

The model has a closed-form solution (Appendix A) and has been estimated for hundreds of products. A meta-analysis of its applications found average values of roughly $p = 0.03$ and $q = 0.38$ ([Sultan, Farley & Lehmann, 1990](#)): imitation typically dominates external influence by an order of magnitude. Figure 3.2 shows how the balance between the two channels shapes the curve. When imitation dominates, adoption begins slowly, then surges. When external influence dominates, the curve loses its S-shape and adoption is fastest at launch.

Figure 3.2 The Bass model: how innovation and imitation shape adoption



Source: H Heuristics, closed-form solution of equation 3.2. The first case uses the meta-analytic averages reported by Sultan, Farley and Lehmann (1990).

For policy, the distinction is consequential. Extension services, demonstration plots and information campaigns raise p ; they matter most when a technology is new and local adopters are scarce. Interventions that strengthen peer learning (farmer field schools, supplier networks, industry associations) raise q ; they matter most once a base of adopters exists. Most programmes implicitly focus on one channel. The model suggests the optimal mix shifts over the life cycle of a technology.

3.3 Diffusion on networks

Real contact patterns are neither uniform (as in the logistic model) nor purely spatial (as in Fick's law). They are networks. Diffusion on a network generalises equation 2.1 by letting each unit i exchange with the units j to which it is connected, with weights w_{ij} reflecting the strength of each tie:

$$\frac{da_i}{dt} = \beta(1 - a_i) \sum_j w_{ij} a_j \quad (3.3)$$

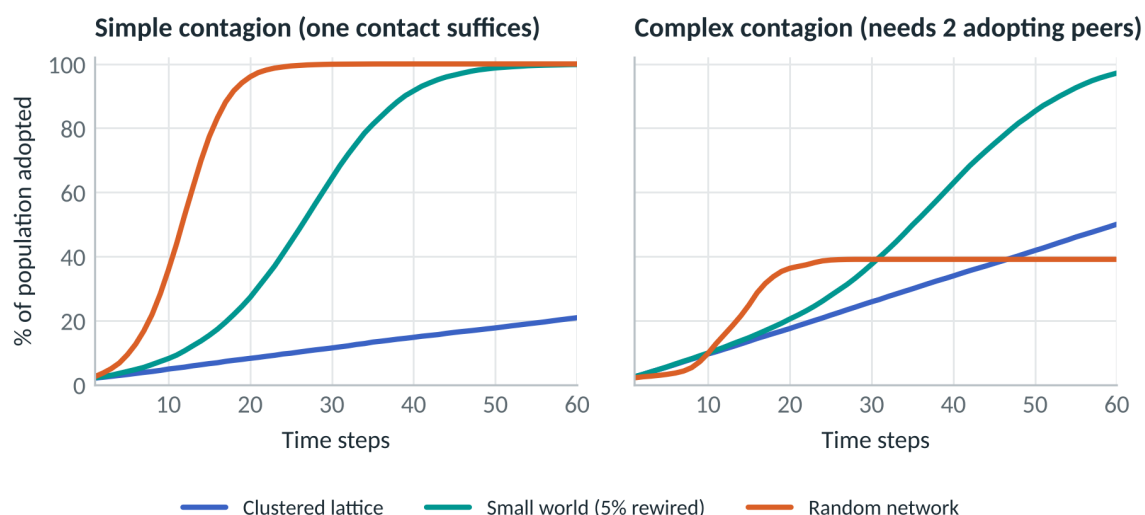
The linearised version of this equation is governed by the network's graph Laplacian, the discrete analogue of the second derivative in Fick's second law. Network structure therefore plays the role that geometry plays in physical diffusion. Two structural features have proved especially important. Watts and Strogatz showed that adding a small number of random long-range links to a clustered network sharply reduces the typical path length between nodes, producing a **small world** (Watts & Strogatz, 1998). Barabási and Albert showed that many real networks have highly unequal connectivity, with a few hubs and many sparsely connected nodes (Barabási & Albert, 1999); in such networks, contagion can spread even when transmission is weak (Pastor-Satorras & Vespignani, 2001).

Simple and complex contagion

A crucial distinction concerns what it takes for an individual to adopt. For a **simple contagion**, such as information about a price, a single contact suffices. For a **complex contagion**, such as a costly new production technique or a change in social norms, people may need reinforcement from several adopting peers before they act (Granovetter, 1978; Centola & Macy, 2007). Thresholds of this kind give rise to cascades and tipping points; the conditions under which a behaviour spreads through an entire network depend on local structure (Morris, 2000).

Figure 3.3 shows the consequences using simulations on three networks with identical numbers of nodes and ties. For simple contagion, the random network is fastest, because its long links carry information across the population in a few steps. For complex contagion, the ranking changes. Random networks lack the redundant local ties needed for reinforcement: in roughly three of five trials the contagion died out near the seed, and averaged across trials adoption plateaued around 40 percent. The clustered lattice spread reliably but slowly. The small-world network, with mostly local clustering and a few bridges, spread both reliably and fastest. Centola's online experiment found that health behaviours spread farther and faster through clustered networks than through random ones (Centola, 2010).

Figure 3.3 Network structure and the speed of adoption



Source: H Heuristics simulations. 500 nodes, average degree 8 (Watts–Strogatz construction). Simple contagion: per-contact adoption probability 0.06. Complex contagion: adoption with probability 0.6 once at least two neighbours have adopted. Averages over 40 runs seeded with one node and its neighbours.

3.4 Learning, costs and heterogeneity

Field evidence from developing economies has enriched these models in four ways.

- **Learning from others.** Indian farmers adopting high-yielding seed varieties during the Green Revolution learned how to use them both from their own experience and from neighbours' experience, and the presence of experienced neighbours raised profitability ([Foster & Rosenzweig, 1995](#)). Pineapple farmers in Ghana adjusted fertiliser use in response to the observed results of farmers in their information networks ([Conley & Udry, 2010](#)).
- **Heterogeneous returns.** Low aggregate adoption need not signal irrationality. In Kenya, farmers with high gross returns to hybrid maize sometimes faced high costs of acquiring it, so their net returns were low ([Suri, 2011](#)). The relevant gradient is in net payoffs, and it varies across adopters.
- **Behavioural frictions.** Small, well-timed offers to buy fertiliser immediately after harvest, when farmers had cash, substantially increased use in western Kenya, consistent with present bias ([Duflo, Kremer & Robinson, 2011](#)).
- **Organisational barriers.** In Pakistan's soccer-ball cluster, a cost-reducing cutting technology diffused slowly because piece-rate workers who would need to change their methods had no incentive to do so; adjusting the incentive raised adoption ([Atkin et al., 2017](#)). The resistance lay inside the firm.

Seeding: the role of early adopters

If network structure matters, so does the position of the first adopters. In Indian villages, microfinance participation was higher where the first people informed were more central in village networks ([Banerjee et al., 2013](#)). In Malawi, a randomised trial found that seeding agricultural techniques with farmers chosen using network theory increased adoption relative to the extension system's default choices ([Beaman et al., 2021](#)). Both results support a practical principle: the cost-effectiveness of a diffusion programme depends on *where* it injects knowledge into a network, not only on how much it injects.

3.5 Why adoption accelerates and then slows

Combining these elements explains the canonical S-curve as the joint outcome of several mechanisms, each of which can be measured and targeted:

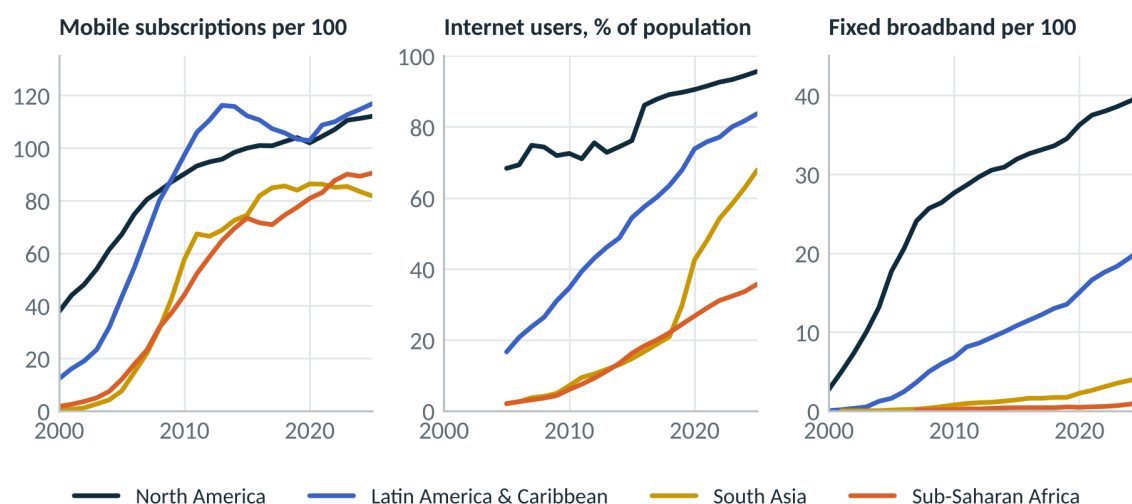
- **Acceleration** comes from imitation (q), learning from neighbours, network effects that raise the value of a technology as more people use it, and falling costs as producers move down learning curves.
- **Deceleration** comes from saturation of the potential market, increasing heterogeneity of remaining non-adopters (the last adopters are often those with the lowest net returns or the highest costs), and binding complementary constraints that limit the ceiling.
- **The ceiling itself** is economic, not technical. It is set by the share of potential users for whom adoption is profitable given local prices, infrastructure and skills, and it rises when those conditions improve.

3.6 Leapfrogging and the digital wave

Digital technologies offer a natural experiment in diffusion under different conductances. Figure 3.4 compares three technologies across four World Bank regions. Mobile telephony, which requires little fixed

infrastructure, spread with remarkable speed in South Asia and Sub-Saharan Africa: subscriptions in Sub-Saharan Africa rose from under 2 per 100 people in 2000 to about 90 by 2025. Internet use, which depends on affordable data, devices and literacy, has grown steadily but remains far below high-income levels. Fixed broadband, which requires dense wired networks, has barely diffused in the lowest-income regions.

Figure 3.4 Digital diffusion by region: mobile, internet and fixed broadband



Source: [Our World in Data](#) based on [ITU](#) and [World Bank WDI](#). World Bank regional aggregates, 2000–2025.

The economic consequences of the mobile wave are well documented. In Kerala, the spread of mobile phones among fishermen reduced price dispersion across markets and nearly eliminated waste ([Jensen, 2007](#)). In Niger, mobile phone coverage reduced grain price dispersion between markets ([Aker, 2010](#)). In Kenya, mobile money allowed households to share risk across long distances ([Jack & Suri, 2014](#)) and was associated with an estimated 2 percent of Kenyan households (some 194,000) moving out of poverty, with especially large effects for female-headed households ([Suri & Jack, 2016](#)). When fast submarine internet cables arrived in Africa, employment rose in connected locations, particularly in higher-skill occupations ([Hjort & Poulsen, 2019](#)).

These cases illustrate the core lesson of the diffusion framework. Mobile technologies spread rapidly because their conductance requirements were low: they bypassed the binding constraint of fixed infrastructure. Technologies that cannot bypass that constraint diffuse at the speed the constraint allows. Leapfrogging is possible, but only over obstacles that a technology does not require.

SECTION 04

The Architecture of Economic Convergence

If knowledge flows from where it is abundant to where it is scarce, poorer economies should grow faster than richer ones. For most of modern history they did not. This section examines why, what has changed since 2000, and how technology diffusion links the micro-dynamics of adoption to the macro-dynamics of catch-up.

4.1 The convergence hypothesis

Neoclassical growth theory predicts convergence for a simple reason. In the model of Solow (1956) and Swan, capital is subject to diminishing returns, so an economy with little capital per worker earns a high return on additional investment and grows quickly; as capital accumulates, growth slows. Near its steady state, income per worker y approaches its long-run level y^* at a rate λ :

$$\frac{d \ln y}{dt} \approx -\lambda(\ln y - \ln y^*), \quad \lambda = (1 - \alpha)(n + g + \delta) \quad (4.1)$$

where α is the capital share and n , g and δ are the rates of population growth, technological progress and depreciation. Equation 4.1 is a diffusion equation in disguise: the rate of change is proportional to the gap between the current state and a target, and λ plays the role of a conductance.

Empirically, convergence is tested by regressing average growth over a period on initial income:

$$g_i = \alpha + \beta \ln y_{i,0} + \gamma' X_i + \varepsilon_i \quad (4.2)$$

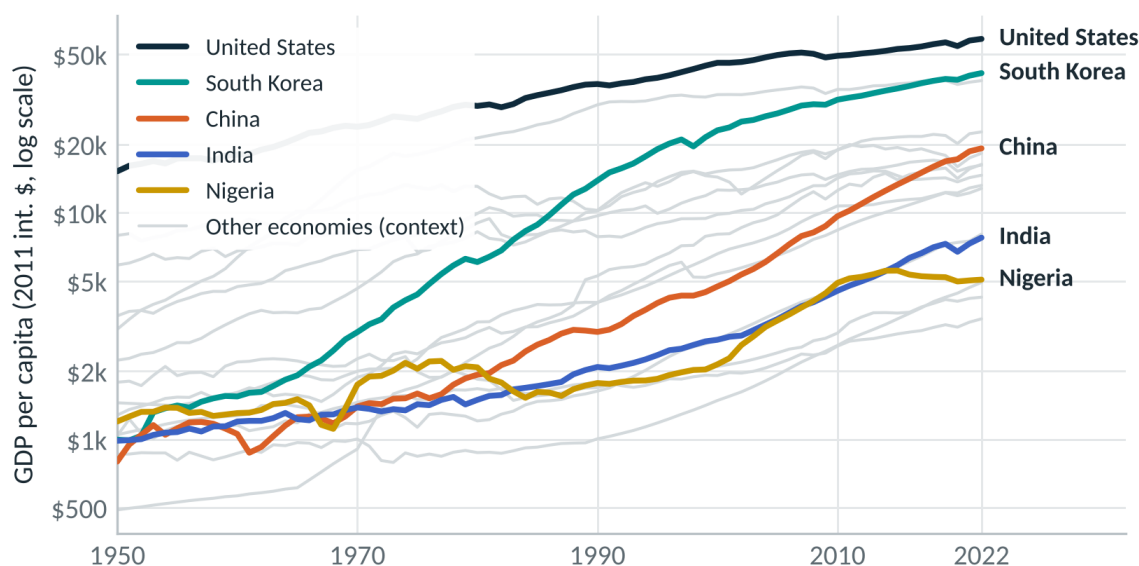
A negative β indicates **β -convergence**: poorer economies grow faster. If no controls X are included, the test is for *unconditional* convergence; with controls for saving, population growth and human capital, it is for *conditional* convergence toward economy-specific steady states. A separate concept, **σ -convergence**, asks whether the cross-country dispersion of income is falling. Through the 1990s the consensus was that conditional convergence held at about 2 percent per year, while unconditional convergence did not (Barro, 1991; Barro & Sala-i-Martin, 1992; Mankiw, Romer & Weil, 1992). Economies were converging, but toward different destinations.

4.2 The long view: divergence, big time

Over the long run, the dominant pattern was divergence. Pritchett estimated that the ratio of income per capita between the richest and poorest countries rose roughly fivefold between 1870 and 1990 (Pritchett, 1997). Baumol's finding of convergence among industrialised economies (Baumol, 1986) applied to a club of countries that had already acquired the capabilities to absorb frontier technology. Outside that club, many economies stagnated.

Figure 4.1 traces income per capita since 1950 for five economies. South Korea's trajectory is the archetype of catch-up: from about \$1,000 per person in 1950 (in 2011 international dollars) to over \$41,000 in 2022, a roughly forty-fold increase, narrowing the ratio to the United States from about 15:1 to 1.4:1. China's acceleration after 1980 followed a similar path. Nigeria, starting from a comparable level to Korea in 1950, grew far more slowly and with long interruptions. The gradient to the frontier was available to all; the flux it produced was not.

Figure 4.1 Catching up and falling behind, 1950–2022

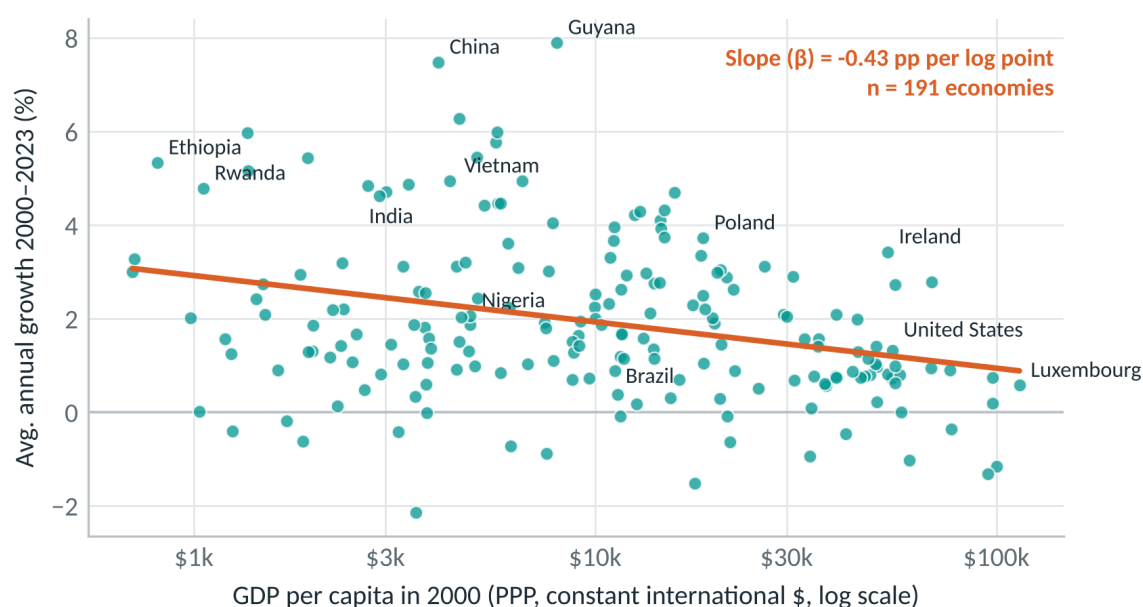


Source: [Maddison Project Database 2023](#), via [Our World in Data](#). GDP per capita in 2011 international dollars, log scale. Grey lines show twelve other economies for context.

4.3 A new era of convergence, and its fading

Since the late 1990s the picture has changed. Patel, Sandefur and Subramanian document that unconditional convergence emerged from the mid-1990s onward ([Patel, Sandefur & Subramanian, 2021](#)). Kremer, Willis and You find that convergence in income has been accompanied by convergence in many of the policies and institutions that previously separated rich from poor economies ([Kremer, Willis & You, 2022](#)). A comprehensive review by Johnson and Papageorgiou concludes that the evidence for long-run absolute convergence remains weak, while conditional convergence and convergence clubs are well supported ([Johnson & Papageorgiou, 2020](#)).

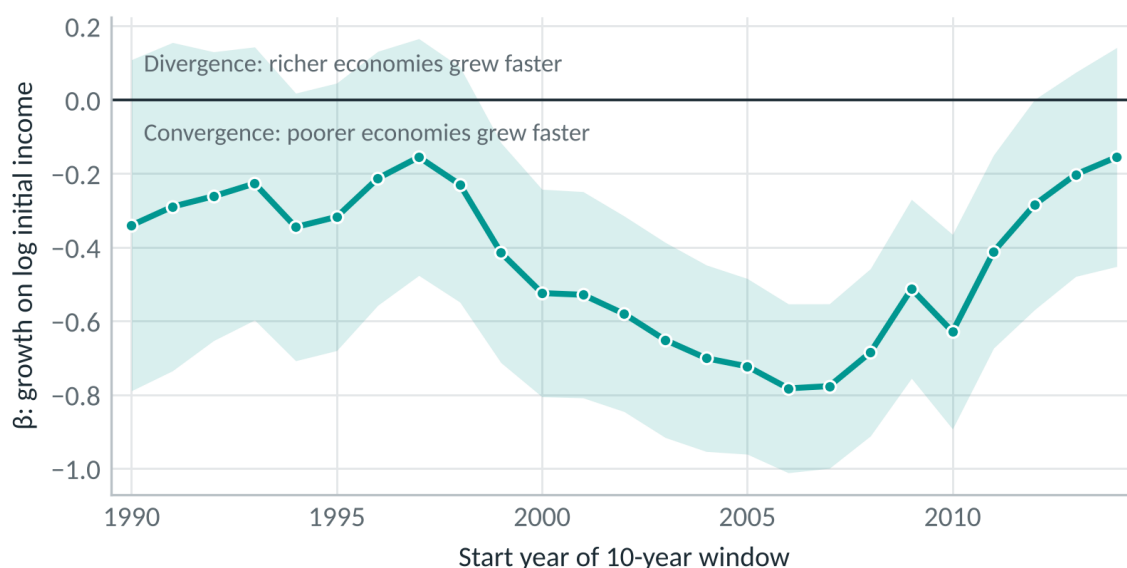
We re-estimated equation 4.2 without controls using the most recent World Bank data on GDP per capita at purchasing power parity. Figure 4.2 shows the result for 2000–2023 across 191 economies. The slope is negative and statistically significant: an economy with half the initial income of another grew on average about 0.3 percentage points faster per year ($0.43 \times \ln 2$).

Figure 4.2 Unconditional convergence, 2000–2023

Source: H Heuristics calculations from [World Bank WDI](#) via [Our World in Data](#). GDP per capita, PPP, constant international dollars. Each point is one economy; the line is an ordinary least squares fit.

The magnitude matters as much as the sign. Converting the estimated β into a continuous rate of convergence (Appendix A) gives $\lambda \approx 0.45$ percent per year, which implies that half of an initial gap would close in roughly 150 years. This is roughly a fifth of the 2 percent conditional rate of the classic literature. Measured σ -convergence is correspondingly modest: for a balanced panel of 184 economies, the standard deviation of log income per capita fell from 1.20 in 2000 to 1.15 in 2023.

Figure 4.3 asks whether the convergence of the 2000s has persisted. It reports β for every ten-year window beginning between 1990 and 2014. Convergence strengthened through windows starting in the early 2000s, peaking for the windows beginning in 2006 and 2007 ($\beta \approx -0.78$), a period that coincided with a commodity price boom, rapid growth in China and India, and a wave of mobile-phone adoption. It has since weakened considerably. For windows beginning in 2012, 2013 and 2014, the estimate is no longer distinguishable from zero at the 95 percent level.

Figure 4.3 The rise and fade of unconditional convergence

Source: H Heuristics calculations from [World Bank WDI](#) via Our World in Data. β from regressions of 10-year average growth on log initial GDP per capita (PPP); 184–197 economies per window. Shaded band shows the 95 percent confidence interval.

The diffusion framework offers a natural interpretation. A one-time increase in conductance (the opening of trade, the spread of mobile connectivity, macroeconomic stabilisation across many low-income economies in the late 1990s) produces a surge of catch-up as accumulated gradients are released. If conductance then stops rising, catch-up slows as the easiest gains are exhausted. Sustained convergence requires continued improvement in absorptive capacity, not a single reform.

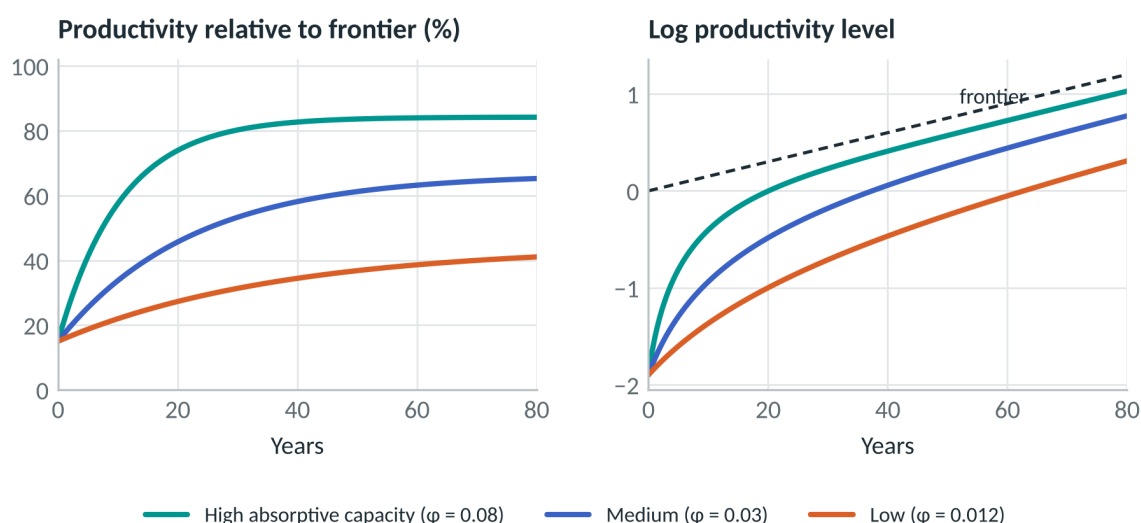
4.4 Technology diffusion as the engine of catch-up

Most cross-country differences in income are not explained by differences in capital or schooling but by differences in the efficiency with which inputs are used: total factor productivity ([Hall & Jones, 1999](#); [Easterly & Levine, 2001](#); [Caselli, 2005](#)01009-9)). Convergence is therefore, at root, a question about the diffusion of productive knowledge.

Nelson and Phelps proposed that the rate at which an economy closes its technology gap depends on its human capital ([Nelson & Phelps, 1966](#)). In a simple version, productivity A in a follower economy evolves as:

$$\frac{dA}{dt} = \phi(h) \cdot (T - A) \quad (4.3)$$

where T is the frontier level, growing at rate g , and $\phi(h)$ is an absorptive capacity that rises with human capital h . Equation 4.3 is Fick's first law applied to productivity: the flux of knowledge is a conductance times a gradient. Its steady-state solution has a simple and important property: the follower grows at the frontier rate g in the long run, but its *relative* level converges to $\phi/(\phi + g)$. Absorptive capacity determines not whether a country eventually grows, but how close to the frontier it settles. Benhabib and Spiegel found cross-country evidence that human capital affects growth chiefly through this catch-up channel ([Benhabib & Spiegel, 1994](#)90047-7)).

Figure 4.4 Absorptive capacity determines how close to the frontier an economy settles

Source: H Heuristics simulation of equation 4.3. Frontier grows at 1.5 percent per year; each follower starts at 15 percent of the frontier. Steady-state relative productivity equals $\phi/(\phi + g)$.

Figure 4.4 illustrates this result. All three followers eventually grow at the frontier rate, so measured growth rates converge. But their *levels* settle at 84, 67 and 44 percent of the frontier respectively. This is precisely the pattern described as conditional convergence: economies converge to different steady states determined by their capabilities.

Two historical insights complement the model. Gerschenkron argued that relative backwardness can be an advantage, because latecomers can adopt proven technologies without bearing the cost of inventing them. Abramovitz qualified this: the potential for rapid catch-up is realised only when a country has the **social capability** to absorb advanced technologies, including education, organisational experience and institutions (Abramovitz, 1986). In the language of this report, backwardness supplies the gradient; social capability supplies the conductance.

4.5 Arrival versus intensity

Comin and Hobijn assembled data on the adoption of 15 major technologies across 166 countries over two centuries (Comin & Hobijn, 2010). They found an average lag of about 45 years between a technology's invention and its arrival in a typical country, with substantial variation across countries and a tendency for more recent technologies to arrive faster. Variation in adoption lags accounted for at least a quarter of cross-country differences in income per capita.

A subsequent study separated two dimensions of diffusion (Comin & Mestieri, 2018). Adoption **lags**, the time until a technology first arrives, have converged sharply between rich and poor countries. The **intensity** of use once a technology has arrived, how many units per capita are installed and used, has diverged. Technologies reach poor countries far sooner than they used to; they penetrate those economies much less deeply. The authors show that these two patterns together can account for a significant part of the great income divergence since the nineteenth century.

The digital data in Figure 3.4 display the same signature in real time. Mobile networks arrived almost everywhere within a decade; fixed broadband, a high-intensity technology that requires complementary capital, remains confined to economies with the infrastructure to support it. In the terms of the reaction–diffusion model, arrival corresponds to the advance of the wave front, intensity to the height of the plateau behind it. The front depends mainly on connectivity; the plateau depends on local conductance.

4.6 Ideas, meetings and the global diffusion of knowledge

A recent generation of growth models builds the contact process of Section 2 directly into macroeconomics. In these models, producers improve their productivity by meeting others and learning from them; the distribution of productivity evolves as better ideas diffuse through the population ([Lucas & Moll, 2014](#); [Perla & Tonetti, 2014](#)). Buera and Oberfield extend the approach to international trade: when producers learn from the sellers they buy from, opening to trade raises the quality of the ideas producers encounter, not just the variety of goods available ([Buera & Oberfield, 2020](#)).

These models formalise the idea, introduced in Section 1, that bridging ties determine the inflow of knowledge into a module. They also clarify a policy-relevant point: the gains from openness depend on *whom* an economy is connected to. Links to more productive partners raise the gradient across which knowledge flows.

4.7 Structural transformation and the escalator of manufacturing

Convergence can be strong within sectors even when it is weak for whole economies. Rodrik showed that labour productivity in formal manufacturing industries converges unconditionally toward the frontier at roughly 2 to 3 percent a year, regardless of country characteristics ([Rodrik, 2013](#)). Manufacturing behaves like a high-conductance channel: it is tradable, standardised and exposed to global competition and supply chains. Aggregate convergence is weak because too little of the labour force works in such sectors, and because the expansion of high-conductance sectors in low-income economies has often been limited. Structural transformation, the movement of workers into activities connected to the global frontier, is therefore not separate from technology diffusion. It is the process that determines how much of the economy is exposed to the gradient.

SECTION 05

The Bottlenecks of Development

A technology can arrive without transforming living standards. Between arrival and impact lie a series of constraints: unreliable electricity, inadequate skills, expensive finance, weak infrastructure and limited state capacity. This section shows how such constraints combine, and why the weakest one usually governs the outcome.

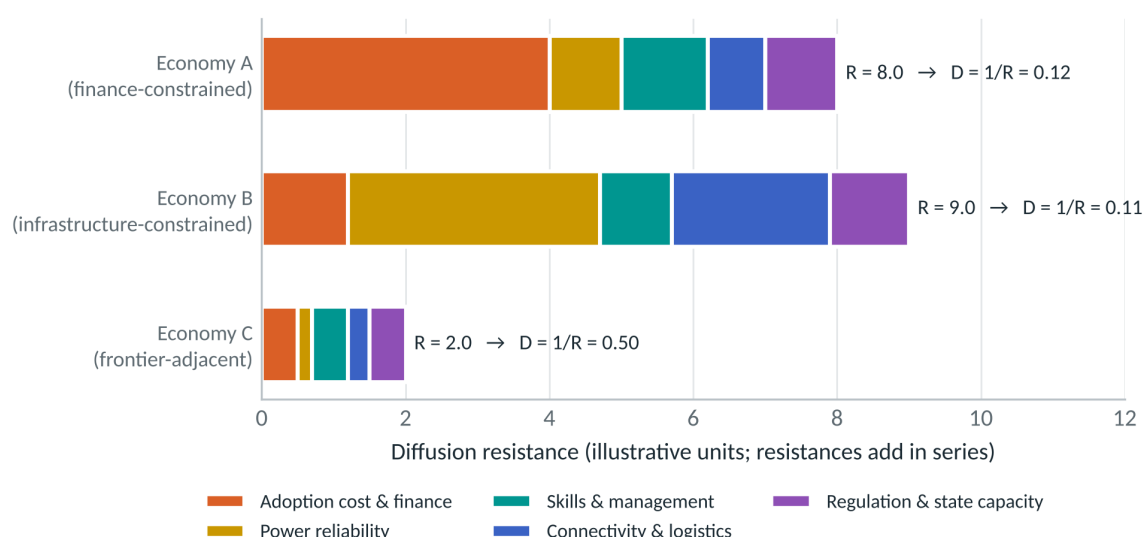
5.1 Resistances in series

Return to the electrical analogy of Section 2. For a technology to raise productivity in a firm or household, knowledge and equipment must pass through a sequence of stages: it must be affordable and financeable, it must be powered, people must know how to use it, it must be connected to markets and suppliers, and the regulatory and institutional environment must allow its returns to be captured. Each stage imposes a resistance. When stages are sequential, resistances add:

$$\frac{1}{D_{eff}} = \sum_k R_k = R_{finance} + R_{power} + R_{skills} + R_{connectivity} + R_{institutions} \quad (5.1)$$

Two implications follow. First, the effective conductance is dominated by the largest resistance. Reducing a small resistance by half achieves little; reducing the largest by half can transform the system. Second, the identity of the dominant resistance differs between economies. Figure 5.1 illustrates three stylised cases. In a finance-constrained economy, the priority is the cost of adoption; in an infrastructure-constrained economy, it is reliable power and logistics. The same intervention will have very different returns in the two places.

Figure 5.1 Constraints combine like resistances in series



Source: H Heuristics. Illustrative values chosen to show how the composition of diffusion resistance differs across economies; not estimates for specific countries.

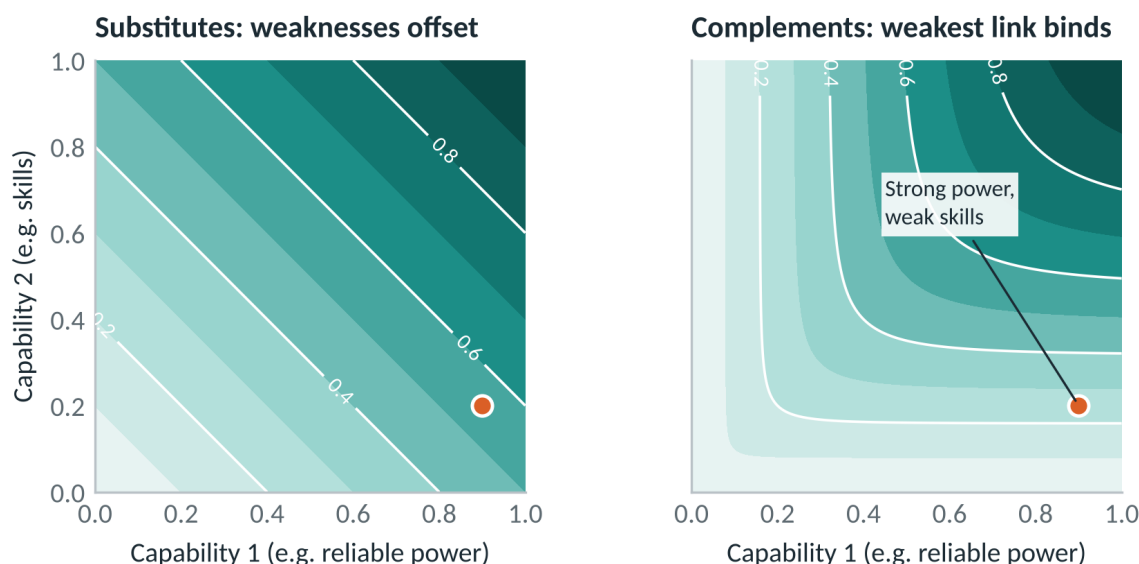
5.2 Weak links and complementarity

A related principle comes from production theory. Kremer's O-ring theory of development observes that many production processes consist of tasks that must all be performed well for the product to have value, so that output depends on the *product* of the quality of each task ([Kremer, 1993](#)):

$$Y = q_1 \times q_2 \times \dots \times q_n \quad (5.2)$$

When inputs are complements, a weakness in any one of them cannot be offset by strength in the others. Jones shows that such complementarities between intermediate inputs can greatly amplify small differences in productivity into large differences in income ([Jones, 2011](#)). Figure 5.2 contrasts the two cases. When capabilities are substitutes, strong electricity can compensate for weak skills. When they are complements, the economy is stuck at the level of its weakest capability, no matter how strong the others.

Figure 5.2 Substitutes versus complements: why the weakest link binds

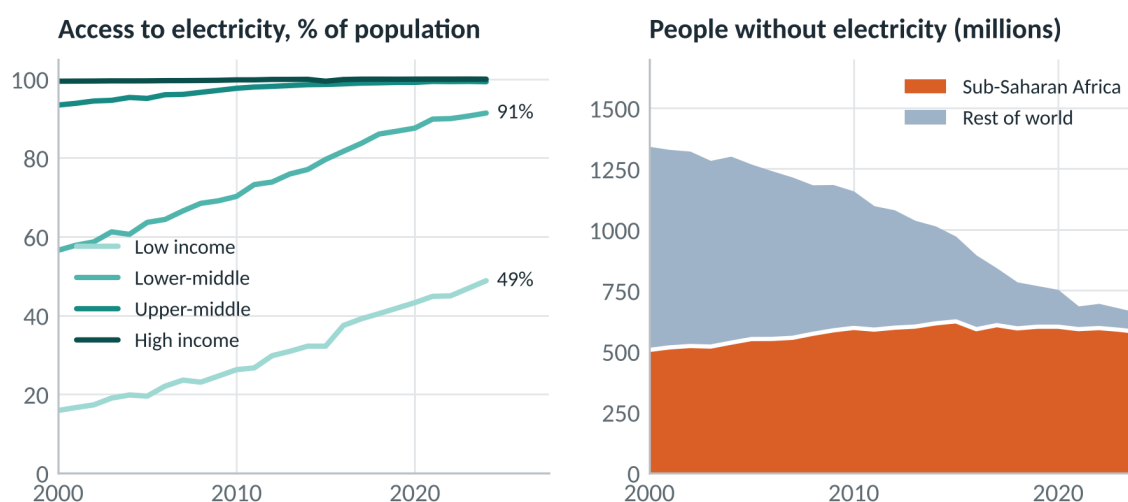


Source: H Heuristics. Contours show effective productivity as a function of two capabilities. Left: additive (perfect substitutes). Right: strong complements (CES with elasticity of substitution 0.25). The marked point has strong power and weak skills.

This principle explains a pattern visible throughout the empirical literature: interventions that relax one constraint often show modest average effects, because another constraint binds. The appropriate inference is not that the intervention “does not work” but that its effect is conditional on complements. Section 7 proposes testing this capability-complementarity hypothesis directly.

5.3 Electricity: the foundational conductance

Electricity is the clearest example of a foundational constraint, because nearly every modern production technology requires it. Figure 5.3 shows both progress and its limits. Globally, the share of people with access to electricity rose from 78 percent in 2000 to 92 percent in 2024, and the number without access fell from about 1.34 billion to 657 million. In low-income countries, access more than tripled, from 16 to 49 percent.

Figure 5.3 Electricity access: the wave advances, but the medium grows

Source: [Our World in Data](#) based on World Bank and [Tracking SDG 7](#). Left: share of population with access by World Bank income group. Right: number of people without access, millions.

The right panel reveals the difficulty. Outside Sub-Saharan Africa, the number of people without power fell by more than 90 percent, from about 840 million to under 80 million. In Sub-Saharan Africa the share with access more than doubled, from 26 to 55 percent, yet the number without access *rose*, from about 506 million to 579 million, because population grew almost as fast as connections. By 2024 the region accounted for roughly 88 percent of the global deficit. In diffusion terms, the wave front advanced, but the medium expanded beneath it.

Access is only the first dimension. Reliability matters as much. Electricity shortages in India materially reduced manufacturing output and productivity, with the costs falling most heavily on plants without their own generators ([Allcott, Collard-Wexler & O'Connell, 2016](#)). Rural electrification in South Africa raised women's employment by releasing time from home production ([Dinkelman, 2011](#)). Yet an experiment in rural Kenya found that demand for grid connections fell steeply as price rose and that household connections produced few measurable economic gains in the medium run ([Lee, Miguel & Wolfram, 2020](#)). The two findings are consistent with the weak-link view: power raises productivity where complementary capabilities exist to use it.

5.4 Skills and management

Human capital is the conductance in the Nelson–Phelps model, but the relevant skills extend beyond formal schooling. A randomised trial that provided management consulting to large Indian textile firms raised productivity by 17 percent in the first year, through better quality control, inventory management and efficiency ([Bloom et al., 2013](#)). The practices involved were neither secret nor expensive; they had simply not diffused. Management know-how is a technology whose adoption faces the same resistances as any other, including the organisational misalignments documented in Pakistan's soccer-ball industry ([Atkin et al., 2017](#)).

5.5 Finance and the cost of adoption

The gradient that drives adoption is net of cost. Where finance is scarce or expensive, adopters cannot fund upfront investments even when returns are high, and the resistance appears as a high discount rate on future benefits. Heterogeneity compounds the problem: those with the highest potential returns are not always those with the cheapest access to inputs and credit ([Suri, 2011](#)). Digital financial services have lowered some of these barriers, which is one reason mobile money has been associated with gains in resilience and consumption ([Jack & Suri, 2014](#)). Data on account ownership and borrowing from the [Global Findex database](#) provide a direct measure of this resistance.

5.6 Infrastructure, connectivity and logistics

Transport, water and telecommunications networks determine both the physical cost of moving goods and the informational cost of moving ideas. The World Bank's *Lifelines* report estimates that infrastructure disruptions impose costs of hundreds of billions of dollars a year on households and firms in low- and middle-income countries, and that investing in more resilient infrastructure yields high returns ([Hallegatte, Rentschler & Rozenberg, 2019](#)). In the framework of this report, infrastructure enters twice: as a conductance that determines how fast technologies diffuse, and as a stock whose resilience determines how much accumulated capability survives a shock.

5.7 State capacity, institutions and allocation

Institutions shape the incentive to adopt by determining whether the returns from investment can be captured. Differences in what Hall and Jones call **social infrastructure**, the institutions and policies that determine the economic environment, account for much of the cross-country variation in output per worker ([Hall & Jones, 1999](#)). Institutions also determine whether resources flow to the firms best able to use new technologies. Hsieh and Klenow estimate that if capital and labour in China and India were allocated as efficiently as in the United States, manufacturing productivity would rise by 30 to 50 percent in China and 40 to 60 percent in India ([Hsieh & Klenow, 2009](#)).

Misallocation is a distinctive kind of resistance. It does not block the arrival of a technology but prevents it from reaching the users who would gain most, flattening the gradient that would otherwise drive adoption.

5.8 Diagnosing the binding constraint

The growth diagnostics approach of Hausmann, Rodrik and Velasco ([2008](#)) proposes that development strategy should begin by identifying the single most binding constraint on private investment, rather than addressing a long list of reforms at once. The resistance framework provides a quantitative rationale for this approach and a way to operationalise it. Table 5.1 maps each resistance to observable indicators and data sources.

Table 5.1 Measuring diffusion resistances

Resistance	Illustrative indicators	Principal sources
Adoption cost and finance	Account ownership; firms citing finance as a major constraint; lending rates; price of devices relative to income	Global Findex ; Enterprise Surveys ; WDI
Power reliability	Access rate; outages per month; share of firms owning generators; losses due to outages	Tracking SDG 7 ; IEA ; Enterprise Surveys
Skills and management	Years and quality of schooling; management practice scores; share of workers with tertiary education	WDI ; Penn World Table human capital index
Connectivity and logistics	Mobile broadband coverage and price; road density; time to export; fixed broadband subscriptions	ITU DataHub ; WDI
Institutions and state capacity	Contract enforcement; regulatory quality; dispersion of firm-level productivity	WDI ; Enterprise Surveys
Capability base	Economic complexity; export diversification; proximity to new products	Atlas of Economic Complexity

Source: H Heuristics.

SECTION 06

A Unified Architecture of Development

The preceding sections examined diffusion, convergence and bottlenecks separately. This section integrates them into a single framework, states its core propositions, adds resilience as a fourth pillar, and shows how the framework can be used to identify where interventions would most accelerate development.

6.1 The core equation

Let A_i denote the level of productive capability in a unit i (a region, sector or economy), measured relative to the frontier. Drawing together the elements developed above, its evolution can be written as:

$$\frac{dA_i}{dt} = \sum_j D_{ij}(\theta_i) \max(A_j - A_i, 0) + r_i A_i \left(1 - \frac{A_i}{K_i(\theta_i)}\right) - s_i(t)(1 - \rho_i)A_i \quad (6.1)$$

with a conductance determined by resistances in series and network ties:

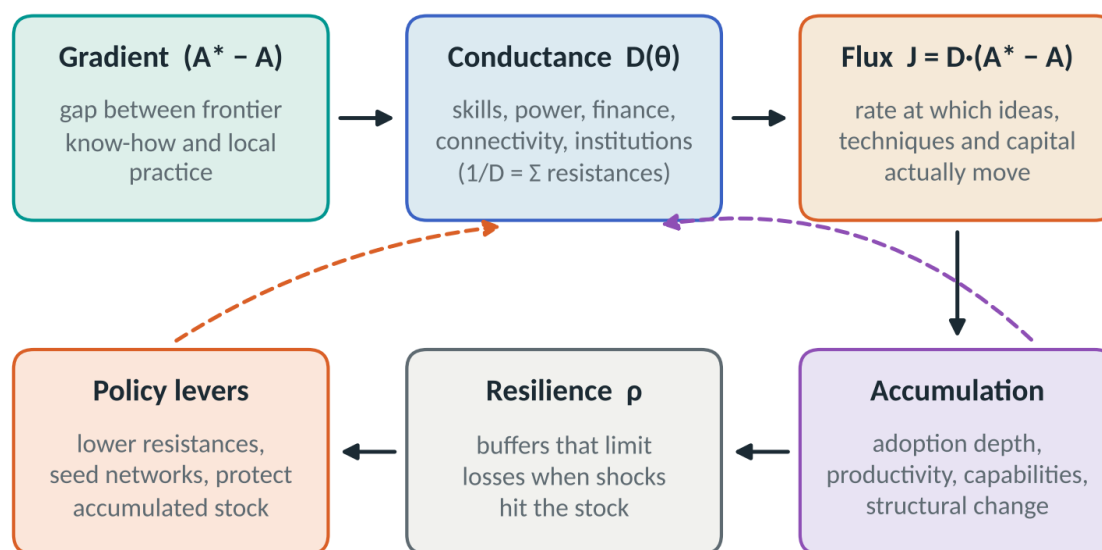
$$D_{ij}(\theta_i) = \frac{w_{ij}}{\sum_k R_k(\theta_i)} \quad (6.2)$$

and capabilities θ_i that themselves evolve with accumulated capability and policy:

$$\frac{d\theta_i}{dt} = f(A_i, \text{policy}_i) \quad (6.3)$$

Each term corresponds to a layer of the architecture in Section 1 and to evidence reviewed in Sections 2 to 5.

- **The gradient** $\max(A_j - A_i, 0)$ is the gap between unit i and the more advanced units j to which it is linked. Only positive gaps drive inflow; a unit does not lose capability by being connected to a less advanced partner (knowledge is non-rival).
- **The conductance** D_{ij} combines the strength of the tie w_{ij} (trade, investment, migration, communication) with the unit's total internal resistance $\sum R_k$. It formalises absorptive capacity and the bottlenecks of Section 5.
- **Local reproduction** $r_i A_i (1 - A_i/K_i)$ captures imitation, learning and network effects within the unit, which convert the arrival of an idea into a travelling wave. The ceiling K_i reflects the intensity that local complements can support: the plateau behind the wave front in Section 4.5.
- **Shocks and resilience** $s_i(t)(1 - \rho_i)A_i$ capture the loss of accumulated capability when conflicts, disasters, financial crises or pandemics strike, scaled down by resilience ρ_i .
- **Feedback** (equation 6.3) makes conductance and ceiling endogenous: accumulated capability funds better infrastructure, institutions and skills. This is the loop in Figure 1.1.

Figure 6.1 The unified architecture of development

Accumulated capability feeds back into conductance: development is self-reinforcing once flows begin.

Source: H Heuristics. Schematic of equations 6.1 to 6.3. Solid arrows show the primary flow from gradient to accumulation; dashed arrows show feedback from accumulation and policy into conductance.

6.2 Six propositions

The framework yields six propositions. Each is consistent with the evidence reviewed in this report, and each can be tested with the designs set out in Section 7.

Table 6.1 Core propositions of the unified architecture

Proposition	Statement	Principal evidence
1. Gradients are necessary but not sufficient	A large gap to the frontier creates potential for rapid growth, but realised catch-up is proportional to conductance.	Abramovitz (1986); Figure 4.1; Comin & Hobijn (2010)
2. The largest resistance governs	Because constraints act in series and as complements, relaxing the binding one yields disproportionate gains; relaxing slack ones yields little.	Kremer (1993) ; Jones (2011) ; Section 5
3. Reproduction turns arrival into waves	Local imitation and learning make diffusion advance at a constant speed set jointly by conductance and reproduction.	Fisher (1937) ; Griliches (1957) ; Figure 2.2
4. Network architecture sets speed and reliability	Long ties accelerate simple contagion; clustered ties with bridges are needed for costly, complex adoption.	Centola (2010) ; Beaman et al. (2021) ; Figure 3.3
5. Ceilings are economic	The intensity of use, not only the arrival, of technology determines income; intensity depends on complements.	Comin & Mestieri (2018) ; Figure 3.4

Proposition	Statement	Principal evidence
6. Resilience protects the stock	Without resilience, shocks erase accumulated capability and recoveries are incomplete.	Cerra & Saxena (2008) ; Hallegatte et al. (2019)

Source: H Heuristics.

6.3 Thresholds, lock-in and the case for coordinated pushes

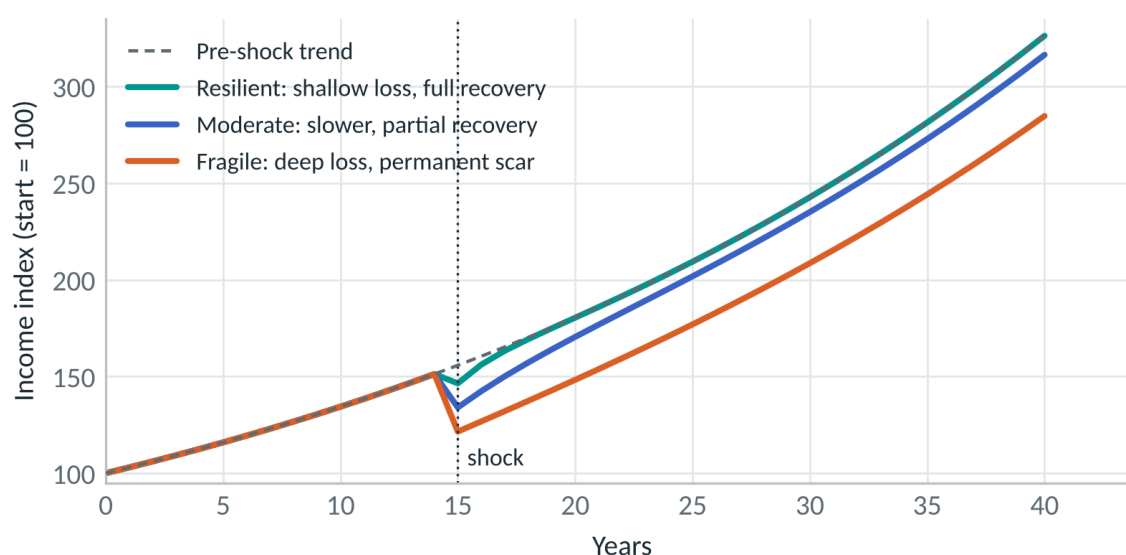
Because conductance rises with accumulated capability (equation 6.3), the system can have more than one stable state. An economy with low capability has low conductance and therefore receives little inflow; an economy with high capability has high conductance and receives much. Between them may lie a threshold. This is the formal structure of the **big push** argument: individually unprofitable investments can become jointly profitable when undertaken together, because each raises the market for the others ([Rosenstein-Rodan, 1943](#); [Murphy, Shleifer & Vishny, 1989](#)). Similar self-reinforcing dynamics underlie the concentration of industry in particular places ([Krugman, 1991](#)) and the lock-in of technologies whose early lead becomes self-perpetuating ([Arthur, 1989](#)).

Two practical implications follow. First, when an economy sits below a threshold, marginal improvements in a single resistance may produce little visible change, and coordinated action across several constraints may be needed to cross it. Second, once a threshold is crossed, progress can become self-sustaining, and the role of policy shifts from pushing to maintaining and protecting. The framework does not imply that big pushes are always warranted; it specifies the conditions (strong complementarity, strong feedback) under which they are.

6.4 Resilience and continuity

Ecologist C. S. Holling distinguished between a system's stability (how quickly it returns to equilibrium after a small disturbance) and its resilience (its ability to absorb large disturbances without shifting into a different state) ([Holling, 1973](#)). The distinction matters for development because shocks are frequent and large. Cerra and Saxena found that output losses associated with financial and political crises are, on average, highly persistent: output does not return to its pre-crisis trend ([Cerra & Saxena, 2008](#)).

Figure 6.2 illustrates the consequences in the framework. Three economies with identical pre-shock growth experience the same event. The resilient economy loses little and recovers fully. The fragile economy loses more, recovers slowly and carries a permanent scar, ending the period with about 13 percent lower income than its pre-shock path. The difference arises not from the shock itself but from the resilience parameter p and the speed of recovery, both of which depend on infrastructure, institutions, savings and social protection.

Figure 6.2 Resilience determines whether shocks leave permanent scars

Source: H Heuristics simulation. Three economies growing at 3 percent per year experience a shock in year 15 with different depths, recovery speeds and permanent losses.

6.5 From diagnosis to intervention

The unified equation maps naturally onto a menu of interventions, each acting on a different term. Table 6.2 sets out this mapping together with the evidence base and the leading indicators that would reveal whether an intervention is working.

Table 6.2 Where interventions act in the unified architecture

Term	Intervention lever	Illustrative evidence	Leading indicator
Gradient ($A_j - A_i$)	Trade and investment links to more productive partners; access to global supply chains	Buera & Oberfield (2020) ; Rodrik (2013)	Share of firms importing inputs or exporting; FDI inflows
Tie strength w_{ij}	Transport and digital connectivity; mobility of people and ideas	Hjort & Poulsen (2019) ; Jensen (2007)	Broadband coverage; data prices; travel time to markets
Resistance R_k	Reliable power; finance for adoption; management and skills; regulatory reform	Bloom et al. (2013) ; Allcott et al. (2016)	Outages; credit access; management scores
Reproduction r_i	Seeding through central adopters; demonstration; peer-learning networks	Banerjee et al. (2013) ; Beaman et al. (2021)	Adoption among peers of early adopters
Ceiling K_i	Complementary investments that raise intensity of use	Comin & Mestieri (2018)	Intensity of use per capita; utilisation rates
Resilience p_i	Resilient infrastructure; social protection; macro-financial buffers	Hallegatte et al. (2019) ; Jack & Suri (2014)	Losses and recovery time after shocks

Source: H Heuristics.

APPLYING THE ARCHITECTURE

A four-step diagnostic

- **Map the gradient.** Identify the technologies, practices and sectors where the gap to the relevant frontier is largest and where the payoff to closing it is highest.
- **Measure the resistances.** Using the indicators in Table 5.1, estimate each resistance and identify the largest. Where capabilities are complements, expect the largest resistance to dominate.
- **Locate the network entry points.** Identify the bridging ties (firms, ports, universities, diaspora networks) through which knowledge enters, and the central local actors through which it reproduces.
- **Protect the stock.** Assess exposure to shocks and the mechanisms that would preserve accumulated capability, so that gains are not lost in the next crisis.

SECTION 07

Testable Hypotheses and Research Agenda

A framework earns its place by generating predictions that could prove it wrong. This section translates the unified architecture into six empirical hypotheses, sets out how each can be tested with available data, and proposes a research programme for H Heuristics.

7.1 Six hypotheses

Table 7.1 Testable hypotheses

Hypothesis	Prediction	Test and data
H1. Diffusion resistance	Higher adoption costs and infrastructure deficits predict slower technology uptake, conditional on income.	Estimate Bass or logistic parameters by country and technology from ITU, Comin–Hobijn and Our World in Data series; regress speed on resistance indicators.
H2. Capability complementarity	Technology adoption raises productivity more where education and infrastructure are stronger; interaction effects exceed additive ones.	Firm-level productivity from Enterprise Surveys interacted with local power reliability and skills; compare additive and multiplicative specifications.
H3. Network acceleration	Greater connectivity predicts faster adoption, controlling for income and institutions; effective distance outperforms geographic distance.	Arrival times of technologies regressed on trade, migration and telecom network distance versus great-circle distance.
H4. Conditional convergence	Economies with comparable structural conditions converge more rapidly toward each other.	Club-convergence tests with Penn World Table and WDI data; β estimated within groups defined by resistance profiles.
H5. Development bottlenecks	Particular constraints are disproportionately responsible for low adoption or productivity; their removal yields non-linear gains.	Event studies of discrete improvements (grid connection, cable arrival, credit reform); test for larger effects where the relaxed constraint was the largest.
H6. Resilience and continuity	More resilient infrastructure and institutions reduce development setbacks during shocks.	Local projections of output and adoption after disasters and crises, interacted with pre-shock resilience indicators.

Source: H Heuristics.

7.2 Measuring the key quantities

Three quantities in the unified equation must be measured before the hypotheses can be tested.

- **The state variable A.** For technology-specific analysis, the adoption share or intensity of use (subscriptions per capita, kilowatt-hours per capita, tractors per hectare). For aggregate analysis, total factor productivity or output per worker relative to the frontier, from the [Penn World Table](#).
- **The network weights w.** Bilateral trade shares, foreign direct investment, migration stocks, air-passenger flows and telecommunication traffic. Each defines a different effective distance; comparing their predictive power is itself a test of mechanism.
- **The resistances R.** A composite resistance index built from the indicators in Table 5.1, normalised and combined both additively (series) and multiplicatively (weak link), so that the two structures can be compared directly.

7.3 Identification

A credible empirical programme must distinguish causation from correlation. Richer economies have more of everything: better power, more skills, deeper finance and faster adoption. Simple cross-country regressions cannot separate the role of each. We propose four complementary strategies.

1. **Event studies around discrete infrastructure changes.** The staggered arrival of submarine cables, grid extensions and mobile networks creates variation in conductance that is plausibly unrelated to local conditions in the short run, as exploited by [Hjort and Poulsen \(2019\)](#).
2. **Randomised and quasi-experimental variation in seeding.** Field experiments that vary who receives a technology first ([Beaman et al., 2021](#)) allow direct tests of network propositions.
3. **Within-country, cross-technology comparisons.** Comparing the adoption of technologies with different complementarity requirements within the same economy and period holds fixed many confounders and isolates the role of specific resistances.
4. **Structural estimation.** Fitting the unified equation to panel data and testing its out-of-sample predictions for adoption paths offers a demanding test of the framework as a whole.

Each strategy has limitations. Infrastructure placement is rarely random over longer horizons; experiments are local; structural models depend on functional-form assumptions. Convergent evidence across designs is more persuasive than any single estimate.

7.4 A research programme

Table 7.2 Proposed H Heuristics research programme

Phase	Focus	Outputs
1. Foundations	Assemble a harmonised panel of adoption, productivity, resistance and network data; publish open code.	Open dataset; technical note on measuring diffusion resistance
2. Diffusion speed	Estimate diffusion parameters for 20 or more technologies across 150 or more economies; test H1 and H3.	Working paper; interactive atlas of diffusion speeds
3. Complementarity and bottlenecks	Firm- and region-level tests of H2 and H5 using event studies.	Working papers; country diagnostic template

Phase	Focus	Outputs
4. Convergence and resilience	Club-convergence and shock-recovery analysis; tests of H4 and H6.	Working paper; resilience dashboard
5. Application	Pilot diagnostics with partner governments and investors; refine the framework in light of results.	Country diagnostics; policy briefs; second flagship report

Source: H Heuristics.

7.5 Limits of the framework

The framework simplifies in ways that should be acknowledged. It treats capability as a scalar when it is multidimensional. It represents institutions as resistances when they are also the outcome of political contests over who gains from new technologies. It says little about distribution within economies: diffusion that raises average productivity can widen inequality if early adopters are already advantaged. And, like all models borrowed from the natural sciences, it risks lending a false sense of mechanical inevitability to processes that depend on human choice.

We regard these limits as an agenda rather than a refutation. The test of the framework is whether it organises evidence better than alternatives and whether its predictions survive confrontation with data. Section 7.1 specifies how that test can be run.

SECTION 08

Conclusion

Structure emerges where flows meet constraints. Development is that process at the scale of societies.

This report began with an observation from the natural sciences: complex structures arise when simple rules channel flows through constrained media, and the structures that result reshape the flows that made them. We have argued that the same architecture organises economic development. Knowledge, technology, capital and energy flow across gradients between frontier and follower. Their rate is set by conductances (skills, infrastructure, finance, institutions) that behave like resistances in series and weak links in a chain. Local imitation and learning convert arrivals into waves. Network structure governs their speed. Accumulated capability feeds back into conductance, making development self-reinforcing once it begins and creating thresholds where it has not.

Fick's law, written for salt in water, supplies the core of this architecture: flux equals conductance times gradient. Its extensions supply the rest: a growth term for non-rival knowledge, a payoff-weighted gradient for purposive adopters, a network in place of distance, and feedback in place of fixed coefficients. Each extension has a direct counterpart in the empirical literature on technology adoption and growth.

The evidence assembled here suggests three conclusions for those who design development strategies and allocate capital to them.

- 1. Diagnose before pushing.** The gradient between frontier and follower is large almost everywhere. What differs is conductance. Identifying the binding resistance is the highest-return analytical step in any development strategy.
- 2. Invest in the channel, not only the content.** Technologies diffuse at the speed their complements allow. The extraordinary spread of mobile telephony shows what happens when a technology bypasses a constraint; the slow spread of fixed broadband and the persistence of the electricity gap show what happens when it cannot.
- 3. Protect what has been built.** Gains in capability can be lost faster than they are accumulated. Resilience is not separate from development; it is the condition for development to compound.

Convergence between rich and poor economies strengthened in the early twenty-first century and has since faded. Whether it resumes will depend less on the arrival of new technologies, which now reach almost everywhere quickly, than on whether economies build the conductance to use them intensively. That is where the architecture of creation meets the practice of development, and where we believe research and investment can do the most good.

APPENDIX A

Mathematical Notes

A.1 The diffusion equation and the square-root law

Conservation requires that the change in concentration within a small interval equals the net flux into it: $\partial\phi/\partial t = -\partial J/\partial x$. Substituting Fick's first law (2.1) gives equation 2.2. The similarity variable $\eta = x/(2\sqrt{Dt})$ reduces 2.2 to an ordinary differential equation whose solution, with $\phi = \phi_0$ at $x = 0$ and $\phi = 0$ initially elsewhere, is $\phi = \phi_0 \operatorname{erfc}(\eta)$. Because the solution depends on x and t only through η , any feature of the profile (such as the point where $\phi = \phi_0/2$) moves as $x \propto \sqrt{Dt}$.

A.2 The Fisher–KPP wave speed

Seek travelling-wave solutions $a(x, t) = U(z)$ with $z = x - ct$. Ahead of the front, a is small and the reaction term is approximately ra . Substituting $U \propto e^{-\lambda z}$ into the linearised equation gives $D\lambda^2 - c\lambda + r = 0$, so $c = D\lambda + r/\lambda$. Real, non-oscillating decay requires $c^2 \geq 4rD$. Fronts starting from localised initial conditions select the minimum speed, $c = 2\sqrt{rD}$, as in equation 2.6.

A.3 The Bass model

Equation 3.2 is a Riccati equation with solution, for $F(0) = 0$:

$$F(t) = \frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}} \quad (\text{A.1})$$

The adoption rate peaks at $t^* = \ln(q/p)/(p+q)$ when $q > p$; otherwise it is highest at launch. With $p = 0.03$ and $q = 0.38$, $t^* \approx 6.2$ years, consistent with Figure 3.2.

A.4 Speed of convergence from β

Integrating equation 4.1 over an interval of length T gives average growth $(\ln y_T - \ln y_0)/T = -[(1 - e^{-\lambda T})/T] \times (\ln y_0 - \ln y^*)$. The coefficient on initial income in regression 4.2 is therefore $\beta = -(1 - e^{-\lambda T})/T$, so:

$$\lambda = -\frac{\ln(1 + \beta T)}{T}, \quad t_{1/2} = \frac{\ln 2}{\lambda} \quad (\text{A.2})$$

With $\beta = -0.0043$ (growth measured in proportions) and $T = 23$, $\lambda \approx 0.0045$ per year and the half-life is about 153 years.

A.5 Steady state of the Nelson–Phelps model

Let $T(t) = T_0 e^{gt}$ and define relative productivity $a = A/T$. Then $da/dt = \phi(1 - a) - ga$, whose stable steady state is $a^* = \phi/(\phi + g)$. With $g = 0.015$, $\phi = 0.08, 0.03$ and 0.012 give $a^* = 0.84, 0.67$ and 0.44 , the plateaus in Figure 4.4.

A.6 Weak links and CES aggregation

With a constant-elasticity aggregator $Y = (\sum_k \omega_k x_k^\rho)^{1/\rho}$, the elasticity of substitution is $1/(1 - \rho)$. As $\rho \rightarrow -\infty$, $Y \rightarrow \min_k x_k$, the pure weak-link case. The right panel of Figure 5.2 uses $\rho = -3$ (elasticity 0.25) with equal weights.

APPENDIX B

Data and Methods

All empirical figures use publicly available data retrieved in October 2026. Simulated and illustrative figures are labelled as such in their source notes. Table B.1 lists the sources for each figure.

Table B.1 Figure data sources and methods

Figure	Data	Method
2.1, 2.2	None (analytical and numerical)	Equation 2.3 evaluated directly; equations 2.2 and 2.5 solved by explicit finite differences ($dx = 0.2$, stable time step).
3.1, Table 3.1	Our World in Data: technology adoption in US households	Series as published; thresholds identified as first year at or above 10 and 75 percent.
3.2	None (analytical)	Closed-form Bass solution (A.1).
3.3	None (simulation)	Watts–Strogatz networks, $n = 500$, $k = 8$, rewiring 0, 0.05 and 1; 40 runs each.
3.4	Our World in Data: mobile , internet , fixed broadband	World Bank regional aggregates, 2000–2025; lines broken where years are missing.
4.1	Maddison Project Database 2023	GDP per capita in 2011 international dollars, 1950–2022.
4.2, 4.3	World Bank GDP per capita, PPP	Country-level series only (aggregates excluded). OLS of annualised log growth on log initial income; classical standard errors.
4.4, 6.2	None (simulation)	Equation 4.3 integrated by Euler’s method; Figure 6.2 uses a stylised shock with geometric recovery.
5.1, 5.2	None (illustrative)	Series resistances and CES contours with stated parameters.
5.3	Our World in Data: access share , people without access	World Bank income groups and Sub-Saharan Africa aggregate, 2000–2024.

Source: H Heuristics.

The convergence estimates in Section 4 are unconditional and unweighted: each economy counts equally regardless of population. Population-weighted estimates, which would give far greater weight to China and India, would be expected to show stronger convergence given those economies’ rapid growth from low initial incomes. Small economies and those with volatile commodity-dependent output contribute disproportionately to dispersion. Results should be read as descriptive patterns rather than causal estimates.

REFERENCES

References

- Abramovitz, M. (1986). Catching up, forging ahead, and falling behind. *Journal of Economic History*, 46(2), 385–406. doi.org/10.1017/S0022050700046209
- Acemoglu, D., Johnson, S., & Robinson, J. A. (2001). The colonial origins of comparative development: An empirical investigation. *American Economic Review*, 91(5), 1369–1401. doi.org/10.1257/aer.91.5.1369
- Aghion, P., & Howitt, P. (1992). A model of growth through creative destruction. *Econometrica*, 60(2), 323–351. doi.org/10.2307/2951599
- Aker, J. C. (2010). Information from markets near and far: Mobile phones and agricultural markets in Niger. *American Economic Journal: Applied Economics*, 2(3), 46–59. doi.org/10.1257/app.2.3.46
- Allcott, H., Collard-Wexler, A., & O’Connell, S. D. (2016). How do electricity shortages affect industry? Evidence from India. *American Economic Review*, 106(3), 587–624. doi.org/10.1257/aer.20140389
- Ammerman, A. J., & Cavalli-Sforza, L. L. (1971). Measuring the rate of spread of early farming in Europe. *Man*, 6(4), 674–688. doi.org/10.2307/2799190
- Arthur, W. B. (1989). Competing technologies, increasing returns, and lock-in by historical events. *Economic Journal*, 99(394), 116–131. doi.org/10.2307/2234208
- Atkin, D., Chaudhry, A., Chaudry, S., Khandelwal, A. K., & Verhoogen, E. (2017). Organizational barriers to technology adoption: Evidence from soccer-ball producers in Pakistan. *Quarterly Journal of Economics*, 132(3), 1101–1164. doi.org/10.1093/qje/qjx010
- Banerjee, A., Chandrasekhar, A. G., Duflo, E., & Jackson, M. O. (2013). The diffusion of microfinance. *Science*, 341(6144), 1236498. doi.org/10.1126/science.1236498
- Barabási, A.-L., & Albert, R. (1999). Emergence of scaling in random networks. *Science*, 286(5439), 509–512. doi.org/10.1126/science.286.5439.509
- Barro, R. J. (1991). Economic growth in a cross section of countries. *Quarterly Journal of Economics*, 106(2), 407–443. doi.org/10.2307/2937943
- Barro, R. J., & Sala-i-Martin, X. (1992). Convergence. *Journal of Political Economy*, 100(2), 223–251. doi.org/10.1086/261816
- Bass, F. M. (1969). A new product growth for model consumer durables. *Management Science*, 15(5), 215–227. doi.org/10.1287/mnsc.15.5.215
- Baumol, W. J. (1986). Productivity growth, convergence, and welfare: What the long-run data show. *American Economic Review*, 76(5), 1072–1085. www.jstor.org/stable/1816469
- Beaman, L., BenYishay, A., Magruder, J., & Mobarak, A. M. (2021). Can network theory-based targeting increase technology adoption? *American Economic Review*, 111(6), 1918–1943. doi.org/10.1257/aer.20200295
- Bejan, A., & Lorente, S. (2010). The constructal law of design and evolution in nature. *Philosophical Transactions of the Royal Society B*, 365(1545), 1335–1347. doi.org/10.1098/rstb.2009.0302
- Benhabib, J., & Spiegel, M. M. (1994). The role of human capital in economic development: Evidence from aggregate cross-country data. *Journal of Monetary Economics*, 34(2), 143–173. [doi.org/10.1016/0304-3932\(94\)90047-7](https://doi.org/10.1016/0304-3932(94)90047-7)
- Bettencourt, L. M. A., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences*, 104(17), 7301–7306. doi.org/10.1073/pnas.0610172104
- Bloom, N., Eifert, B., Mahajan, A., McKenzie, D., & Roberts, J. (2013). Does management matter? Evidence from India. *Quarterly Journal of Economics*, 128(1), 1–51. doi.org/10.1093/qje/qjs044
- Bolt, J., & van Zanden, J. L. (2024). *Maddison Project Database 2023*. Groningen Growth and Development Centre. www.rug.nl/ggdc/historicaldevelopment/maddison/

- Brockmann, D., & Helbing, D. (2013). The hidden geometry of complex, network-driven contagion phenomena. *Science*, 342(6164), 1337–1342. doi.org/10.1126/science.1245200
- Buera, F. J., & Oberfield, E. (2020). The global diffusion of ideas. *Econometrica*, 88(1), 83–114. doi.org/10.3982/ECTA14044
- Caselli, F. (2005). Accounting for cross-country income differences. In P. Aghion & S. Durlauf (Eds.), *Handbook of Economic Growth* (Vol. 1A, pp. 679–741). Elsevier. [doi.org/10.1016/S1574-0684\(05\)01009-9](https://doi.org/10.1016/S1574-0684(05)01009-9)
- Centola, D. (2010). The spread of behavior in an online social network experiment. *Science*, 329(5996), 1194–1197. doi.org/10.1126/science.1185231
- Centola, D., & Macy, M. (2007). Complex contagions and the weakness of long ties. *American Journal of Sociology*, 113(3), 702–734. doi.org/10.1086/521848
- Cerra, V., & Saxena, S. C. (2008). Growth dynamics: The myth of economic recovery. *American Economic Review*, 98(1), 439–457. doi.org/10.1257/aer.98.1.439
- Comin, D., & Hobijn, B. (2010). An exploration of technology diffusion. *American Economic Review*, 100(5), 2031–2059. doi.org/10.1257/aer.100.5.2031
- Comin, D., & Mestieri, M. (2018). If technology has arrived everywhere, why has income diverged? *American Economic Journal: Macroeconomics*, 10(3), 137–178. doi.org/10.1257/mac.20150175
- Conley, T. G., & Udry, C. R. (2010). Learning about a new technology: Pineapple in Ghana. *American Economic Review*, 100(1), 35–69. doi.org/10.1257/aer.100.1.35
- Demirgüç-Kunt, A., Klapper, L., Singer, D., & Ansar, S. (2022). *The Global Findex Database 2021*. World Bank. www.worldbank.org/en/publication/globalfindex
- Dinkelman, T. (2011). The effects of rural electrification on employment: New evidence from South Africa. *American Economic Review*, 101(7), 3078–3108. doi.org/10.1257/aer.101.7.3078
- Duflo, E., Kremer, M., & Robinson, J. (2011). Nudging farmers to use fertilizer: Theory and experimental evidence from Kenya. *American Economic Review*, 101(6), 2350–2390. doi.org/10.1257/aer.101.6.2350
- Easterly, W., & Levine, R. (2001). It's not factor accumulation: Stylized facts and growth models. *World Bank Economic Review*, 15(2), 177–219. doi.org/10.1093/wber/15.2.177
- Einstein, A. (1905). Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen. *Annalen der Physik*, 322(8), 549–560. doi.org/10.1002/andp.19053220806
- Feenstra, R. C., Inklaar, R., & Timmer, M. P. (2015). The next generation of the Penn World Table. *American Economic Review*, 105(10), 3150–3182. Data: Groningen Growth and Development Centre. www.rug.nl/ggdc/productivity/pwt/
- Fick, A. (1855). Ueber Diffusion. *Annalen der Physik*, 170(1), 59–86. doi.org/10.1002/andp.18551700105
- Fisher, R. A. (1937). The wave of advance of advantageous genes. *Annals of Eugenics*, 7(4), 355–369. doi.org/10.1111/j.1469-1809.1937.tb02153.x
- Foster, A. D., & Rosenzweig, M. R. (1995). Learning by doing and learning from others: Human capital and technical change in agriculture. *Journal of Political Economy*, 103(6), 1176–1209. doi.org/10.1086/601447
- Gollin, D., Lagakos, D., & Waugh, M. E. (2014). The agricultural productivity gap. *Quarterly Journal of Economics*, 129(2), 939–993. doi.org/10.1093/qje/qjt056
- Granovetter, M. (1978). Threshold models of collective behavior. *American Journal of Sociology*, 83(6), 1420–1443. doi.org/10.1086/226707
- Griliches, Z. (1957). Hybrid corn: An exploration in the economics of technological change. *Econometrica*, 25(4), 501–522. doi.org/10.2307/1905380
- Growth Lab at Harvard University. (2026). *The Atlas of Economic Complexity*. atlas.hks.harvard.edu/
- Hägerstrand, T. (1967). *Innovation Diffusion as a Spatial Process* (A. Pred, Trans.). University of Chicago Press. (Original work published 1953.)
- Hall, R. E., & Jones, C. I. (1999). Why do some countries produce so much more output per worker than others? *Quarterly Journal of Economics*, 114(1), 83–116. doi.org/10.1162/003355399555954

- Hallegatte, S., Rentschler, J., & Rozenberg, J. (2019). *Lifelines: The Resilient Infrastructure Opportunity*. World Bank. doi.org/10.1596/978-1-4648-1430-3
- Hausmann, R., Rodrik, D., & Velasco, A. (2008). Growth diagnostics. In N. Serra & J. E. Stiglitz (Eds.), *The Washington Consensus Reconsidered*. Oxford University Press. growthlab.hks.harvard.edu/
- Hidalgo, C. A., & Hausmann, R. (2009). The building blocks of economic complexity. *Proceedings of the National Academy of Sciences*, 106(26), 10570–10575. doi.org/10.1073/pnas.0900943106
- Hidalgo, C. A., Klinger, B., Barabási, A.-L., & Hausmann, R. (2007). The product space conditions the development of nations. *Science*, 317(5837), 482–487. doi.org/10.1126/science.1144581
- Hjort, J., & Poulsen, J. (2019). The arrival of fast internet and employment in Africa. *American Economic Review*, 109(3), 1032–1079. doi.org/10.1257/aer.20161385
- Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4, 1–23. doi.org/10.1146/annurev.es.04.110173.000245
- Hsieh, C.-T., & Klenow, P. J. (2009). Misallocation and manufacturing TFP in China and India. *Quarterly Journal of Economics*, 124(4), 1403–1448. doi.org/10.1162/qjec.2009.124.4.1403
- IEA, IRENA, UNSD, World Bank, & WHO. (2025). *Tracking SDG 7: The Energy Progress Report*. Washington, DC: World Bank. trackingsdg7.esmap.org/
- International Energy Agency. (2026). *Data and Statistics*. Paris: IEA. www.iea.org/data-and-statistics
- International Telecommunication Union. (2026). *ITU DataHub*. Geneva: ITU. datahub.itu.int/
- Jack, W., & Suri, T. (2014). Risk sharing and transactions costs: Evidence from Kenya's mobile money revolution. *American Economic Review*, 104(1), 183–223. doi.org/10.1257/aer.104.1.183
- Jaffe, A. B., Trajtenberg, M., & Henderson, R. (1993). Geographic localization of knowledge spillovers as evidenced by patent citations. *Quarterly Journal of Economics*, 108(3), 577–598. doi.org/10.2307/2118401
- Jensen, R. (2007). The digital divide: Information (technology), market performance, and welfare in the South Indian fisheries sector. *Quarterly Journal of Economics*, 122(3), 879–924. doi.org/10.1162/qjec.122.3.879
- Johnson, P., & Papageorgiou, C. (2020). What remains of cross-country convergence? *Journal of Economic Literature*, 58(1), 129–175. doi.org/10.1257/jel.20181207
- Jones, C. I. (2011). Intermediate goods and weak links in the theory of economic development. *American Economic Journal: Macroeconomics*, 3(2), 1–28. doi.org/10.1257/mac.3.2.1
- Keller, W. (2002). Geographic localization of international technology diffusion. *American Economic Review*, 92(1), 120–142. doi.org/10.1257/000282802760015630
- Kermack, W. O., & McKendrick, A. G. (1927). A contribution to the mathematical theory of epidemics. *Proceedings of the Royal Society A*, 115(772), 700–721. doi.org/10.1098/rspa.1927.0118
- Kremer, M. (1993). The O-ring theory of economic development. *Quarterly Journal of Economics*, 108(3), 551–575. doi.org/10.2307/2118400
- Kremer, M., Willis, J., & You, Y. (2022). Converging to convergence. *NBER Macroeconomics Annual*, 36, 337–412. doi.org/10.1086/718672
- Krugman, P. (1991). Increasing returns and economic geography. *Journal of Political Economy*, 99(3), 483–499. doi.org/10.1086/261763
- Lee, K., Miguel, E., & Wolfram, C. (2020). Experimental evidence on the economics of rural electrification. *Journal of Political Economy*, 128(4), 1523–1565. doi.org/10.1086/705417
- Lewis, W. A. (1954). Economic development with unlimited supplies of labour. *The Manchester School*, 22(2), 139–191. doi.org/10.1111/j.1467-9957.1954.tb00021.x
- Lucas, R. E. (1988). On the mechanics of economic development. *Journal of Monetary Economics*, 22(1), 3–42. [doi.org/10.1016/0304-3932\(88\)90168-7](https://doi.org/10.1016/0304-3932(88)90168-7)
- Lucas, R. E., & Moll, B. (2014). Knowledge growth and the allocation of time. *Journal of Political Economy*, 122(1), 1–51. doi.org/10.1086/674363

- Mankiw, N. G., Romer, D., & Weil, D. N. (1992). A contribution to the empirics of economic growth. *Quarterly Journal of Economics*, 107(2), 407–437. doi.org/10.2307/2118477
- Mansfield, E. (1961). Technical change and the rate of imitation. *Econometrica*, 29(4), 741–766. doi.org/10.2307/1911817
- McMillan, M., & Rodrik, D. (2011). *Globalization, Structural Change and Productivity Growth* (NBER Working Paper No. 17143). National Bureau of Economic Research. www.nber.org/papers/w17143
- Morris, S. (2000). Contagion. *Review of Economic Studies*, 67(1), 57–78. doi.org/10.1111/1467-937X.00121
- Murphy, K. M., Shleifer, A., & Vishny, R. W. (1989). Industrialization and the big push. *Journal of Political Economy*, 97(5), 1003–1026. doi.org/10.1086/261641
- Nelson, R. R., & Phelps, E. S. (1966). Investment in humans, technological diffusion, and economic growth. *American Economic Review*, 56(1/2), 69–75. www.jstor.org/stable/1821270
- Our World in Data. (2026). *Technology Adoption*. Global Change Data Lab. ourworldindata.org/technology-adoption
- Pastor-Satorras, R., & Vespignani, A. (2001). Epidemic spreading in scale-free networks. *Physical Review Letters*, 86(14), 3200–3203. doi.org/10.1103/PhysRevLett.86.3200
- Patel, D., Sandefur, J., & Subramanian, A. (2021). The new era of unconditional convergence. *Journal of Development Economics*, 152, 102687. doi.org/10.1016/j.jdeveco.2021.102687
- Perla, J., & Tonetti, C. (2014). Equilibrium imitation and growth. *Journal of Political Economy*, 122(1), 52–76. doi.org/10.1086/674362
- Prigogine, I. (1978). Time, structure, and fluctuations. *Science*, 201(4358), 777–785. doi.org/10.1126/science.201.4358.777
- Pritchett, L. (1997). Divergence, big time. *Journal of Economic Perspectives*, 11(3), 3–17. doi.org/10.1257/jep.11.3.3
- Rodrik, D. (2013). Unconditional convergence in manufacturing. *Quarterly Journal of Economics*, 128(1), 165–204. doi.org/10.1093/qje/qjs047
- Rogers, E. M. (2003). *Diffusion of Innovations* (5th ed.). Free Press.
- Romer, P. M. (1990). Endogenous technological change. *Journal of Political Economy*, 98(5, Part 2), S71–S102. doi.org/10.1086/261725
- Rosenstein-Rodan, P. N. (1943). Problems of industrialisation of eastern and south-eastern Europe. *Economic Journal*, 53(210/211), 202–211. doi.org/10.2307/2226317
- Simon, H. A. (1962). The architecture of complexity. *Proceedings of the American Philosophical Society*, 106(6), 467–482. www.jstor.org/stable/985254
- Skellam, J. G. (1951). Random dispersal in theoretical populations. *Biometrika*, 38(1/2), 196–218. doi.org/10.1093/biomet/38.1-2.196
- Solow, R. M. (1956). A contribution to the theory of economic growth. *Quarterly Journal of Economics*, 70(1), 65–94. doi.org/10.2307/1884513
- Sultan, F., Farley, J. U., & Lehmann, D. R. (1990). A meta-analysis of applications of diffusion models. *Journal of Marketing Research*, 27(1), 70–77. doi.org/10.1177/002224379002700107
- Suri, T. (2011). Selection and comparative advantage in technology adoption. *Econometrica*, 79(1), 159–209. doi.org/10.3982/ECTA7749
- Suri, T., & Jack, W. (2016). The long-run poverty and gender impacts of mobile money. *Science*, 354(6317), 1288–1292. doi.org/10.1126/science.aah5309
- Turing, A. M. (1952). The chemical basis of morphogenesis. *Philosophical Transactions of the Royal Society B*, 237(641), 37–72. doi.org/10.1098/rstb.1952.0012
- Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of ‘small-world’ networks. *Nature*, 393(6684), 440–442. doi.org/10.1038/30918
- West, G. B., Brown, J. H., & Enquist, B. J. (1997). A general model for the origin of allometric scaling laws in biology. *Science*, 276(5309), 122–126. doi.org/10.1126/science.276.5309.122

- Witten, T. A., & Sander, L. M. (1981). Diffusion-limited aggregation, a kinetic critical phenomenon. *Physical Review Letters*, 47(19), 1400–1403. doi.org/10.1103/PhysRevLett.47.1400
- World Bank. (2016). *World Development Report 2016: Digital Dividends*. Washington, DC: World Bank. www.worldbank.org/en/publication/wdr2016
- World Bank. (2024). *World Development Report 2024: The Middle-Income Trap*. Washington, DC: World Bank. www.worldbank.org/en/publication/wdr2024
- World Bank. (2026). *Enterprise Surveys*. Washington, DC: World Bank. www.enterprisesurveys.org/
- World Bank. (2026). *World Development Indicators*. Washington, DC: World Bank. datatopics.worldbank.org/world-development-indicators/