Toward an evolutionary theory of technological change

Complex systems summer school
July 1, 2015

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AT THE OXFORD MARTIN SCHOOL

Why study technology as an evolutionary process?

- Technology is the neglected prong of evolution, whose importance will be ever greater in the future.
- It forms the basis of living things as well as human-made things.
- For better or worse, it is the driver of economic growth.
- The major problems of civilization are created and solved by technology.

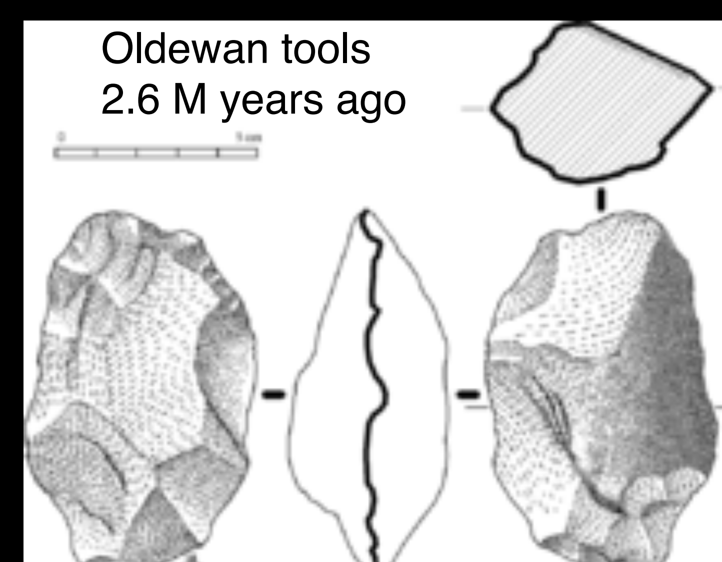
Human evolution and technological evolution are closely interlinked

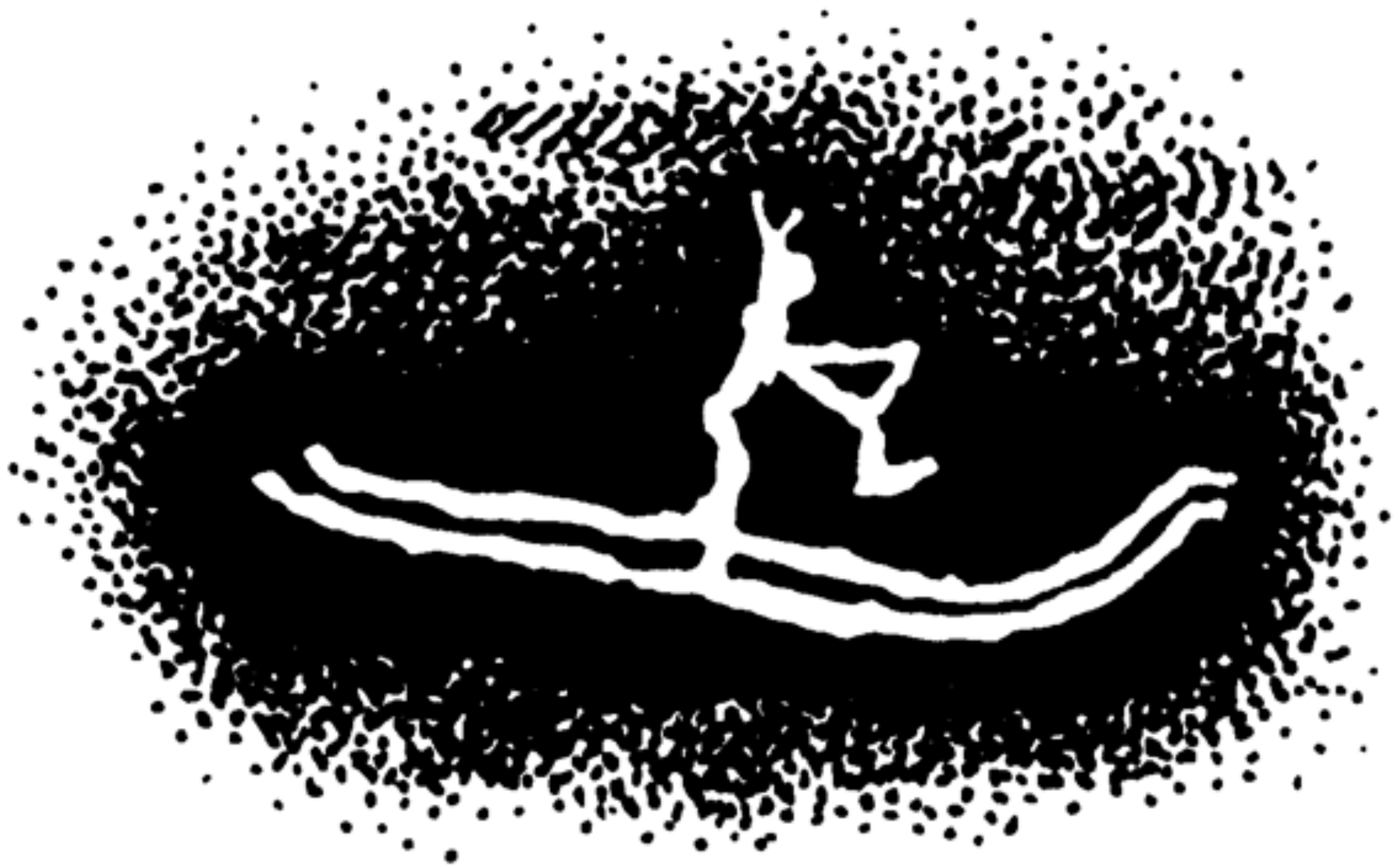
Tool use predates genus homo


Choppers, scrapers and pounders, 3.3 M years ago


homo habilis


Australopithecus garhi


Oldewan tools
2.6 M years ago



Man on skis. Stone Age rock carving, north Norway

Technology co-evolved with early humans

Without technology,
none of us would exist

Human population growth:

Reverend Thomas Malthus

Marquis de Condorcet

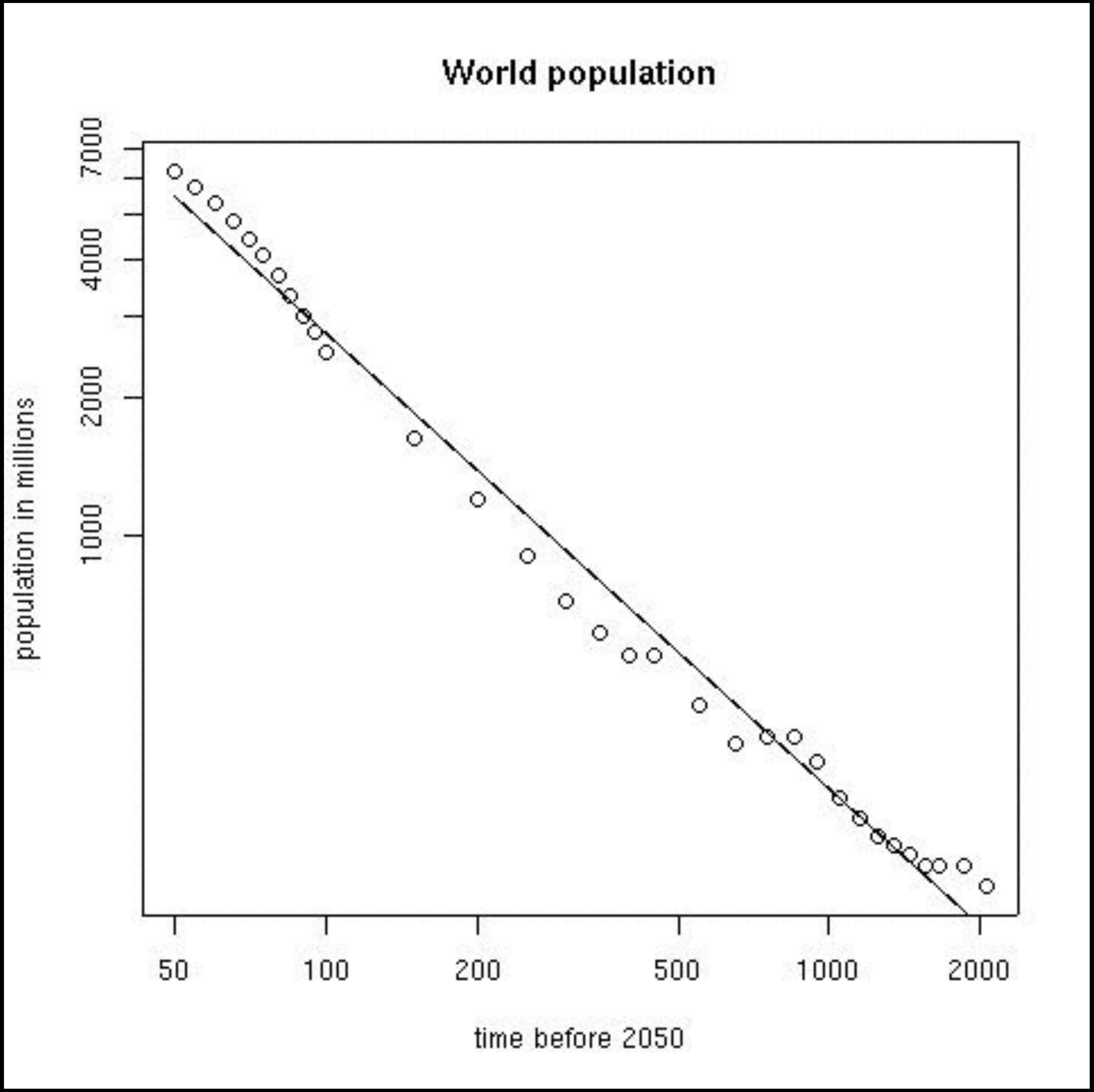
An Essay on the Principle of Population, as it Affects the Future Improvement of Society with Remarks on the Speculations of Mr. Godwin, M. Condorcet, and Other Writers.

- Argued against the perfectability of man
- "I think I may fairly make two postulates:
  - food is necessary to the existence of man.
  - the passion between the sexes is necessary and will remain nearly in its present state.
- Population, when unchecked, increases in a geometrical ratio.
- Subsistence increases only in an arithmetical ratio."
  - implies an overpopulated world of misery and vice.

Sketch for an historical picture of the progress of the human mind (1795)

- Predicted:
  - the end of colonialism, spread of democracy, universal education, equality of sexes, welfare and social security, merit-based venture capital, increase in human lifespan, …
  - acceleration of knowledge and well-being through feedback between education, science, and technology, ...
- A day when the earth would eventually become overpopulated

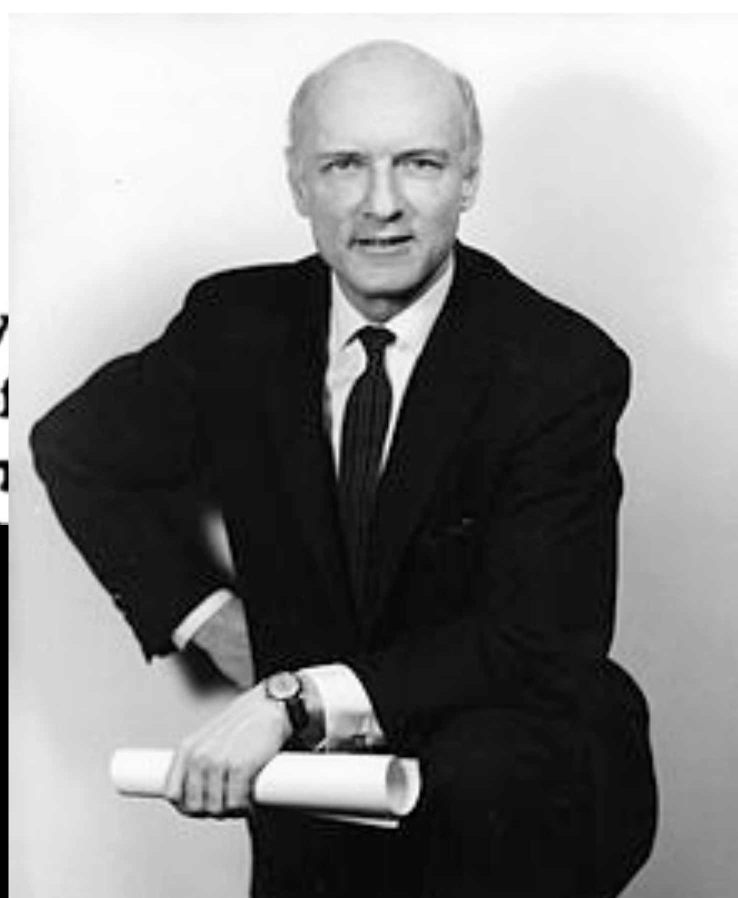
Log-log view of world population



Doomsday: Friday, 13 November, A.D. 2026

At this date human population will approach infinity if it grows as it has grown in the last two millenia.

Heinz von Foerster, Patricia M. Mora, Lawrence W. Amiot



...rent aspects w... in the study o...) is the one in... to estimate

tion and has to be excluded from the population count ("death").

Under conditions which come close to being paradise—that is, no environ-

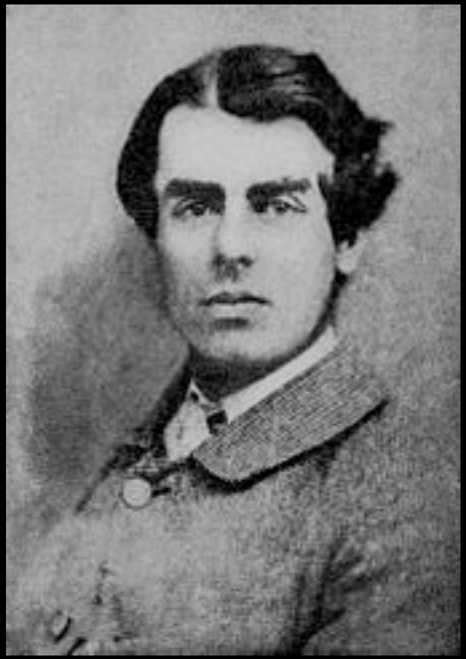
Science, Nov 4., 1960

How does super-exponential growth happen?

- With fixed technology, population growth would follow an “S” curve.
- But technology improves, so carrying capacity of earth increases.
- Population growth depends on technology and technological improvement depends on population (more inventors = more progress)
- This drives super-exponential growth for both population and economy (Condorcet, Romer)

Technology is an evolutionary process

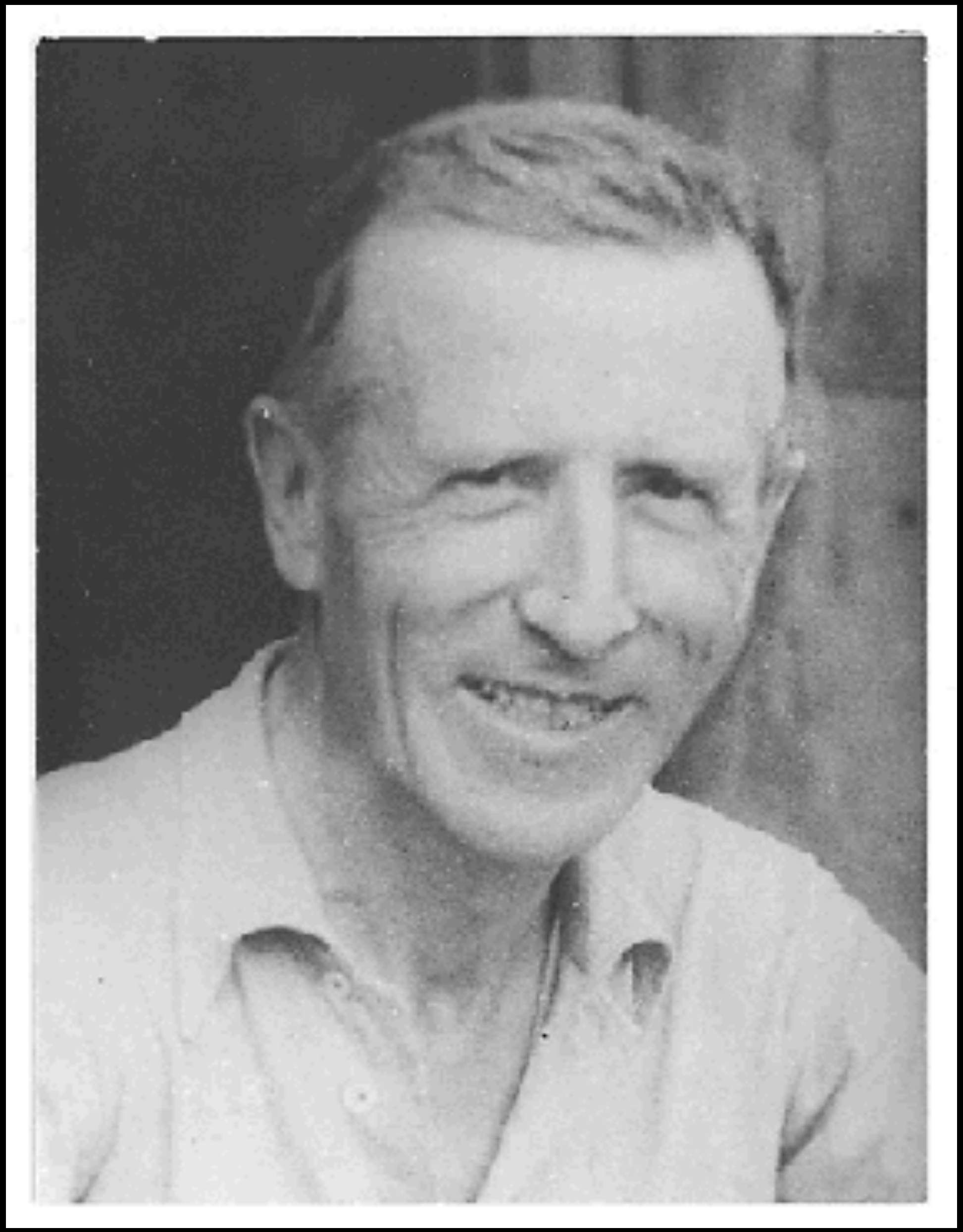
Darwin among the machines
(Samuel Butler, 1863)



- Evolution in the Darwinian sense:
  - descent with modification and selection
  - Erewhon (1872)

Butler imagined technology competing with humanity:
"In the course of the ages we shall find ourselves the inferior race"

The noosphere



Pierre Teilhard de Chardin

- de Chardin envisioned biology, technology and culture co-evolving to form a greater whole, the "noosphere".

State of understanding of technology evolution is still anecdotal

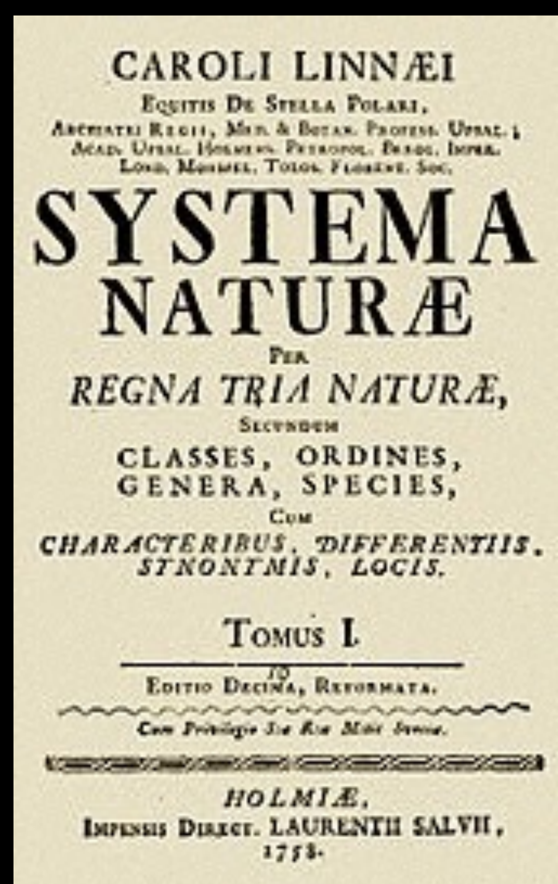
- Lewis Mumford
- George Basala
- Joel Mokyr
- Brian Arthur
- …

Subject is dominated by economic historians.

See also growth economists, e.g. Paul Romer

Understanding is pre-Linnaen

- Linnaeus created the classification system that was the foundation on which Darwin built his theory


CAROLI LINNÆI

EQUITIS DE STELLA POLARI,

SYSTEMA

NATURÆ

PER

REGNA TRIA NATURÆ,

SECUNDUM

CLASSES, ORDINES,
GENERA, SPECIES,

CUM

CHARACTERIBUS, DIFFERENTIIS,
SYNONYMIS, LOCIS.

TOMUS I.

EDITIO DECIMA, REFORMATA.

HOLMIÆ,

IMPENSIS DIRECT. LAURENTII SALVII,

1758.

Carl Linnaeus, 1707 - 1778

Existing classification schemes are due to patent offices and govt. agencies

- Thomas Jefferson, first patent examiner (1790)
  - Congress shall have the power...to promote the progress of science and useful arts by securing for limited times to authors and inventors the exclusive right to their respective writings and discoveries."
- Good start, but highly ad hoc
  - classifications are far from uniform
- SIC, NAICS classify industries (closely related)
- What does one classify?
  - Biological taxonomies are based on heredity
  - For technology, functionality is important

What is technology?

- The collection of techniques, methods or processes used in the production of goods or services or in the accomplishment of objectives … technology can be the knowledge of techniques, processes, etc. or it can be embedded in machines, computers, devices and factories
- Closely related to concept of "machine".

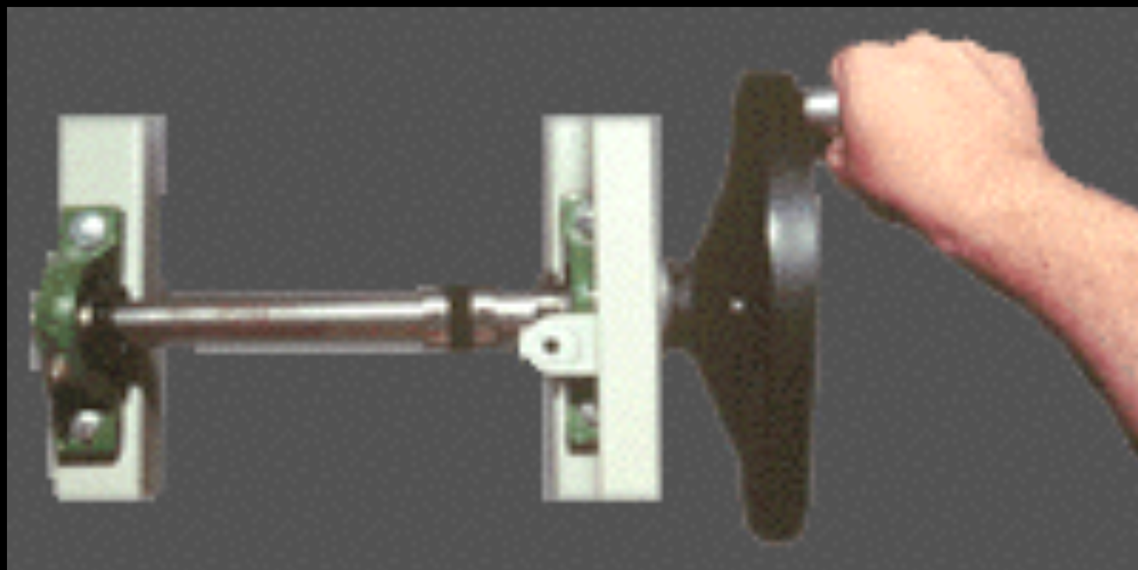
What is a machine?

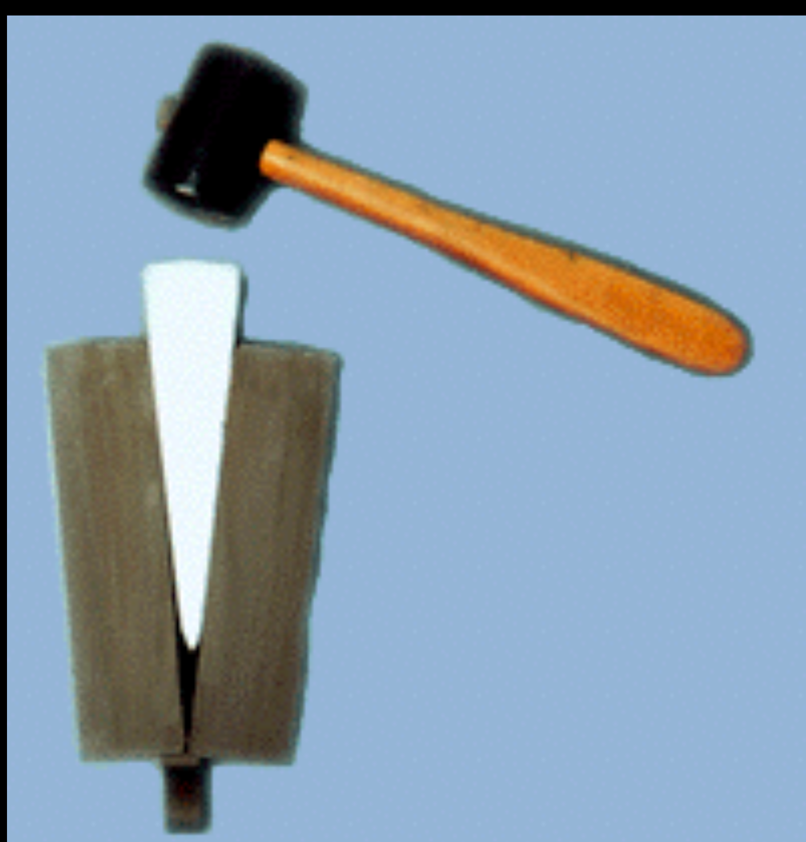
- Modern science is based on the mechanistic view, but there is no good definition of a machine.
- Perhaps by thinking carefully about what a machine is, in more general terms, we can at least make clear what it means to make “progress” in an engineering problem, or in evolution.
- Current complex systems theorizing tends to focus exclusively on information, and neglect the mechanical implementation that is necessary for any kind of self-organized emergent behavior.

Classification of machines?

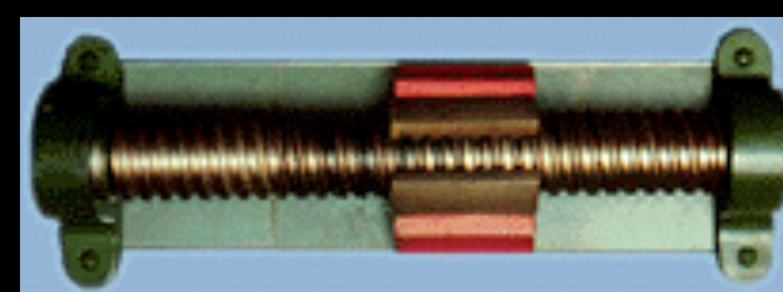
- Early treatises on machines
  - Philo of Byzantium, 200 BC.
  - Hero of Alexandria, 62 AD., “Mechanics”, “Book on the raising of heavy weights”
- Five simple machines known to Archimedes
  - Lever, wedge, screw, wheel and axle, pulley

The five simple machines





wedge



screw

lever

What is a "machine"?

- A machine is an assembly of matter capable of selectively altering other assemblies of matter.
- The key property of a machine is its ability to implement a *functional constraint* in the movement of matter (or energy).
- Not a definition of a machine, but rather of the "machine-ness" of matter.
- Machines can increase or decrease local entropy, creating order or disorder (though they always increase global entropy).

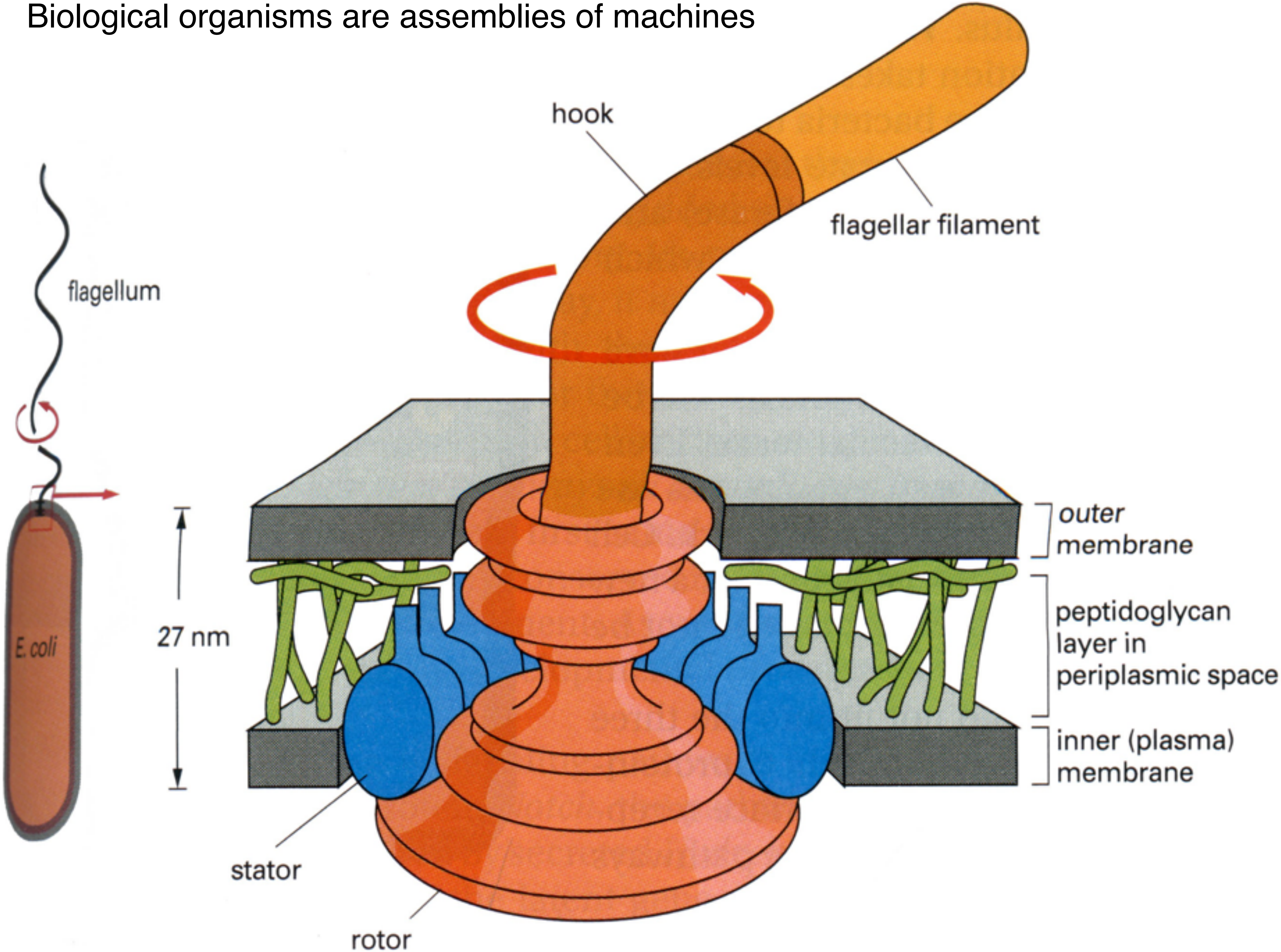
Constraint function

- Specifies what machine does in geometric/ topological and probabilistic terms.
- E.g. for sieve: “Particles of size $x > x_c$ will remain on the same side of the sieve.
- Probability of passage in any given shake of sieve depends on fraction of small vs. large particles.

Taxonomy of machines

- Can potentially classify machines based on their constraint functions.
- General classification of functions is an unsolved mathematical problem.
- Nonetheless, we can identify some important families of machines.

Biological organisms are assemblies of machines



Biological vs. technological evolution

(see Sole et al., Complexity, 2012)

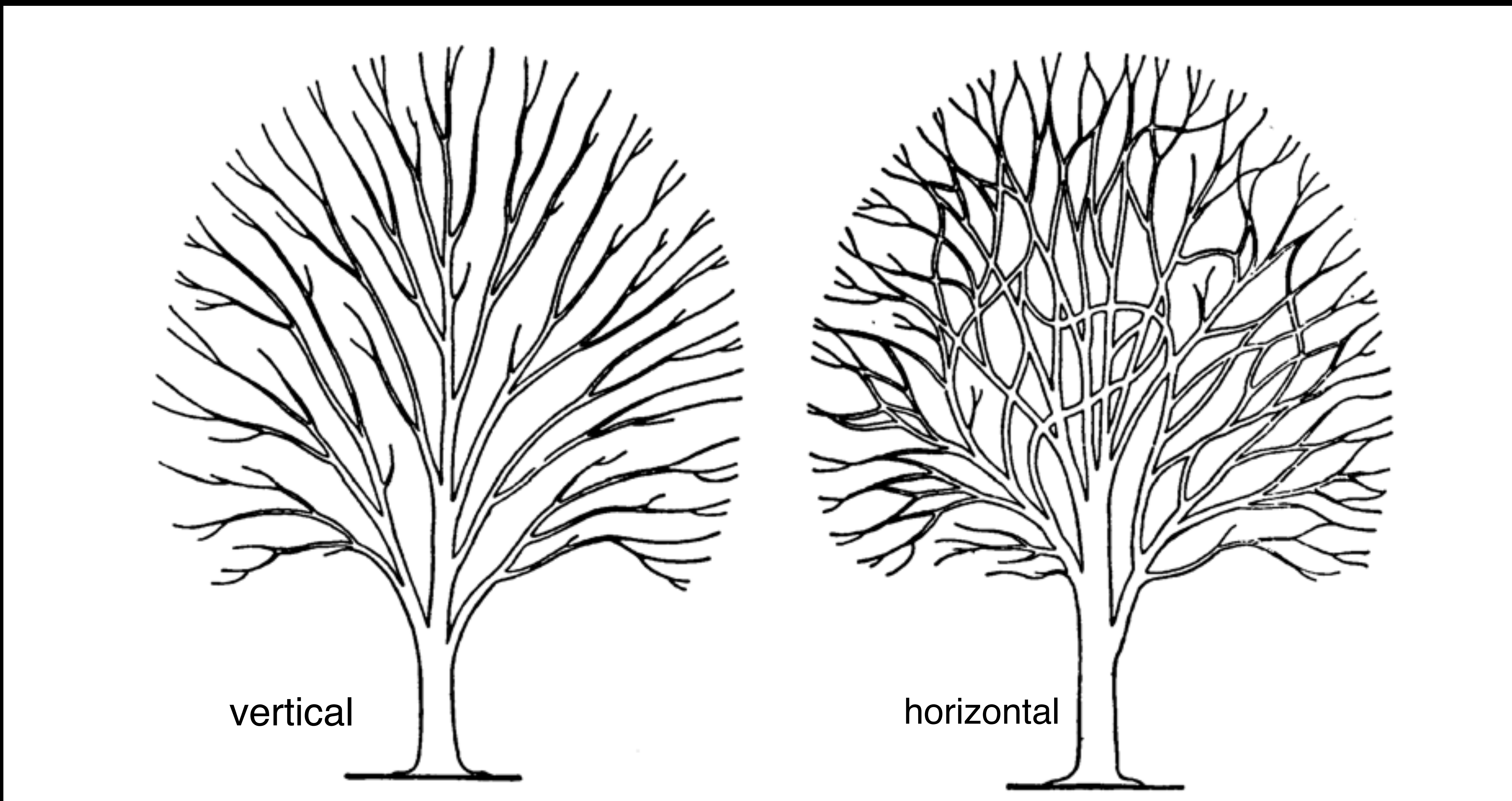
- Similarities
  - Both driven by selection
  - Both result in diversity
  - Incremental variation
  - Temporal progression
  - Purposeful function of units

(See also Wagner and Rosen, 2014)

- Differences
  - Self-reproduction vs. artificial manufacture
  - Random variation vs. conscious design
  - Microscopic vs. macroscopic scale of organization
  - Innovation in technology analogous to horizontal gene transfer (like bacteria)
  - Developmental process of technology is highly distributed

Dividing line will become increasingly blurred

Technological evolution is analogous to horizontal gene transfer



from: "The Evolution of Technology," by George Basalla (1988).

Data available to understand technology is very different than that for biology

- Biology
  - detailed knowledge of pylogeny
  - no knowledge of "performance"
- Technology
  - no good taxonomy, anecdotal polygamy
  - some knowledge of performance

Identify technological eras with US patents

joint work with Ioannis Psorakis, Jose Lobo, Debbie Strumsky, Hyejin Youn

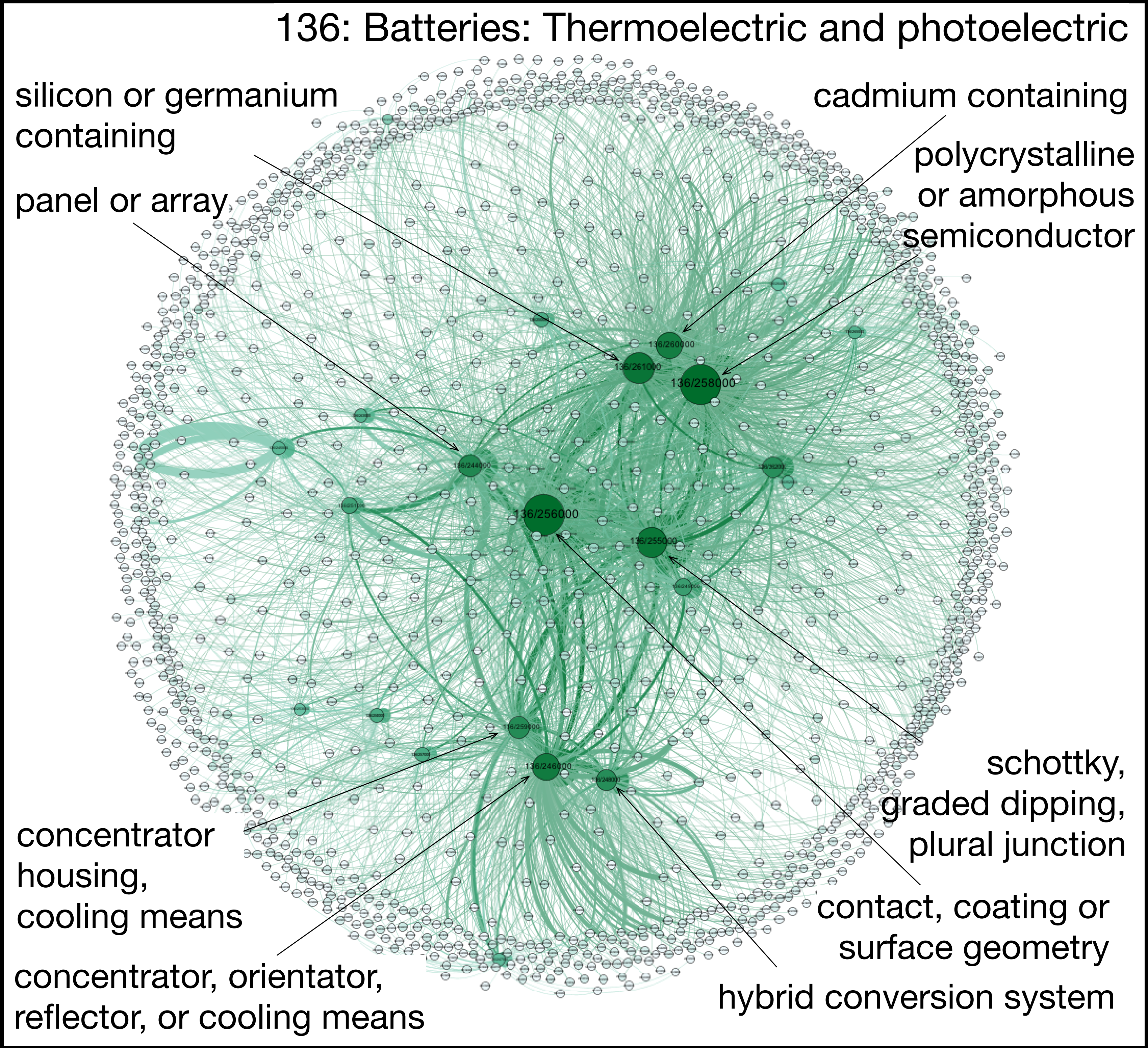
- 9M patents
- 1790 to present:
  - 10,000 tech. codes -> 150,000 tech. codes
- Closest thing to a fossil record of tech. change

Co-occurrence network

(Youn, Lobo, Bettancourt, Strumsky, 2014)

- Can define co-occurrence network as the frequency with which two technology codes appear together.
- Defines network with technology codes as nodes and co-occurrence frequency as weighted links.
- Provides a way to understand how technologies interact with each other and how this evolves through time.

Solar PV ecology



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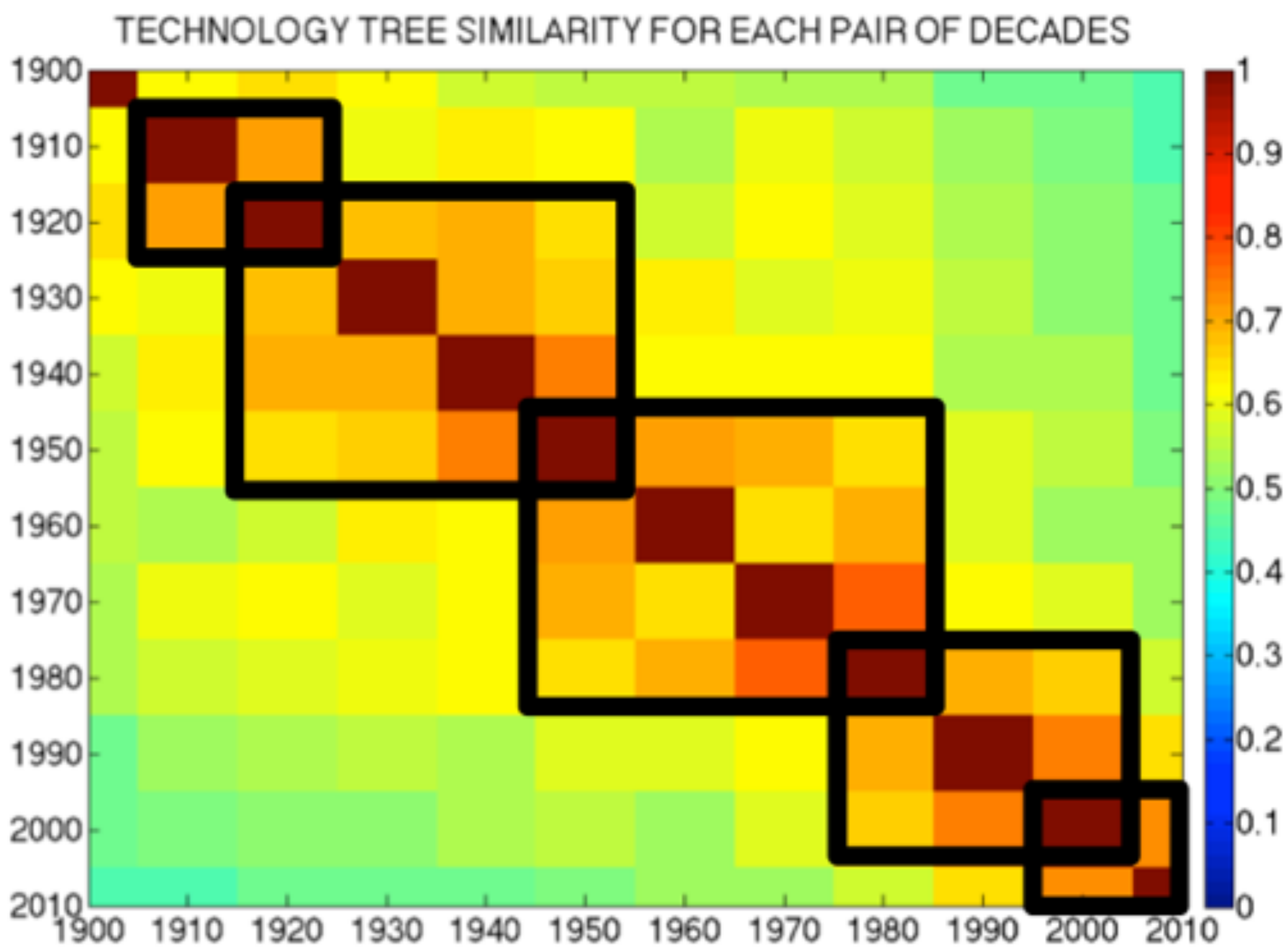
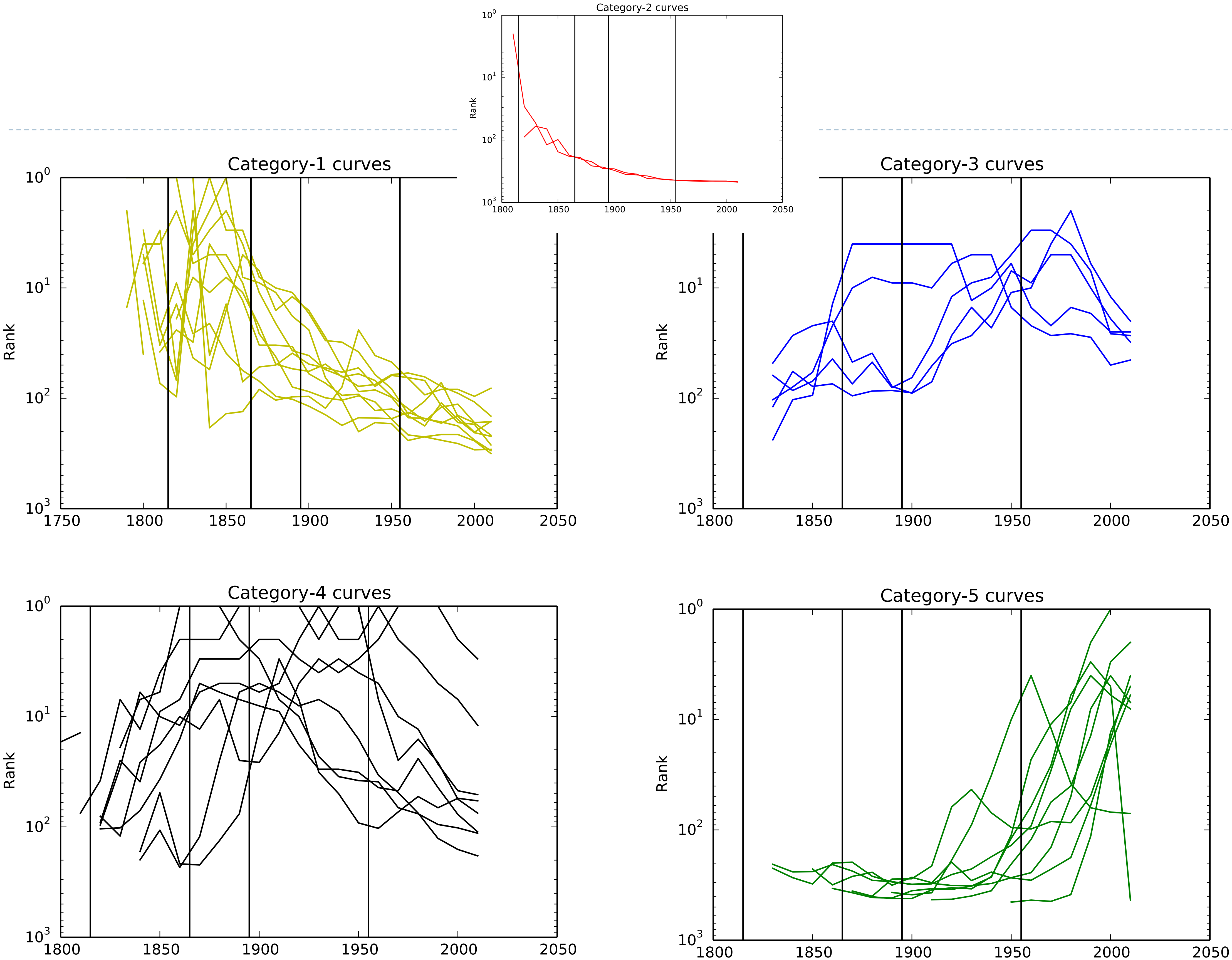
Evidence for technological epochs



- Inventing activity changes, based on technological, economic, social, even geopolitical trends.
- We investigate the self-organization patterns of technologies across time, given our combination-based communities at each decade.
- Our analysis reveals clusters of self-similarity across time, corresponding to various historical eras (WWI, WWII, Cold War, modern era).
- Cluster boundaries correspond to *technological shifts,* that allow us to “sandbox” different models at different time periods.

Eigenvalue centrality (Page rank)

- Make co-occurrence matrix directed by dividing by activity of each code pair
  - assume "influence" flows from more active to less active code.
- Apply page rank algorithm



Category-2 curves
Rank
Category-1 curves
Rank
Category-3 curves
Rank
Category-4 curves
Rank
Category-5 curves
Rank

Category	Class	Description
1	099	Foods and beverages and apparatus
1	030	Cutlery
1	062	Refrigeration
1	126	Stoves and furnaces
1	241	Solid material comminution or disintegration
1	083	Cutting
1	209	Classifying, separating, and assorting solids
1	101	Printing
1	100	Presses
1	144	Woodworking
2	142	Wood turning
2	295	Railway wheels and axles
3	156	Adhesive bonding and miscellaneous chemical manufacture
3	264	Plastic and nonmetallic article shaping or treating and processes
3	427	Coating processes
3	220	Receptacles
3	248	Supports
4	428	Stock material or miscellaneous articles
4	029	Metal working
4	123	Internal-combustion engines
4	074	Machine element or mechanism
4	137	Fluid handling
4	200	Electricity and circuit makers and breakers
4	403	Joints and connections
4	024	Buckles, buttons, clasps, etc.
5	257	Active solid-state devices (e.g., transistors, solid-state diodes)
5	G9B	Information storage based on relative movement between record carrier and transducer
5	327	Miscellaneous active electrical nonlinear devices, circuits, and systems
5	438	Semiconductor device manufacturing and process
5	709	Electrical computers and digital processing systems and multicomputer data transferring
5	370	Multiplex communications
5	455	Telecommunications
5	435	Chemistry and molecular biology and microbiology
5	514	Drug, bio-affecting and body treating compositions

Technology is the engine of economic growth

- Solow (1956): Investment can't explain it — technological progress is dominant cause
  - technology is just a scalar "A(t)".
- Rosenberg: Must get inside the black box.
- Arthur: Emphasizes role of combination

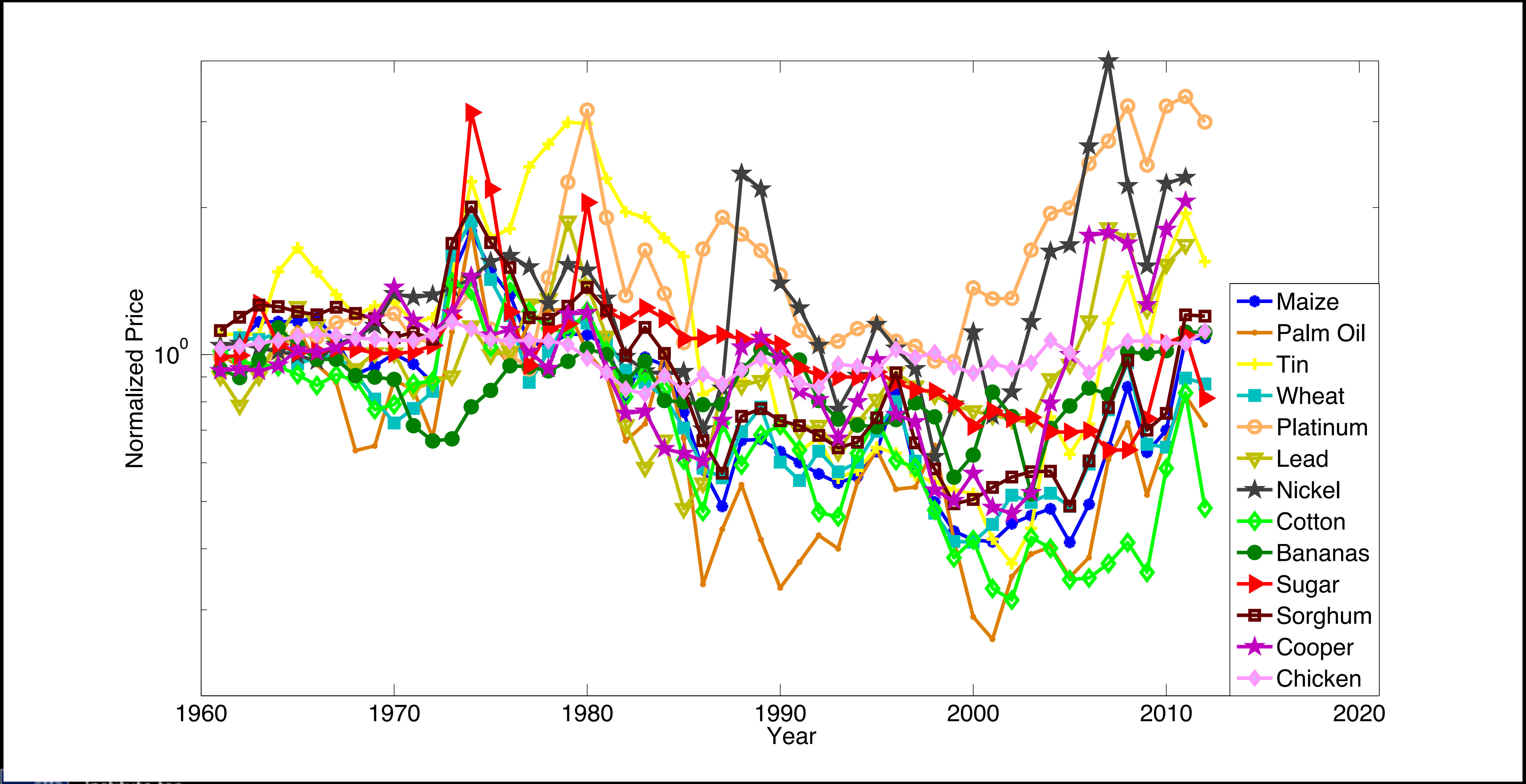
Need a predictive theory - what drives technological improvement?

Technologies improve
at very different rates

with
Miquel
Masoliver

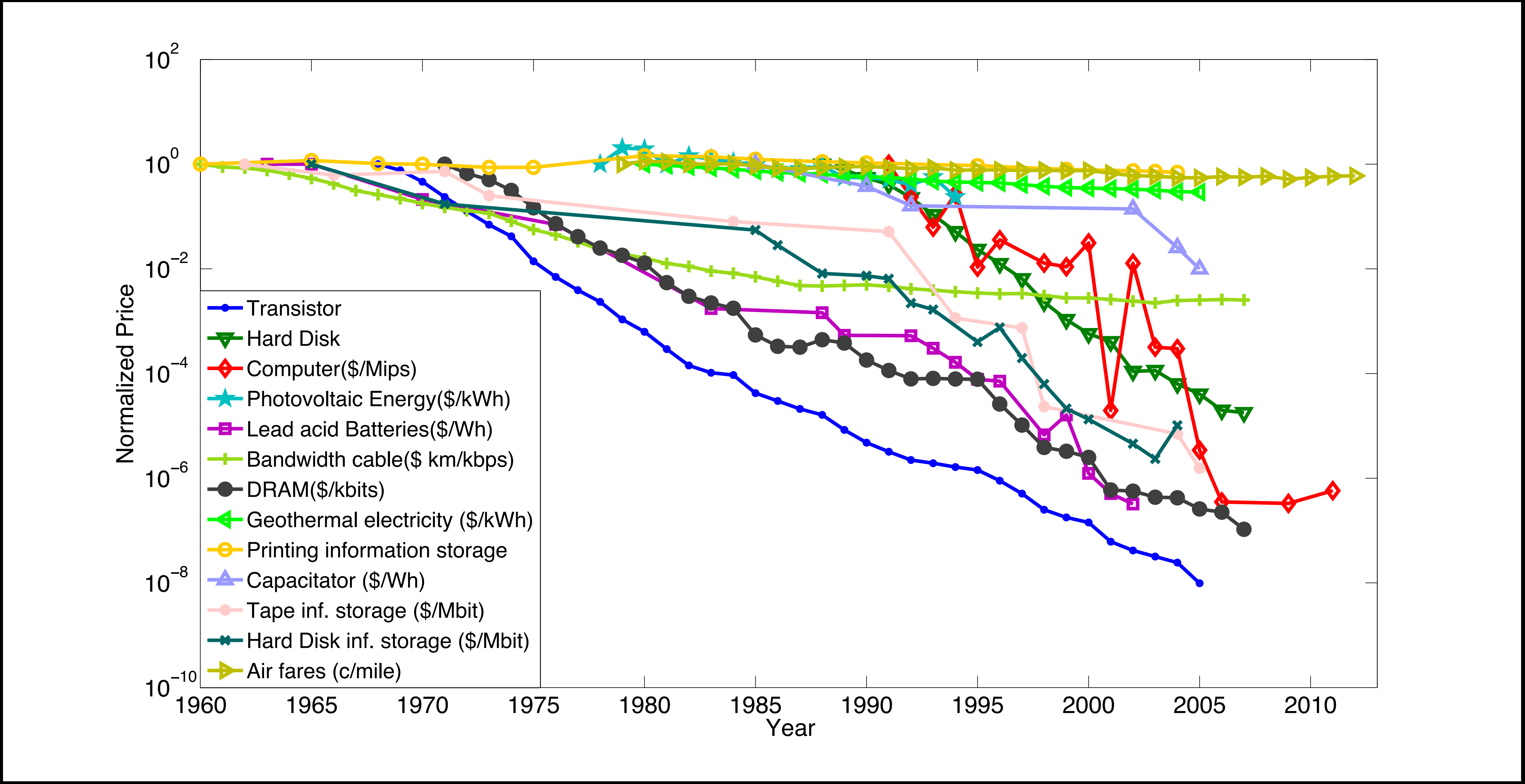
Commodities

(prices adjusted for inflation)

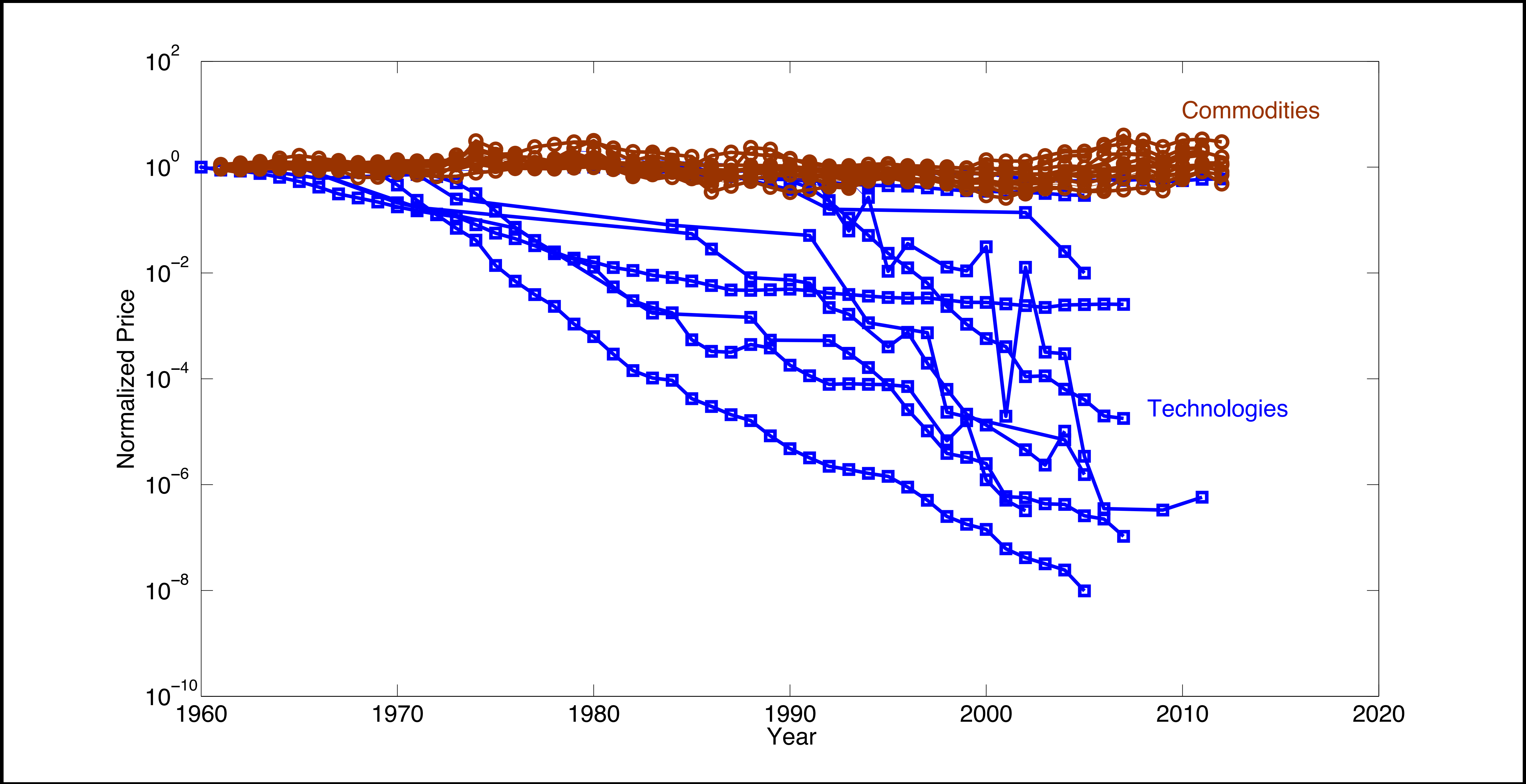


with
Miquel
Masoliver

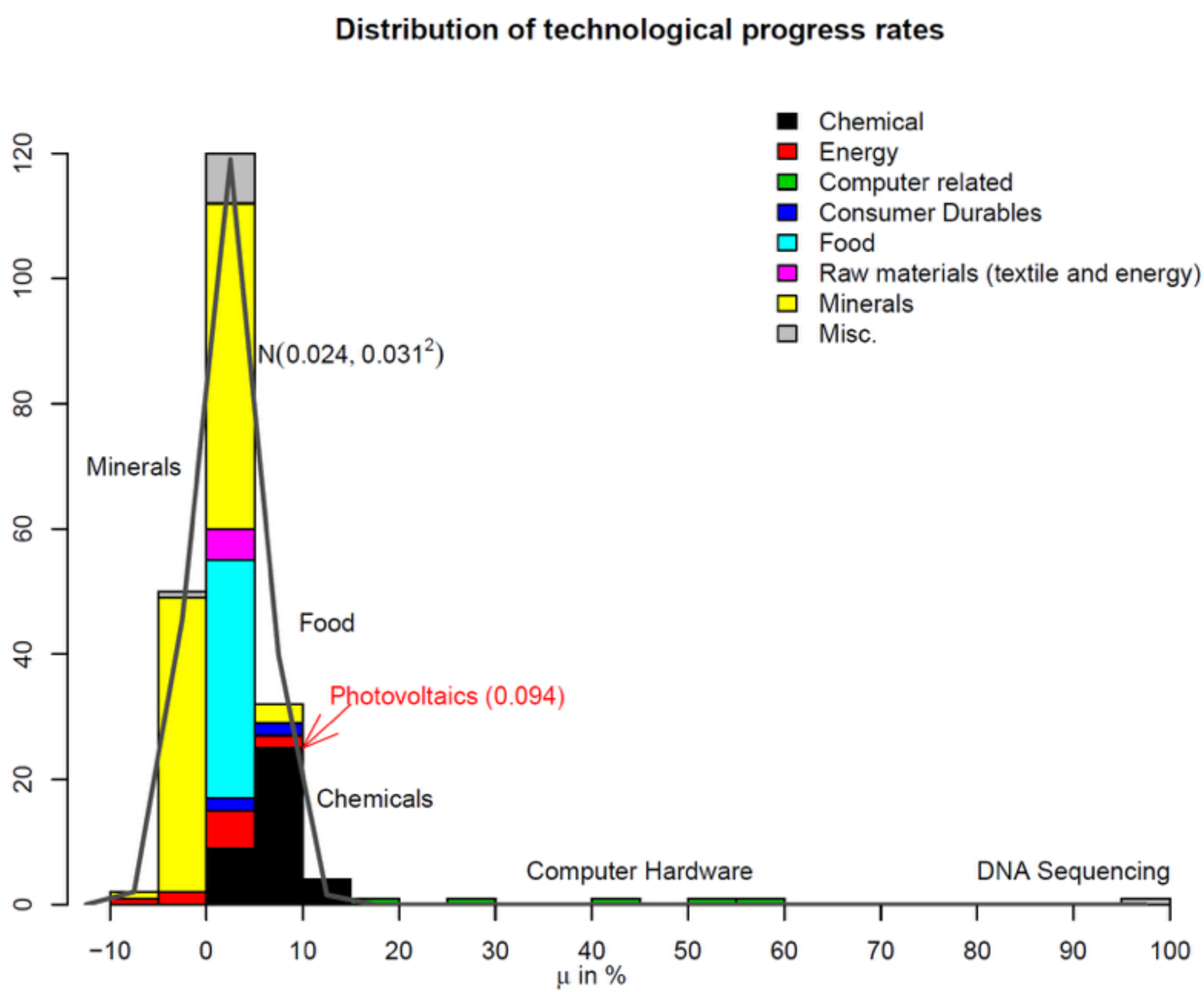
Selected technologies



Comparison



Commodities
Technologies
Normalized Price
Year
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
1960
1970
1980
1990
2000
2010
2020


Distribution of technological progress rates
Chemical
Energy
Computer related
Consumer Durables
Food
Raw materials (textile and energy)
Minerals
Misc.
N(0.024, 0.031²)
Minerals
Food
Photovoltaics (0.094)
Chemicals
Computer Hardware
DNA Sequencing
0
20
40
60
80
100
120
−10
0
10
20
30
40
50
60
70
80
90
100
μ in %

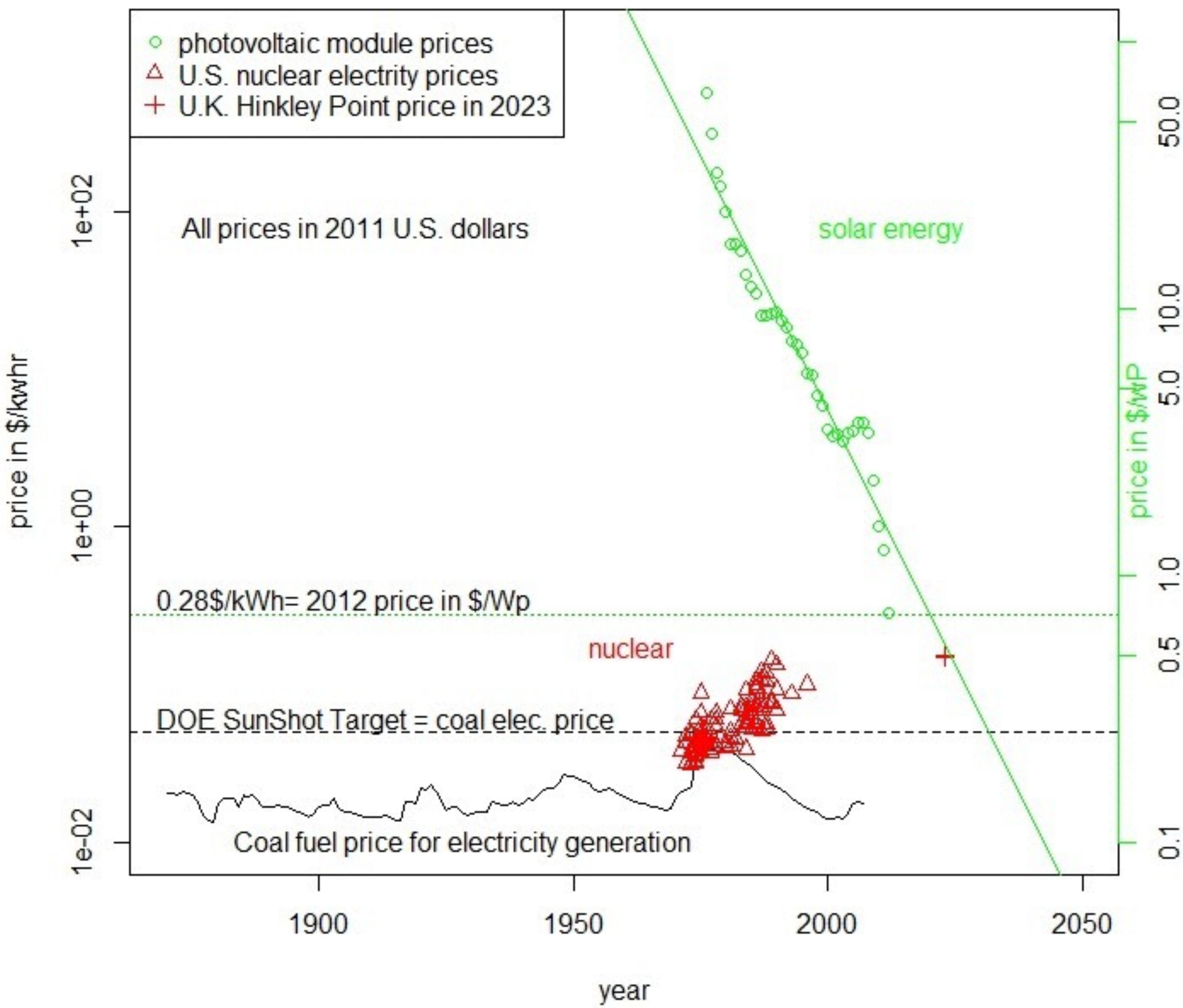
Physics matters to economics

- Evolutionary search finds physical processes capable of rapid improvement
- Interaction between physics, which determines what is possible, and economics, which determines what is wanted
- Physics is key determinant of technological improvement (Funk and Magee)
- Migration toward "good physics" can result in dramatic improvements

Consequences for public investment

It is essential that we take the dramatic differences in rates of technological evolution into account when we consider public investment in technology R&D.

Price trends of coal, photovoltaic and nuclear electricity

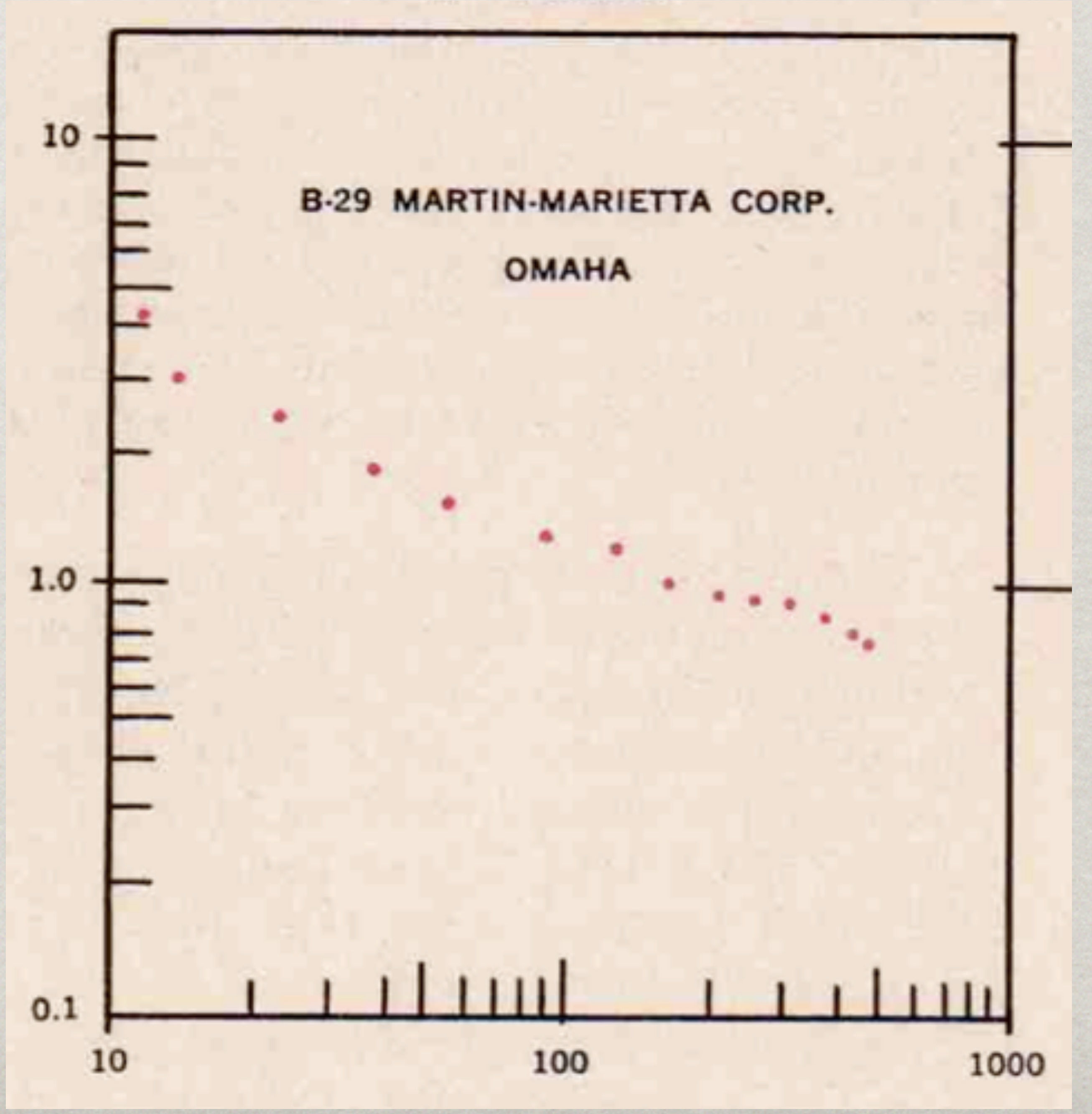


Empirical laws for technological improvement

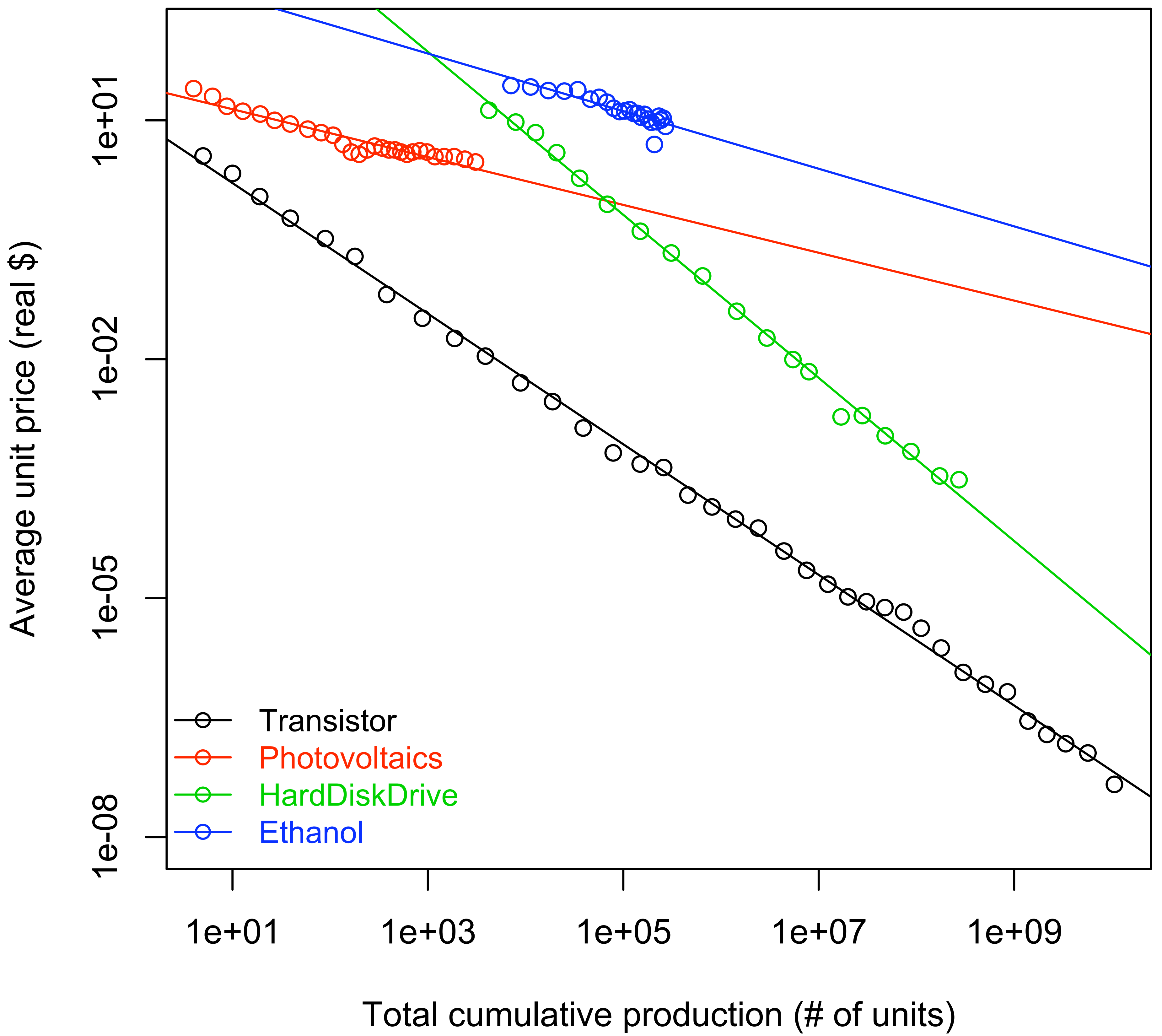
Wright's law
(1936)

Cost vs. cumulative production = power law $y = x^{-\alpha}$

Theodore Paul Wright

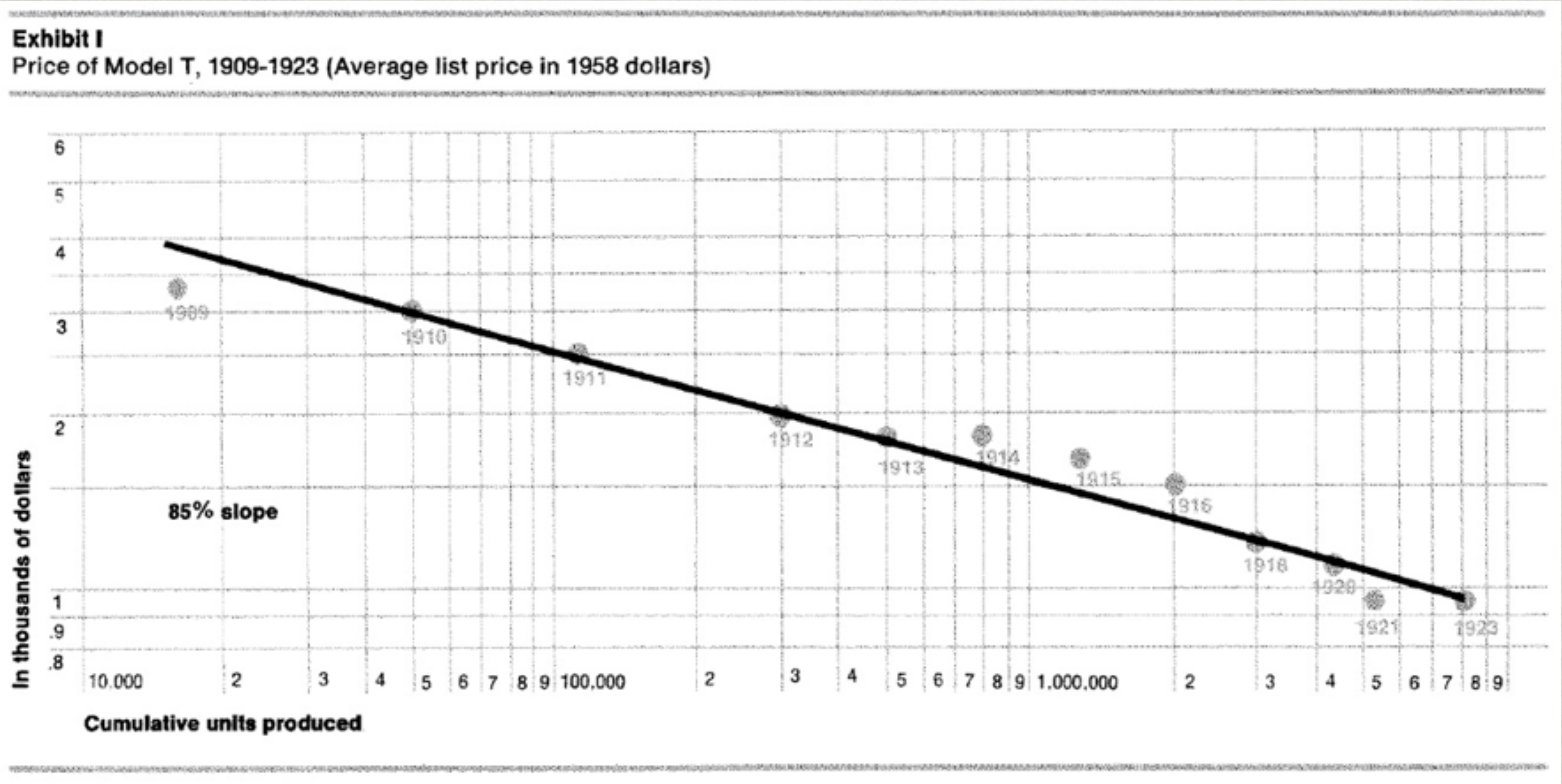


Wright



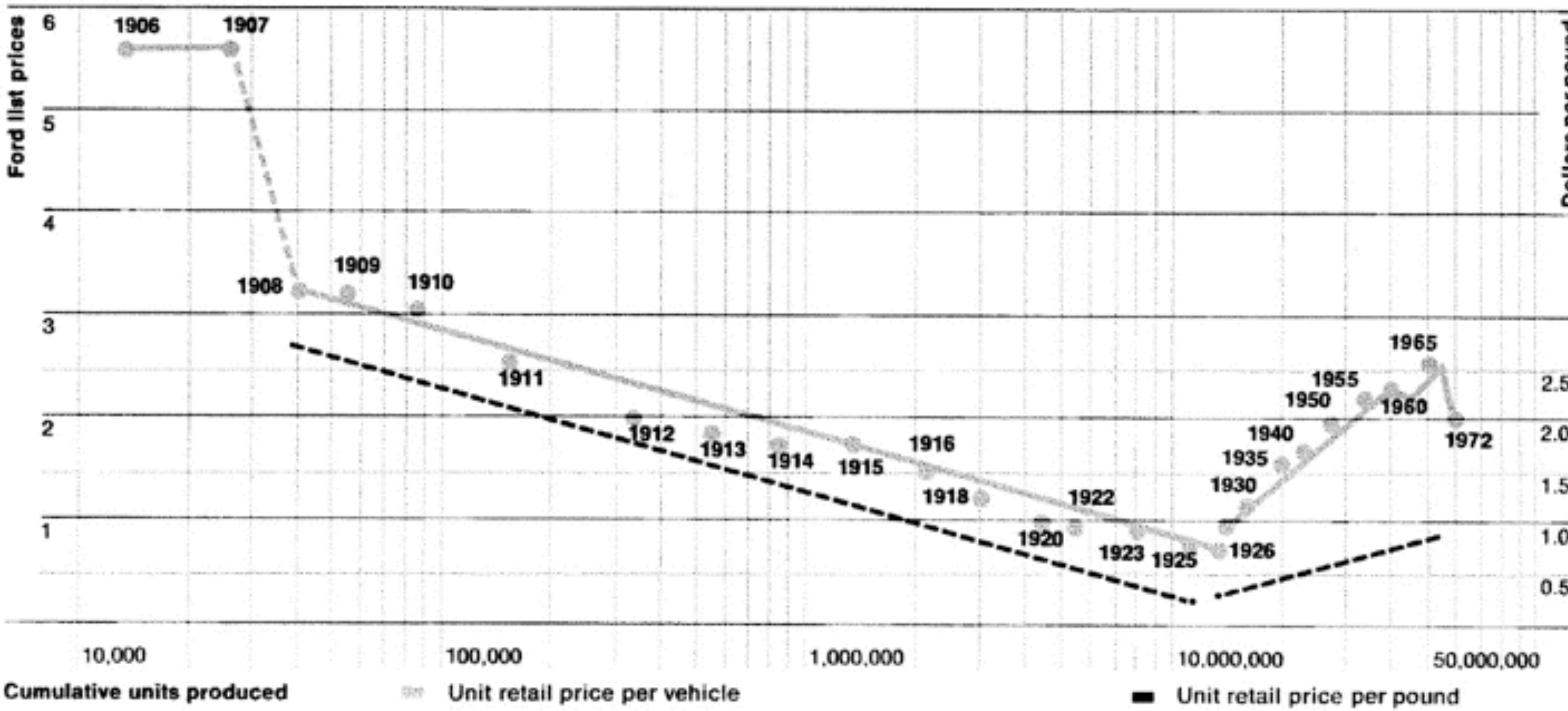
Average unit price (real $)
1e+01
1e-02
1e-05
1e-08
1e+01
1e+03
1e+05
1e+07
1e+09
Total cumulative production (# of units)
Transistor
Photovoltaics
HardDiskDrive
Ethanol

Ford's model T



Wright's law only works when reducing cost is main objective

Models	ABCNRSK	T	A	Annual model changes
Engines (H.P.)	2 (15 & 50)	1 (20)	1 (24)	2 or more (50 & more)
Wheel bases	2	1	1	2 or more
Weights	Up to 1800	1100-1820	2312 (average)	2335 and up (average)

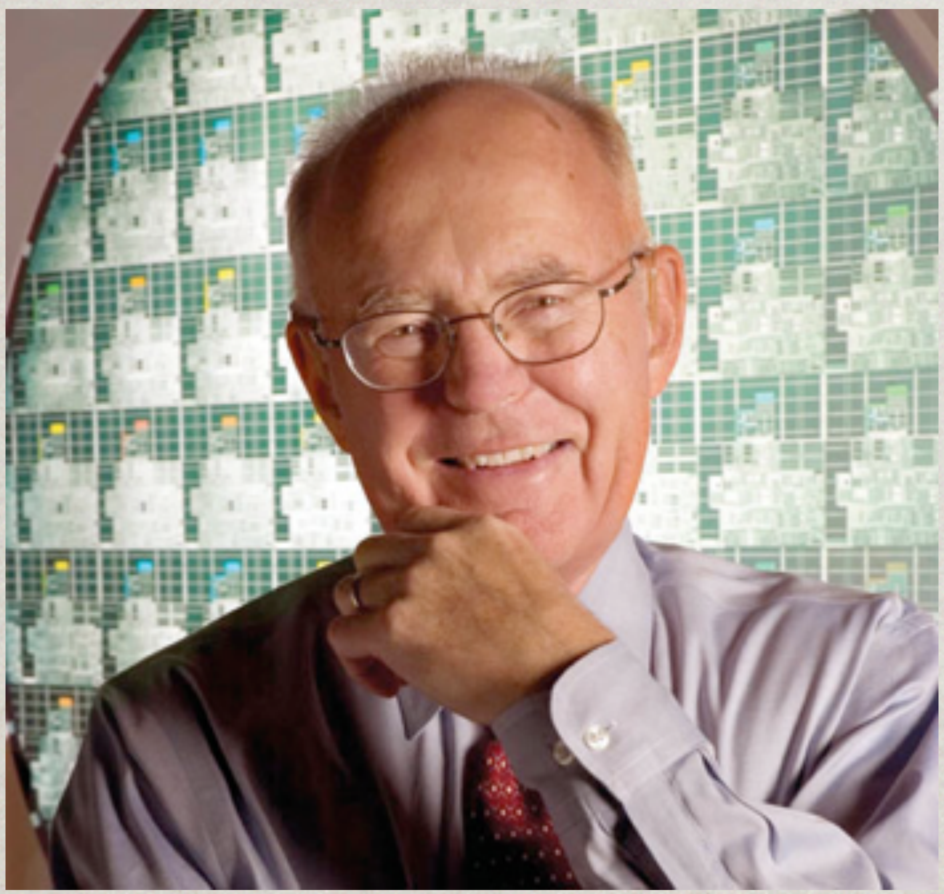


Generality of Wright's law

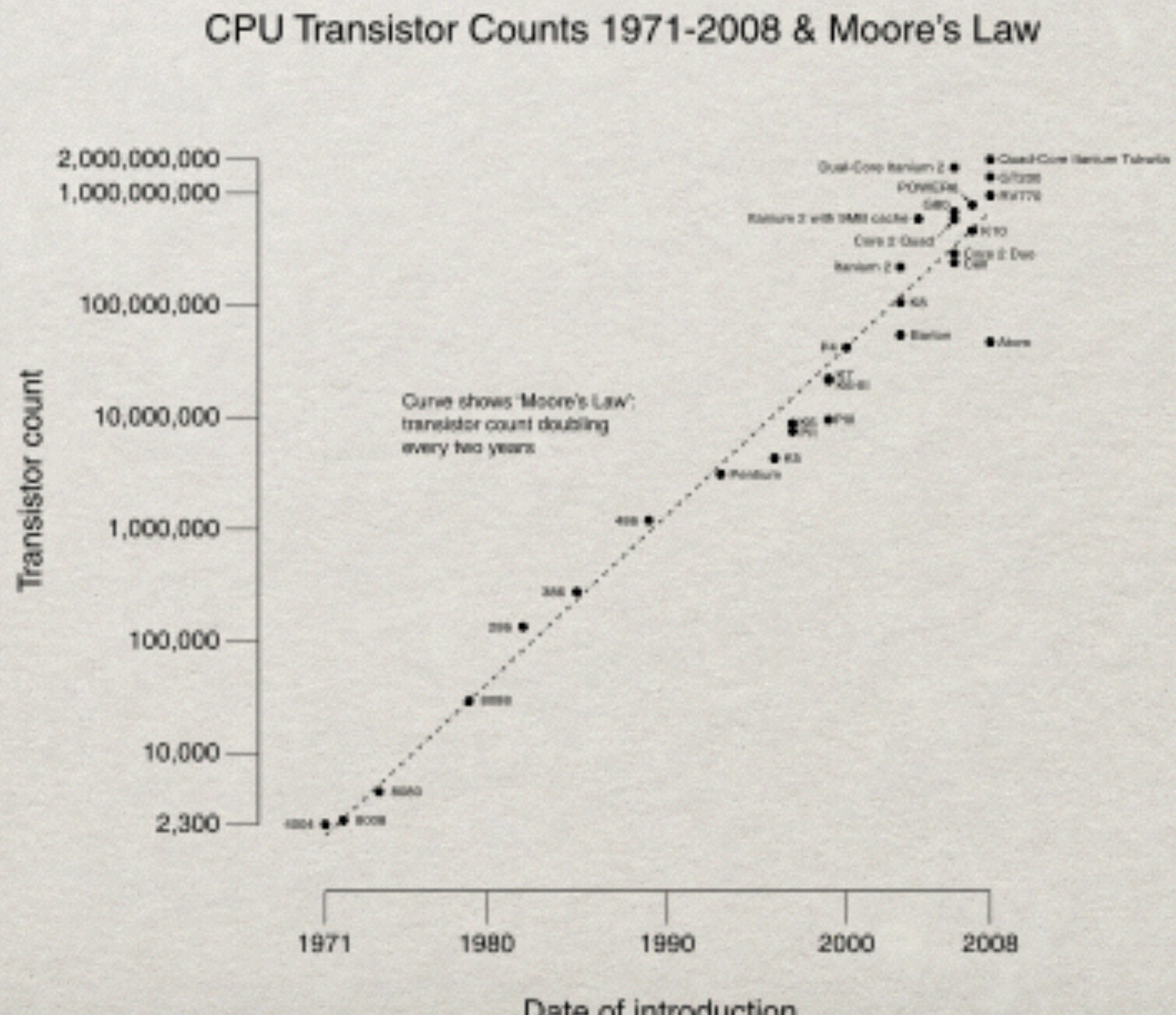
- Holds at the level of products, firms, industries, or best technology performing a given function.
- Explanation must be correspondingly general.

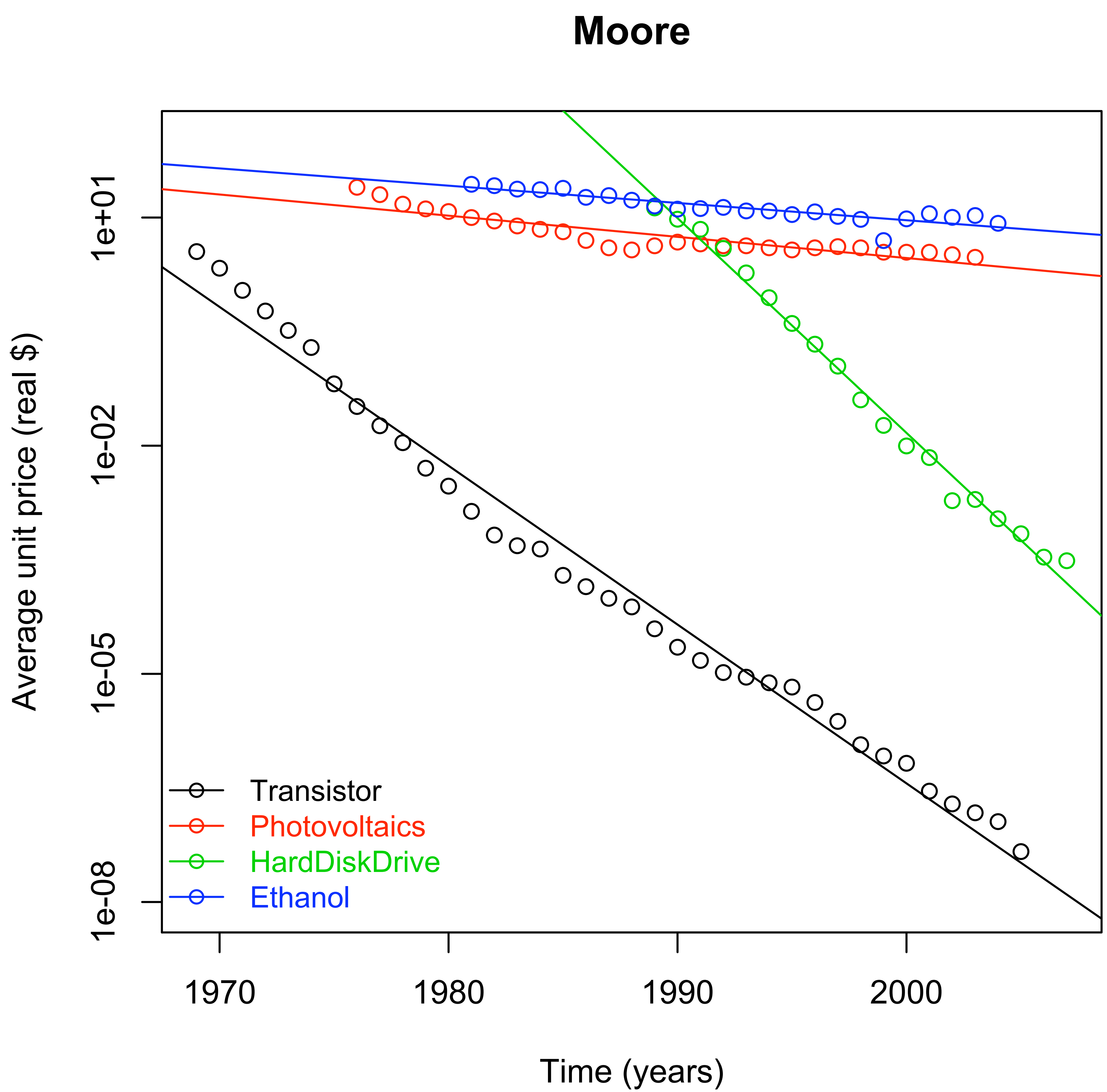
Moore's law
(1965)

Originally a statement about density of transistors
We will use to refer to the hypothesis that technological performance improves exponentially with time

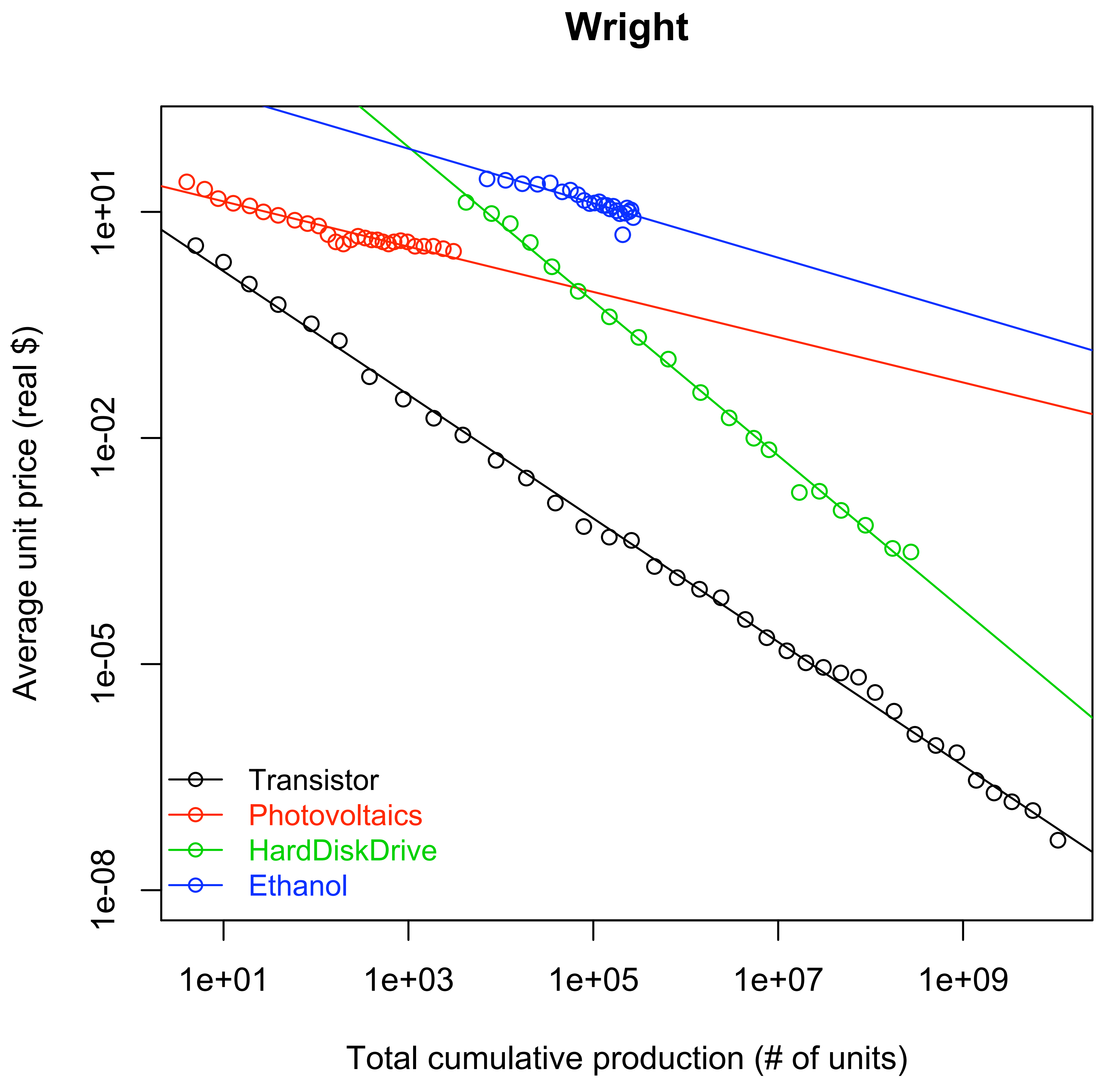


Gordon Moore





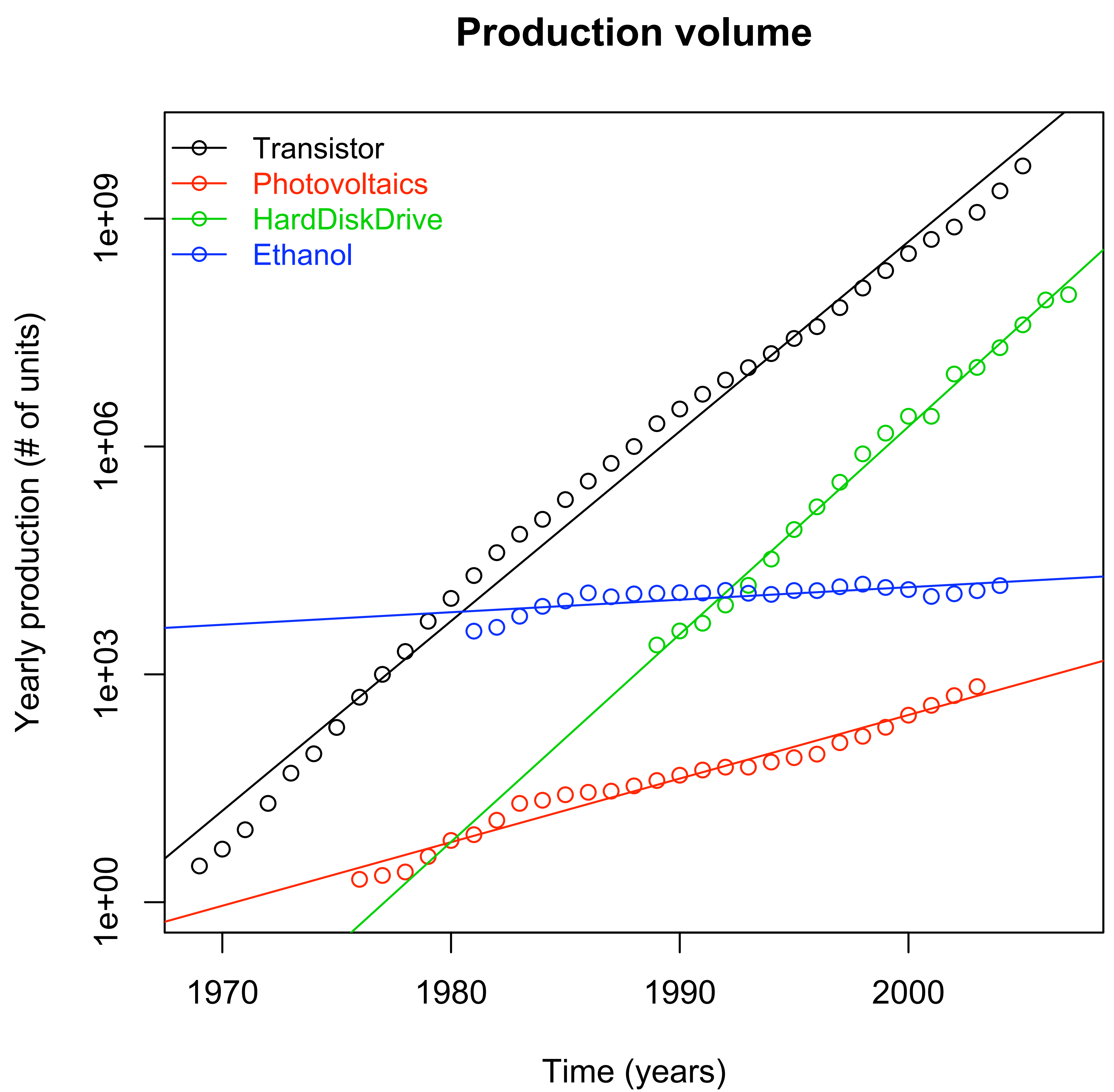
Moore
Average unit price (real $)
1e+01
1e-02
1e-05
1e-08
1970
1980
1990
2000
Time (years)
Transistor
Photovoltaics
HardDiskDrive
Ethanol



Wright
Average unit price (real $)
1e+01
1e-02
1e-05
1e-08
1e+01
1e+03
1e+05
1e+07
1e+09
Total cumulative production (# of units)
Transistor
Photovoltaics
HardDiskDrive
Ethanol

Production vs. time

- For technologies in this sample, also reasonable to postulate that production increases exponentially with time



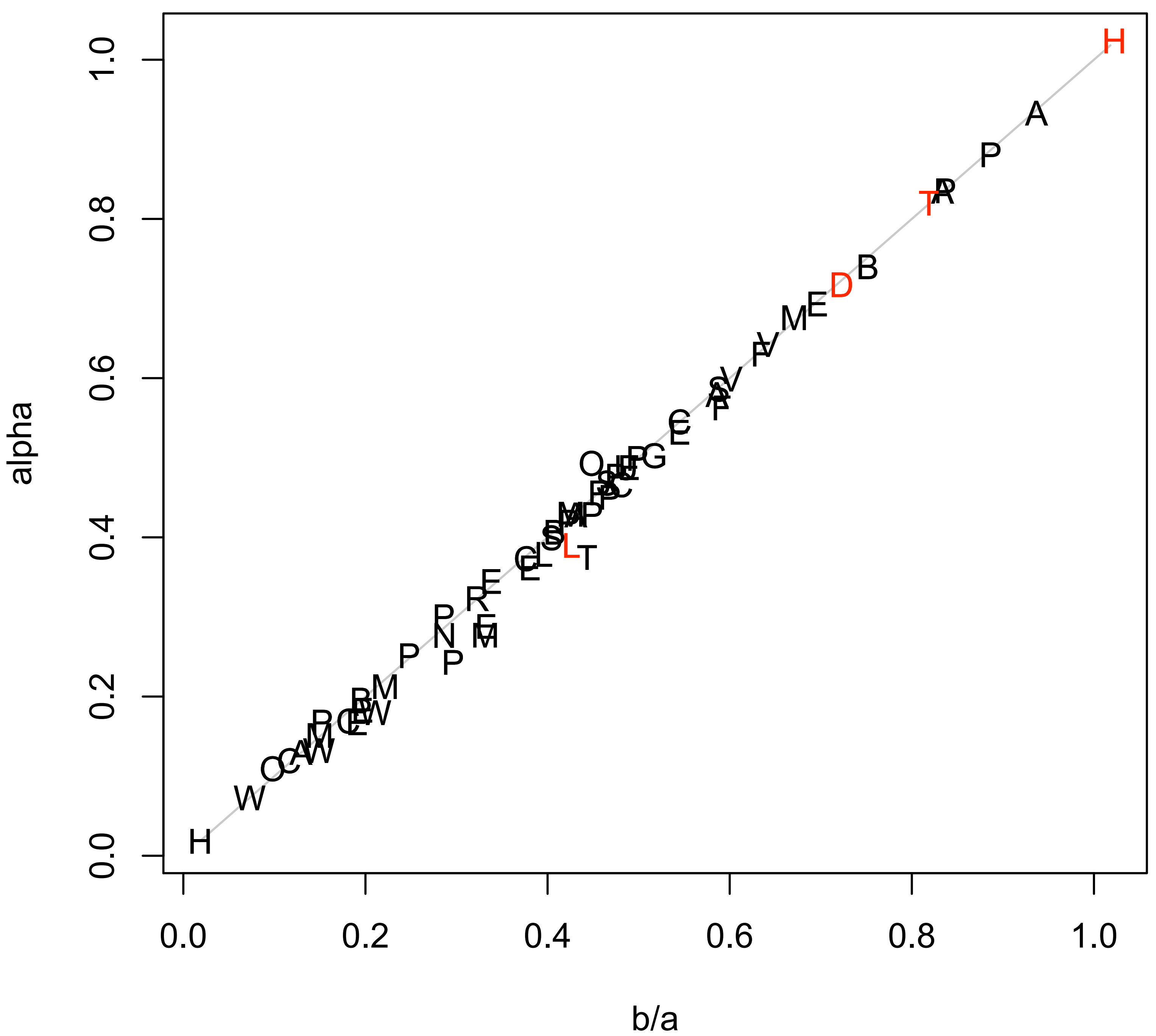
(Nagy, Farmer, Bui, Trancik, PlosOne, 2013)

Compatibility of wright and Moore (Sahal, 1987)

If production expands exponentially and costs drop exponentially, Wright's law will hold.

$$
\begin{aligned}
x(t) &= \exp(at) \\
y(t) &= \exp(-bt) \\
y(x) &= x^{-b/a}
\end{aligned}
$$

Empirical validation of Sahal's identity: alpha = b/a



(Nagy, Farmer, Bui, Trancik, PlosOne, 2013)

Bela Nagy

Laws can be used to make forecasts with reliable error bars

- Nagy, Farmer, Bui, Trancik, PlosOne, 2013
- Farmer and Lafond, Research Policy?, 2015

Key hypothesis

All technologies obey same random process

– parameters vary across technologies

Testing for predictability through hind casting

Nagy, Farmer, Bui, Trancik, PlosOne, 2013
Farmer and Lafond, Research Policy?, 2015

- Pretend to be at a given time in the past
- Forecast each "future" date
- Repeat for all past dates
- Score methods based on forecasting errors
- To pool different technologies, assume improvement process is the same for all technologies, except for parameters.

Can make objective forecasts with reliable error bars

Time series models

Moore's law as a random walk with drift

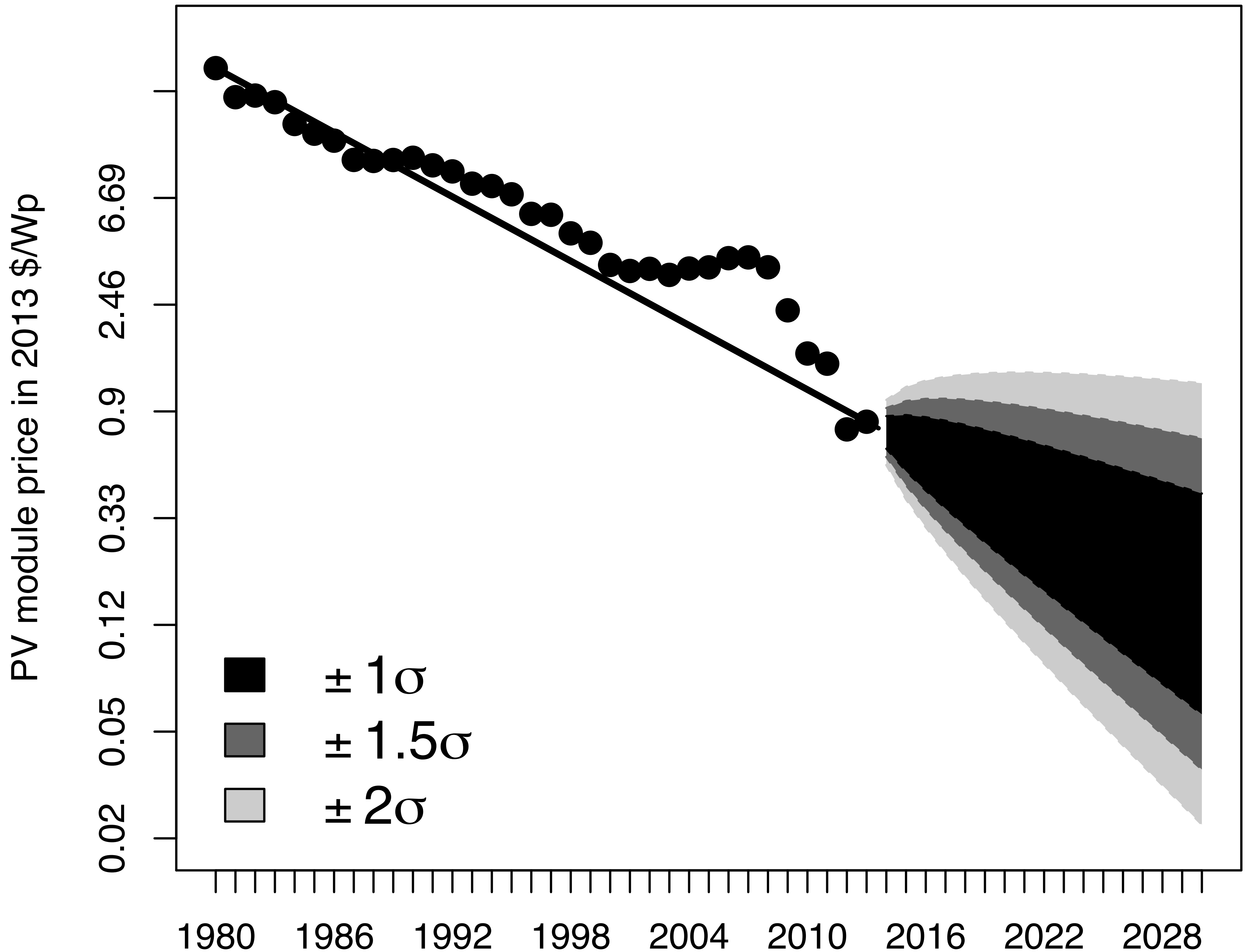
$$y_{t+1} - y_t = \mu + K n_t$$

Change in log(cost) Drift Noise

Wright's law as random walk with drift
dependent on cumulative production

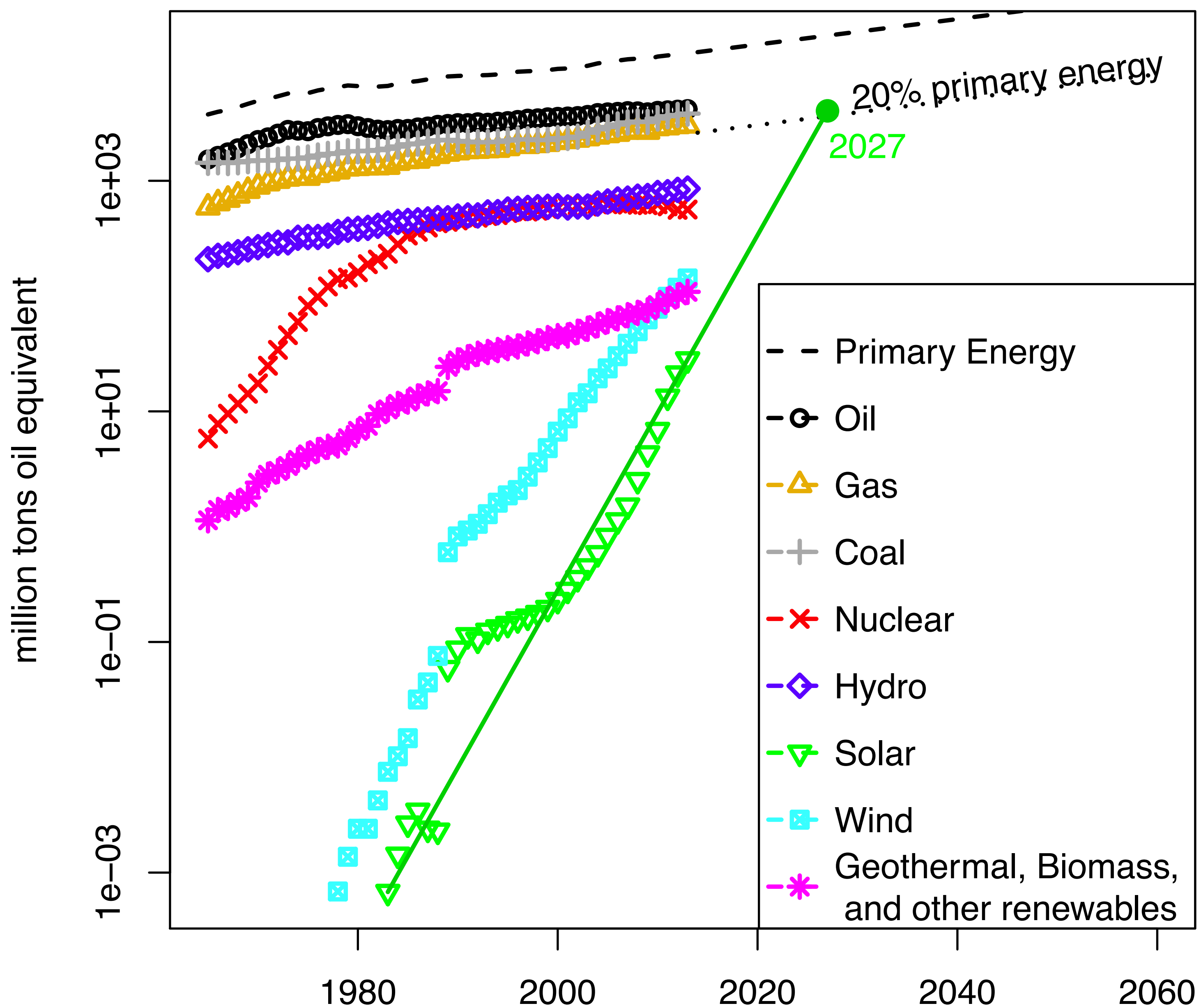
$$y_{t+1} - y_t = \omega \log\left(\frac{x_{t+1}}{x_t}\right) + S n_t$$

Distributional forecast of solar PV assuming business as usual



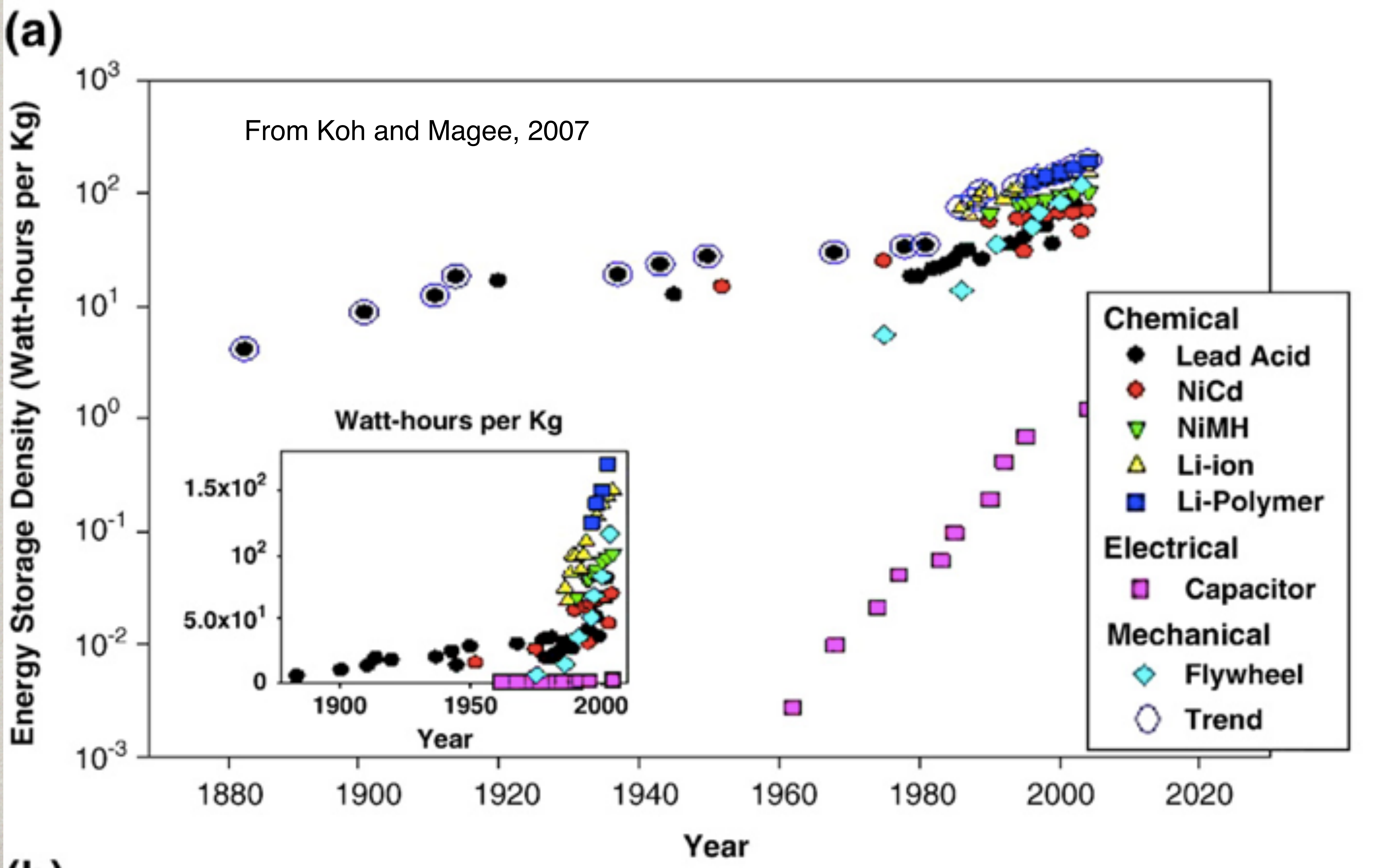
World energy usage by source

- (BP statistical review of world energy)



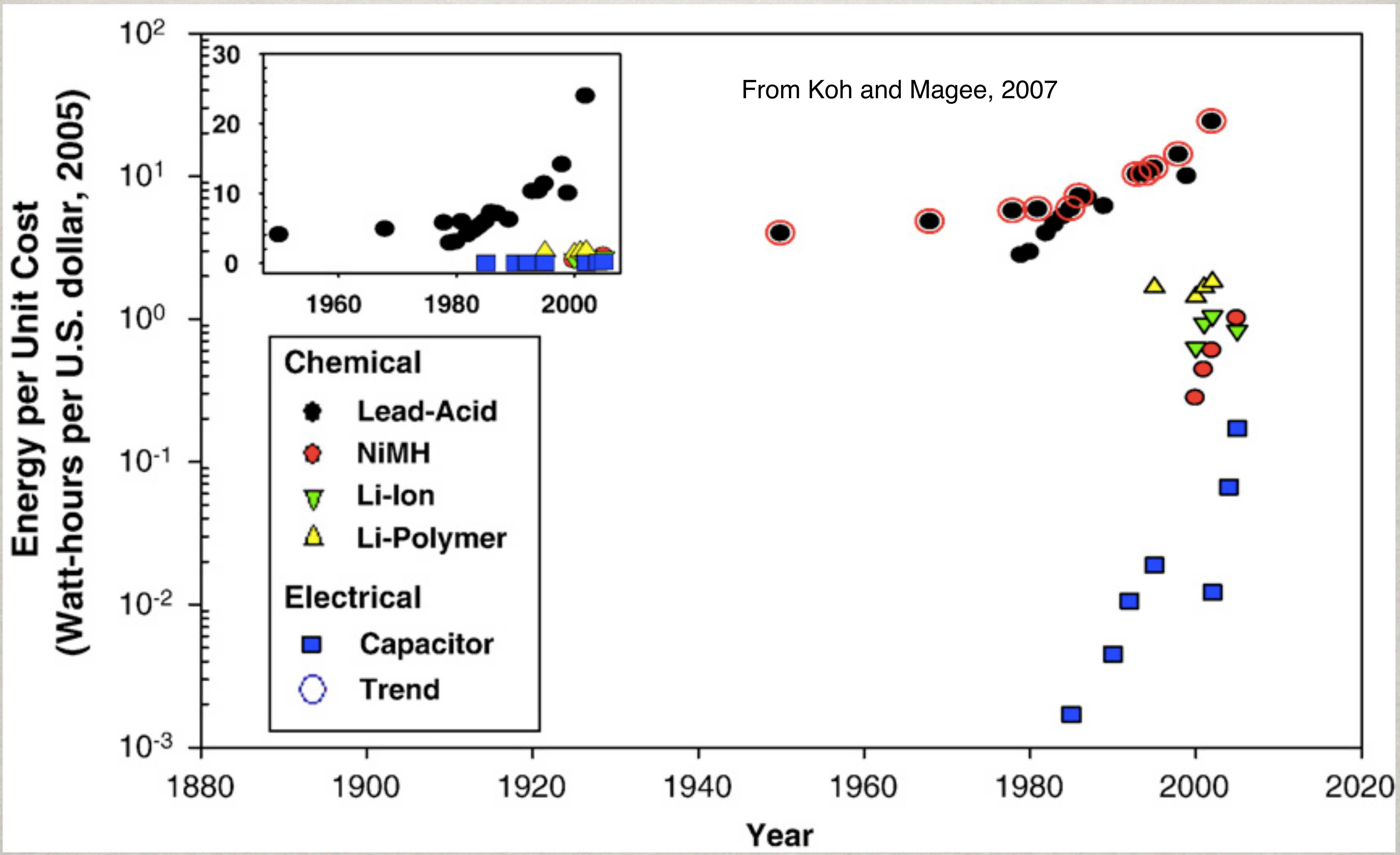
- IEA projection: PV will generate 16% of electricity by 2050

Energy storage



(b)

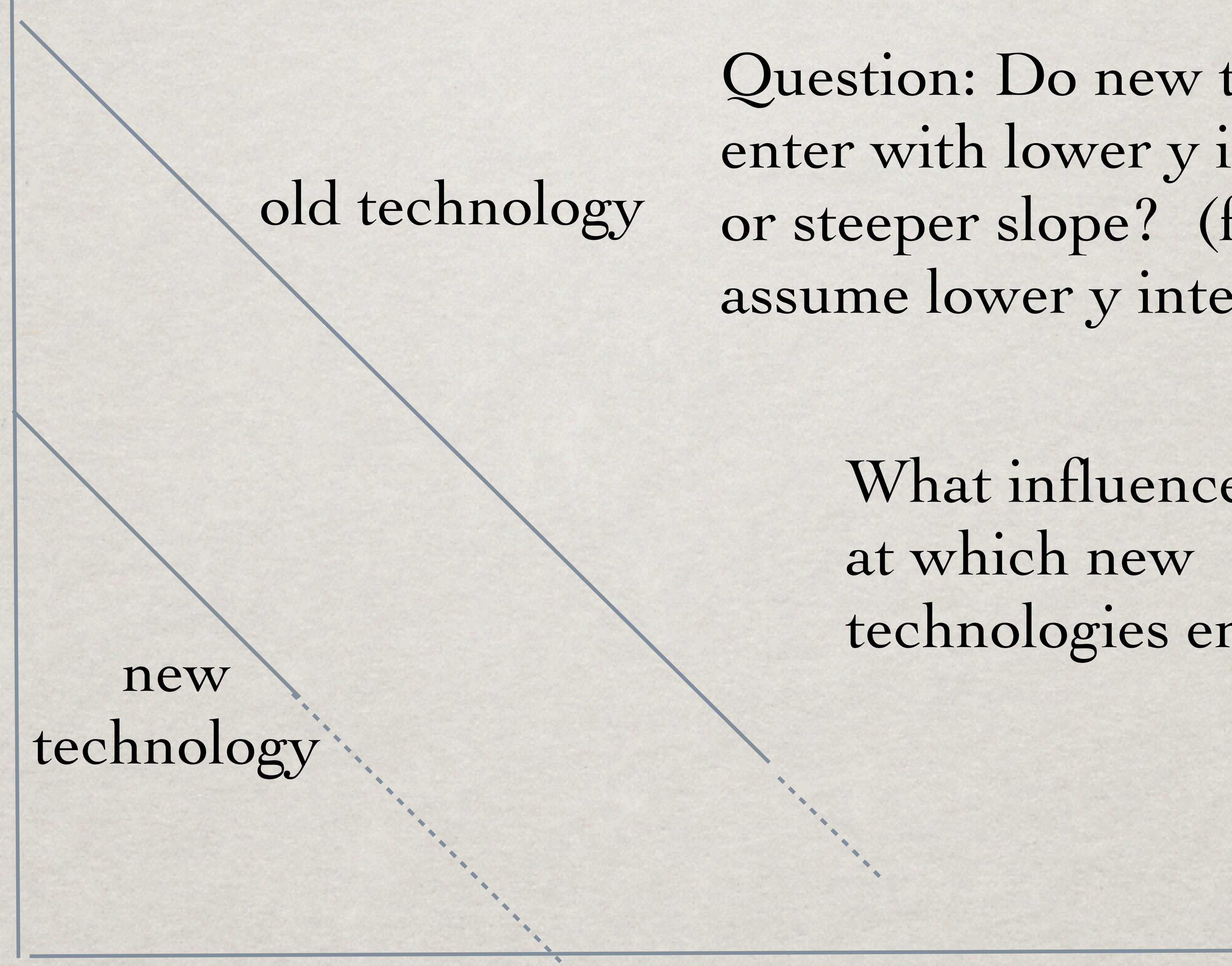
Energy storage cost



Why should public support technology R&D?

- Technologies get stuck in local maxima
- Stimulating production can be used to drive costs down (e.g. WWII)
- Governments do need to “pick winners”

local minima implied by Wright



Question: Do new technologies enter with lower y intercept or steeper slope? (for moment assume lower y intercept)

What influences rate at which new technologies enter?

Hypotheses for explaining Wright's law

Why do costs drop as a power law of cumulative quantity produced?

- Economies of scale
- Learning
- Network effects

Economies of scale

Examples:

- Factory costs c, subsequent units are free

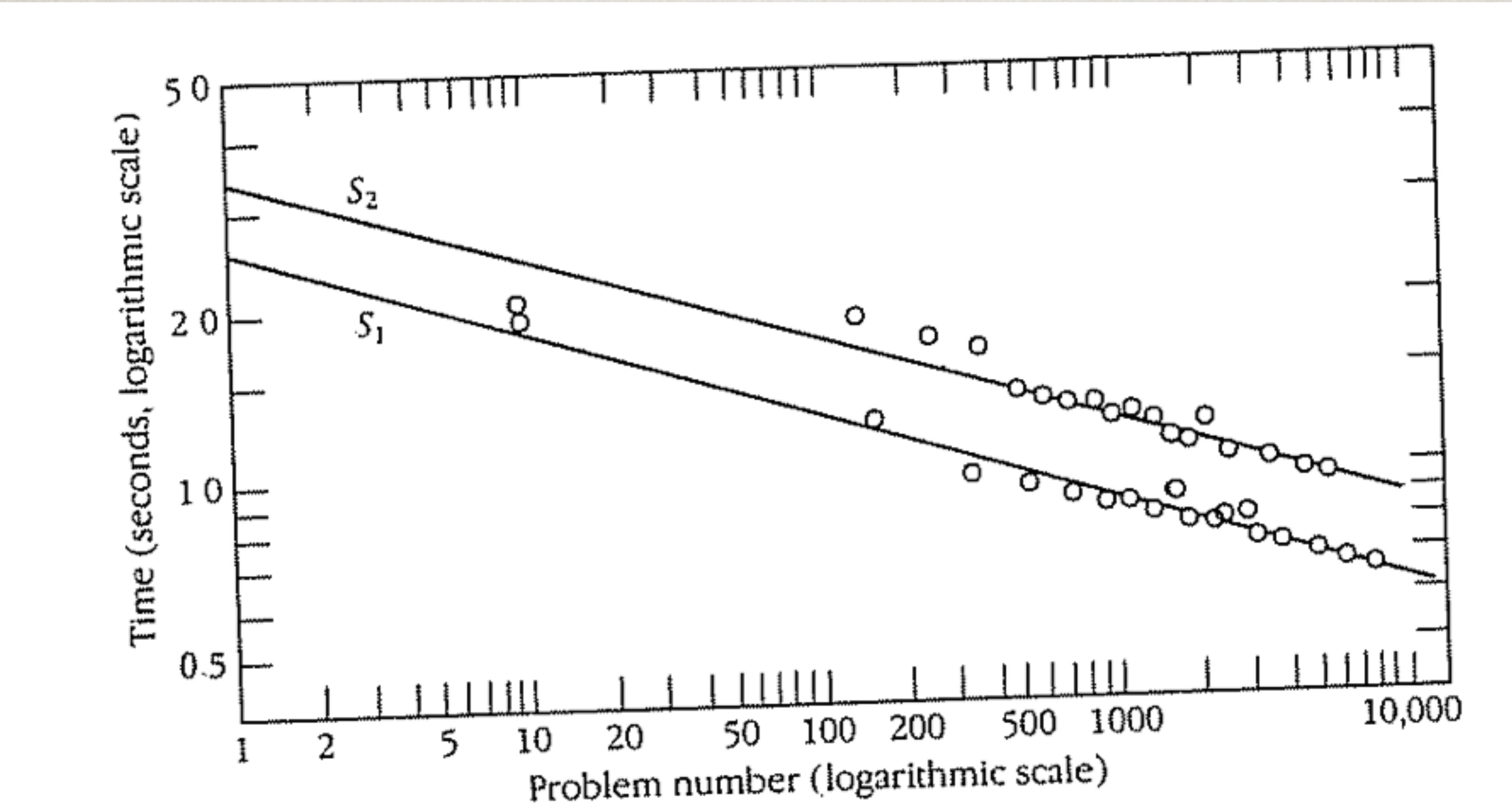
$$c = x^{-1}$$

- Chemical plant where cost is proportional to area, production proportional to volume

$$c = x^{-2/3}$$

- Transistors get faster, cheaper and more efficient as they get smaller. Exponential shrinking in time, exponential increase in production, implies Wright's law.

Power law of practice



Improvement with practice in time to add two numbers (Blackburn, 1936)

Learning + networks: Recipe model

- Muth (1986) assumed engineers throw darts at random to create new designs, only accept solutions that are improvements. Implies

$$c = x^{-1}$$

- Auerwald, Kauffman, Lobo Shell (2000). Assume components are interconnected so designers must coordinate, show simulations give power laws.
- McNerney, Farmer, Redner, Trancik (2011) show that

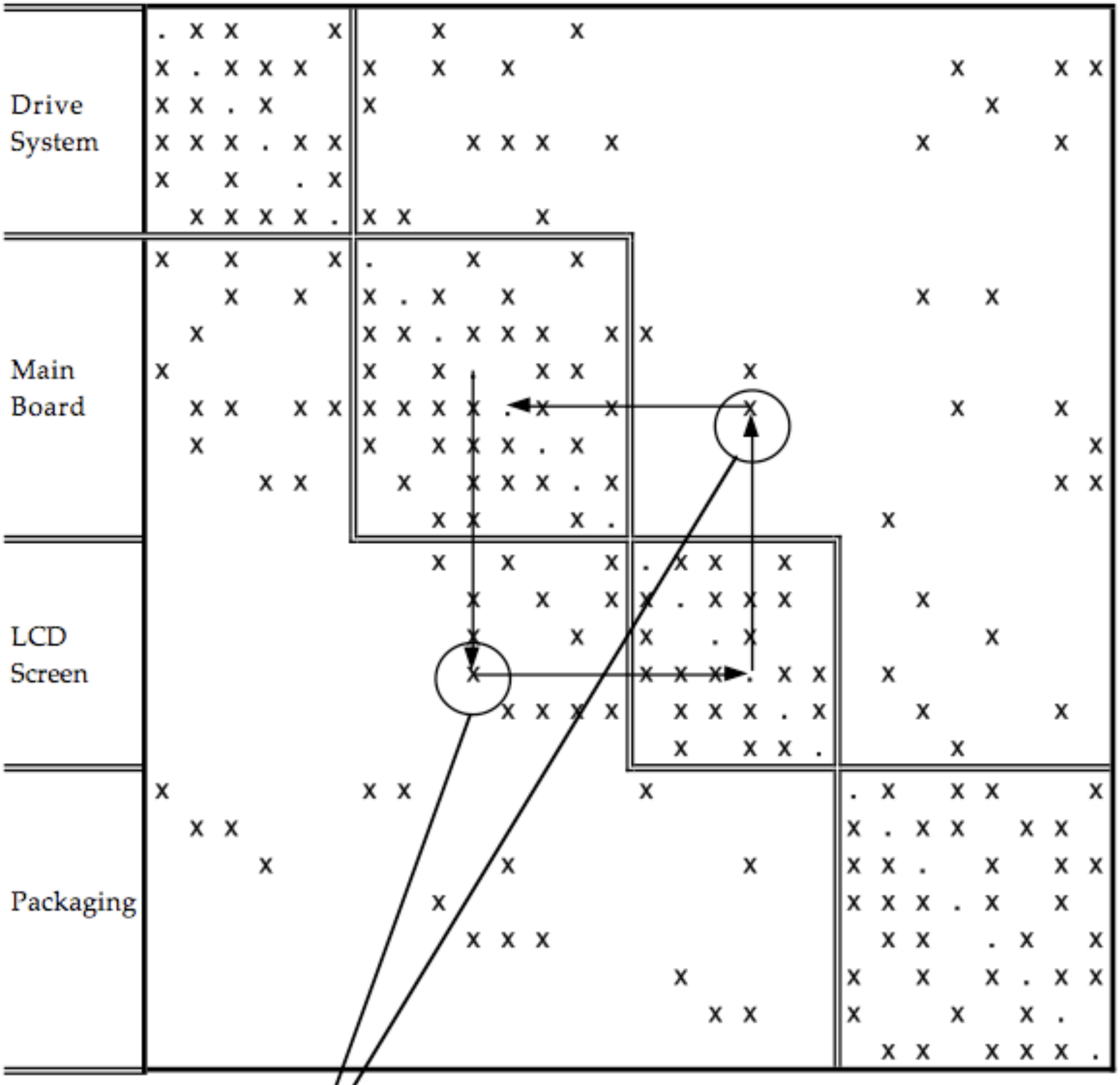
$$c = x^{-1/(\gamma d^*)}$$

where d* is "design complexity" of network

Recipe model of technological improvement

- Muth (Management Science, 1987)
  - Engineers generate new solutions at random, accept them if they are better. Single component: Implies Wright's law with exponent = -1.
- Auerswald, Kauffman, Lobo and Shell (JEDC, 2000)
  - Multiple components that depend on each other. Accept improvements only if sum score improves.

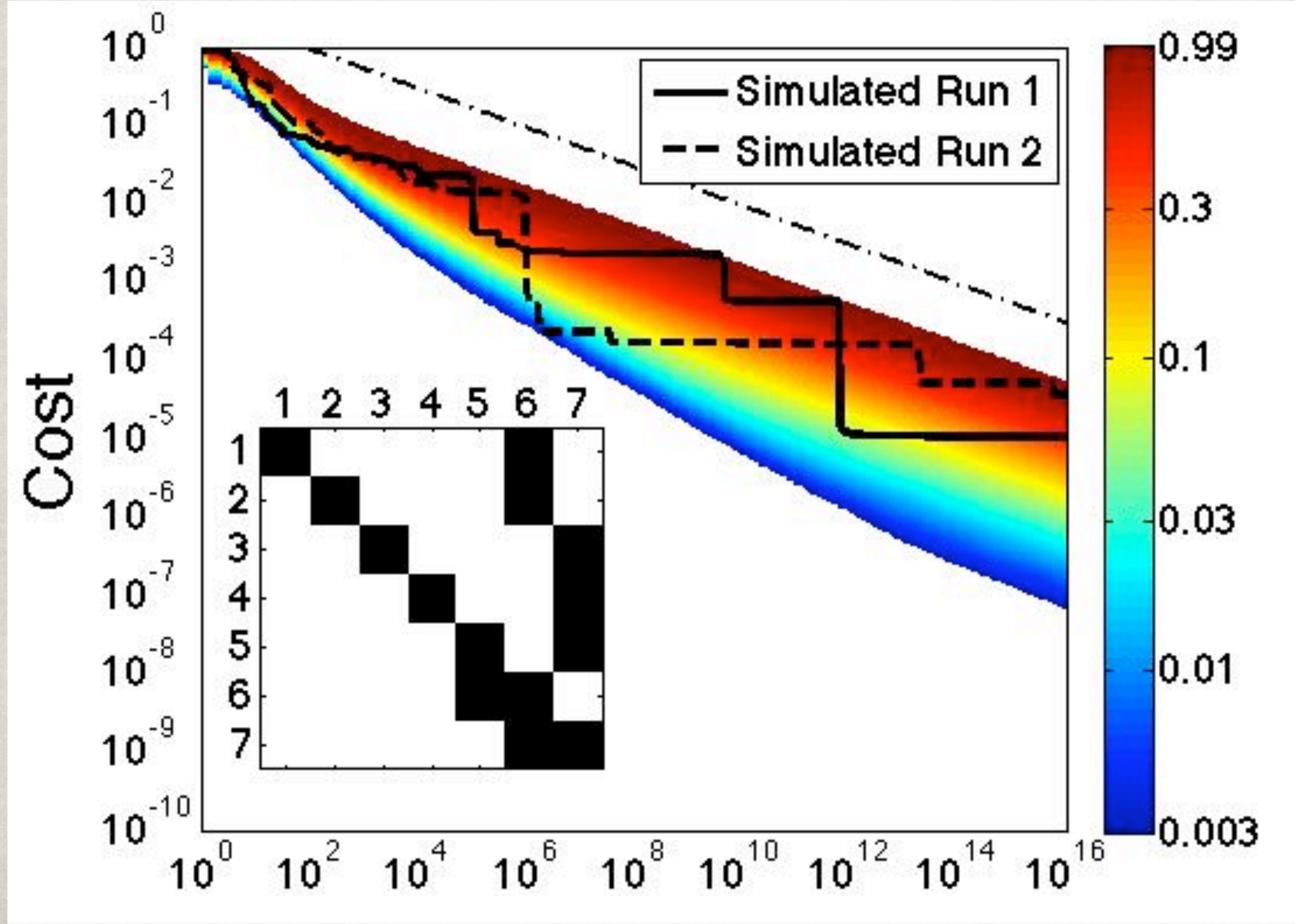
Design Structure Matrix Map of a Laptop Computer



Recipe model (continued)

- McNerney, Farmer, Redner, Trancik (PNAS, 2011)
  - simplified and solved recipe model
  - generates power law with exponent -(1/d), where d = "design complexity", which depends on DSM. For homogeneous networks d is in-degree of DSM.
  - for heterogeneous networks there are typically bottleneck components, d is more complicated to compute, and progress typically occurs via a sequence of punctuated equilibria

Cost vs. time for recipe model

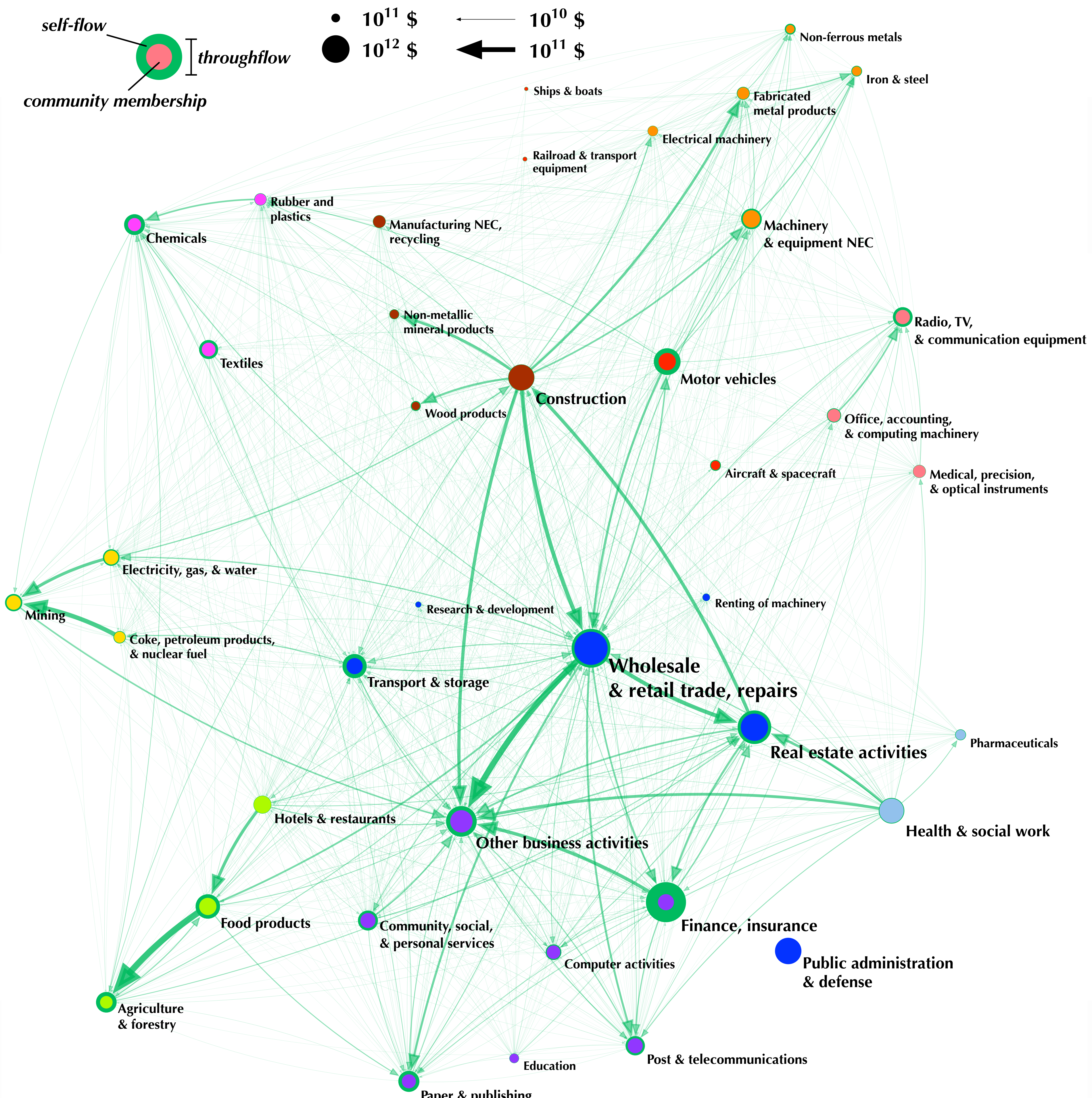


Need to go beyond recipe model

- Nice start, but only part of story
- Anecdotally: Innovations in one industry often drive innovations in others
  - solar PV, laser printers, digital cameras, ...
- Interactions between technologies are key
  - must model evolution of entire technological ecology to understand a single technology

LEONTIEF: INPUT-OUTPUT MODEL OF AN ECONOMY

- Nodes are industries, (weighted) directed links are inputs to each industry.
- Can be based on physical flows or on monetary flows.
- Precise analogy to equilibrium chemical kinetics (allowing non-integer stoichiometric parameters)
- Conservation laws lead to linear system of equations
- Used in national accounting, central planning.



U.S. industry network, 1997

McNerney, Fath, Silverberg (2013)

Input tinkering/design improvement

- Incremental changes in the recipe
- New designs involve variations of inputs
- Successful variations are selected
  - cheaper or better performance

How do technologies improve?

- Design improvement
  - Input tuning
  - Substitution of cheaper or better inputs
  - Creation of new goods: Network growth
  - Improved social technologies of production, distribution, ... invisible to Leontief network
- Increase in combinatorial possibilities -- palette gets larger and more efficient

Focus on very simple model of technological change

- The net result of a design improvement is an overall decrease in material inputs to perform same function

$$\phi_{ij} \rightarrow \alpha\phi_{ij}$$

- ϕ_{ij} is the flow of material inputs from sector j to sector i, $\alpha < 1$ means improvement

Overall rate of progress depends on network structure

- Let A_{ij} be normalized flow of money from sector i to j
- Assume uniform learning rate $\gamma = \dot{\alpha}/\alpha$
- Implies rate of improvement of GDP is

$$g = \bar{\mathcal{L}}\gamma$$

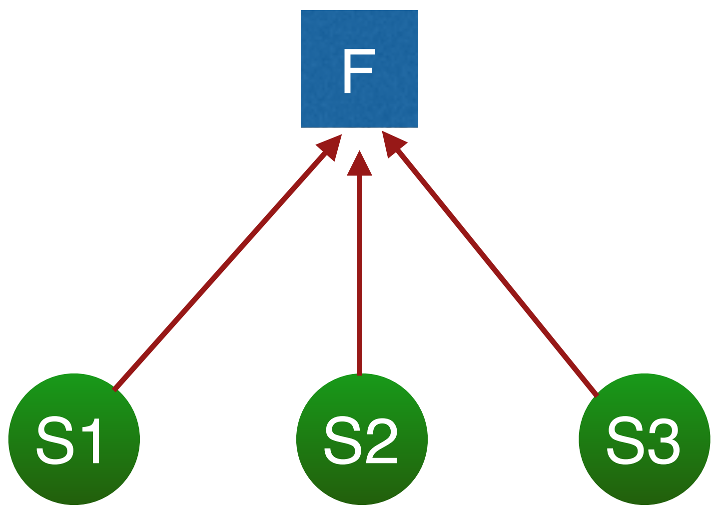
$$\mathcal{L} = (I - A^T)^{-1}\mathbf{1}$$

- $\bar{\mathcal{L}}$ is weighted by GDP in each sector

Production networks

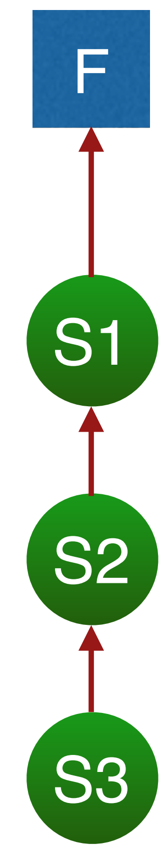
Money flow structure

Flat economy



$$\bar{\mathcal{L}} = 1$$

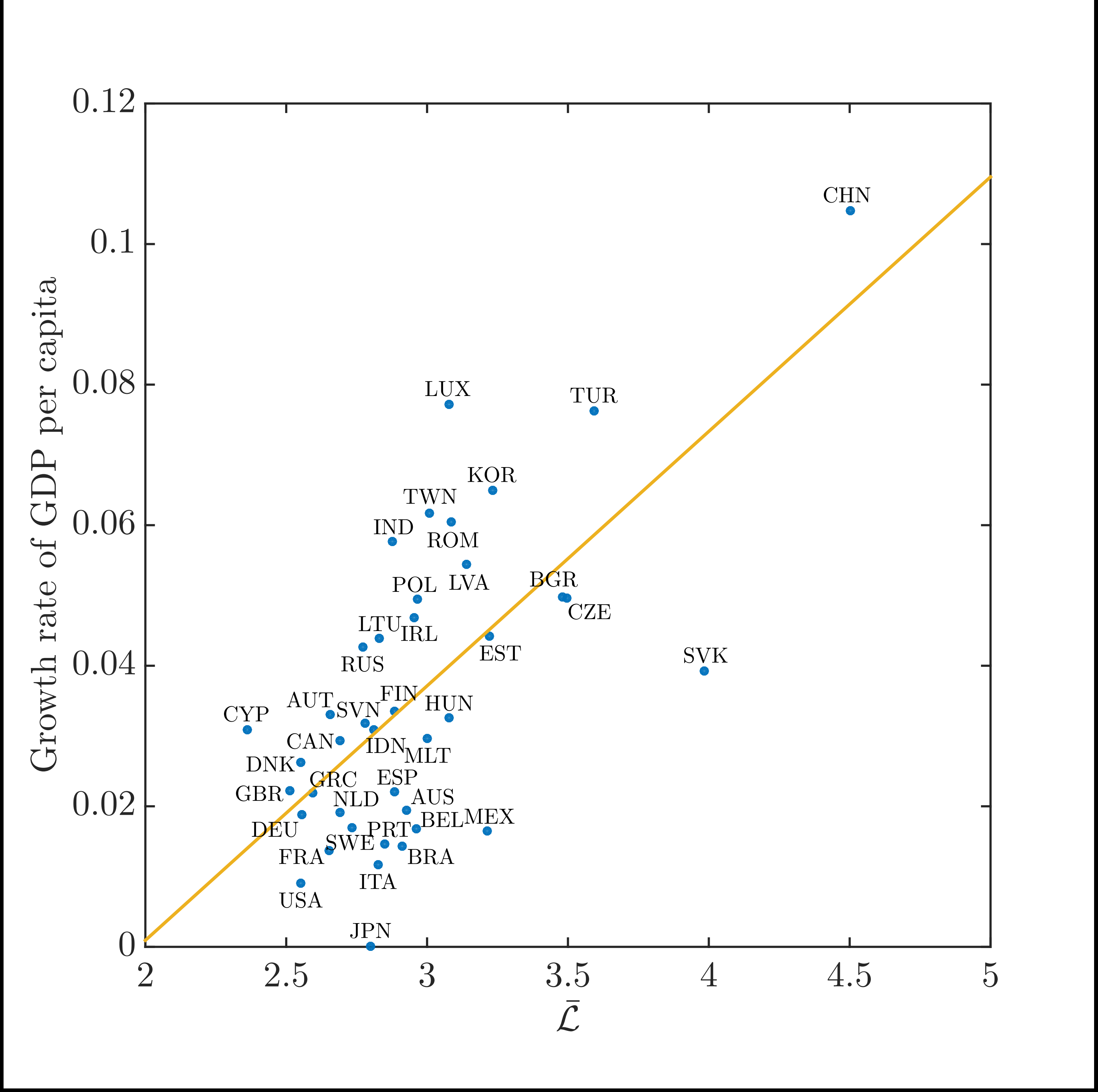
Chain economy



$$\bar{\mathcal{L}} = 2$$

Chain economy amplifies technological changes.

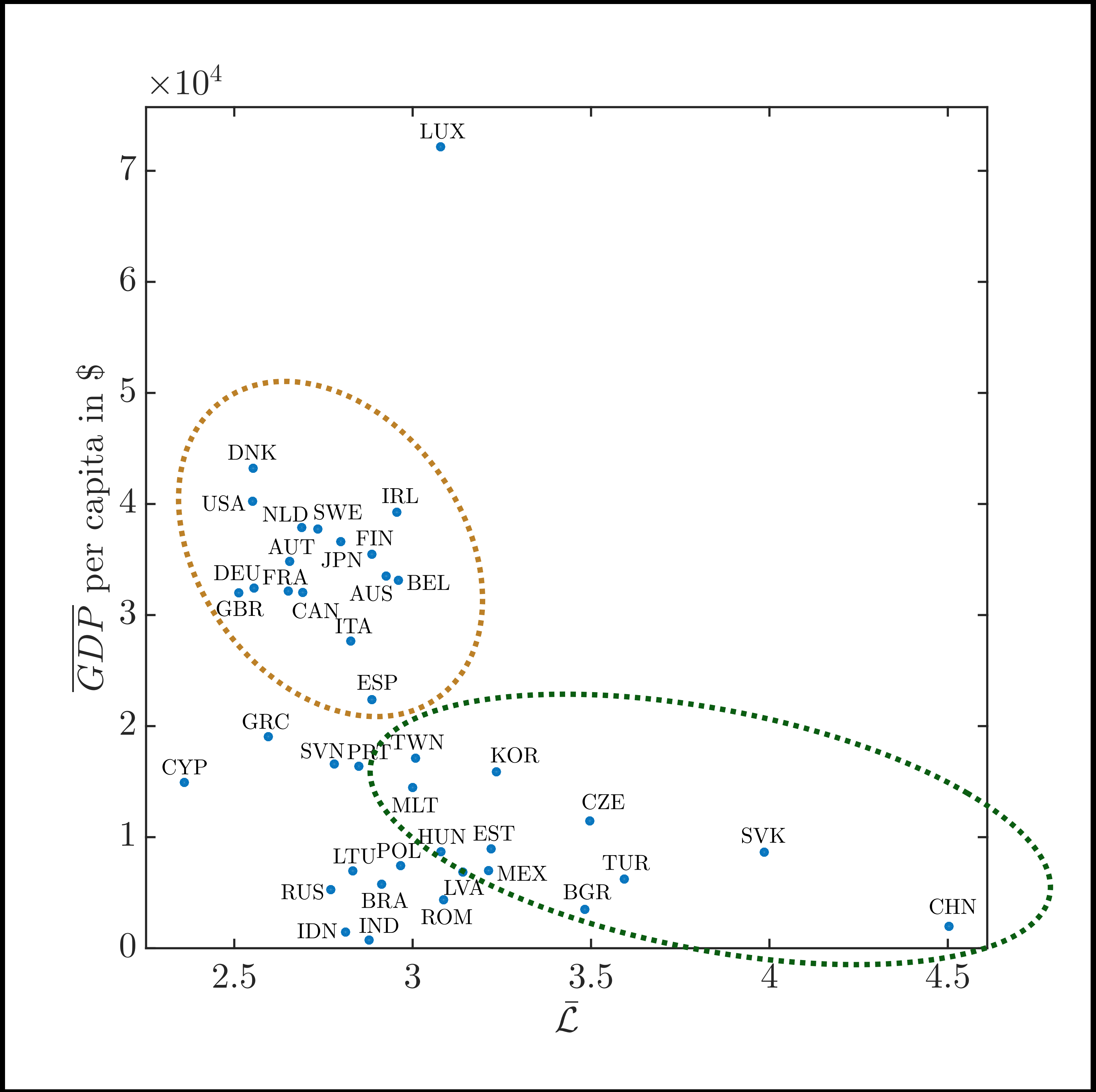
Growth rate and trophic depth



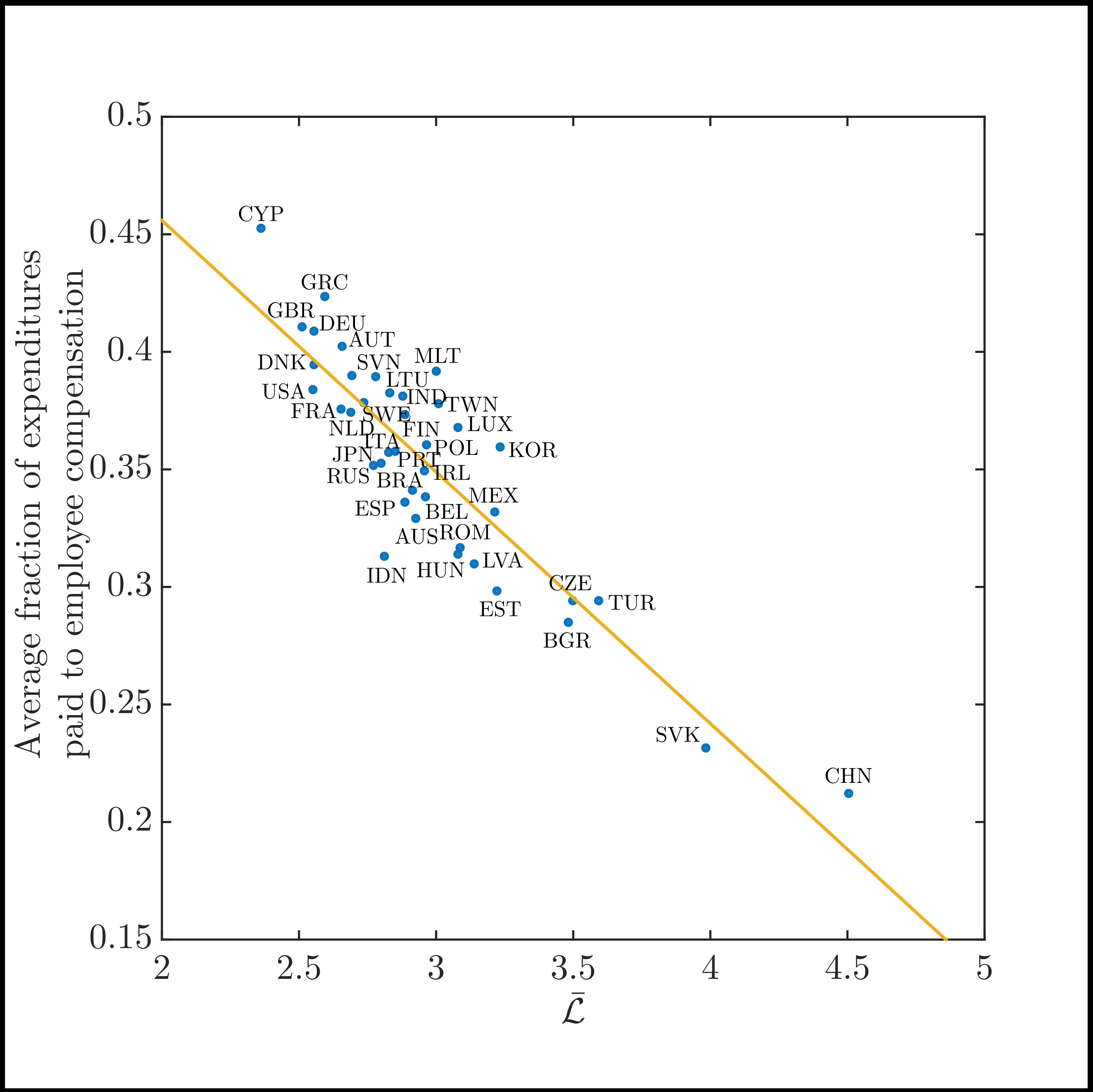
$R^2 = 0.452$

P-Value = $2.0\ 10^{-6}$

GDP vs. trophic depth



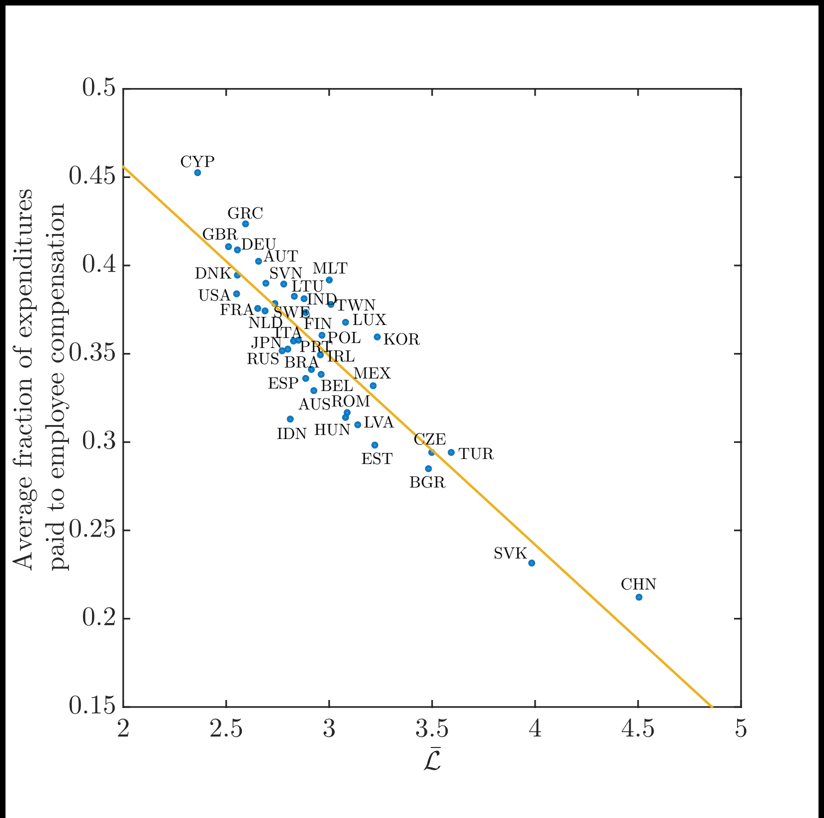
Expenditure share



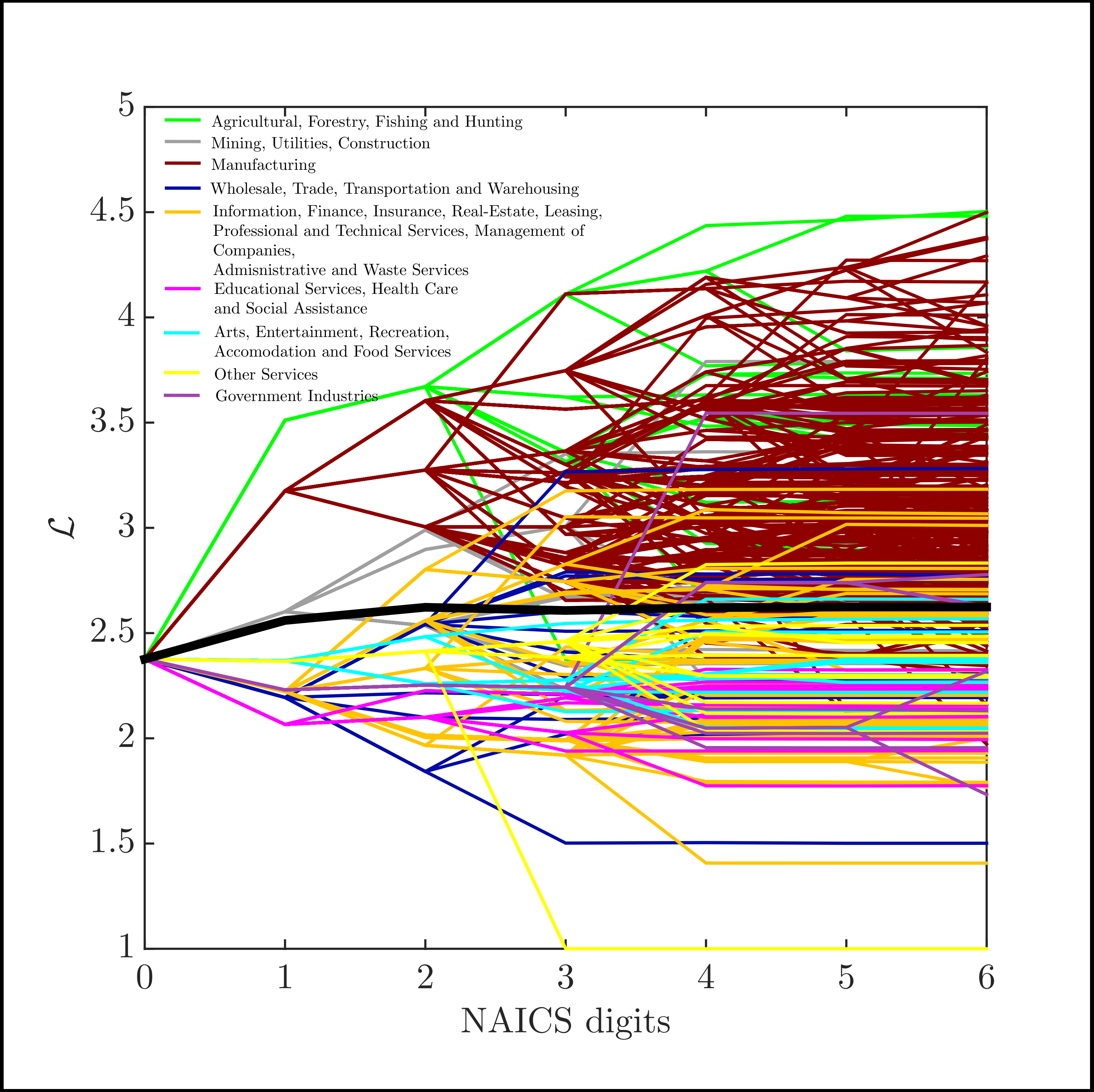
Comparison to standard growth models

	Standard growth model			**Standard growth model+$\bar{\mathcal{L}}$**		
Explanatory variable	Estimate	SE	P-Value	Estimate	SE	P-Value
$\bar{\mathcal{L}}$				$2.85 \cdot 10^{-2}$	$8.35 \cdot 10^{-3}$	$1.63 \cdot 10^{-3}$
log(GDP in 1995)	$-6.01 \cdot 10^{-4}$	$2.83 \cdot 10^{-4}$	$4.11 \cdot 10^{-2}$	$-3.03 \cdot 10^{-4}$	$2.54 \cdot 10^{-4}$	0.241
Saving rate	$1.15 \cdot 10^{-3}$	$5.46 \cdot 10^{-4}$	$4.23 \cdot 10^{-2}$	$5.60 \cdot 10^{-4}$	$5.03 \cdot 10^{-4}$	0.273
Expenditure share	$-9.06 \cdot 10^{-2}$	$7.60 \cdot 10^{-2}$	0.241			
Constant	$4.97 \cdot 10^{-2}$	$3.22 \cdot 10^{-2}$	0.132	$-5.76 \cdot 10^{-2}$	$2.33 \cdot 10^{-2}$	$1.84 \cdot 10^{-2}$
R-Squared	0.351			0.493		

Fraction of expenditure paid to employee compensation is not significant to explain growth.



Aggregation



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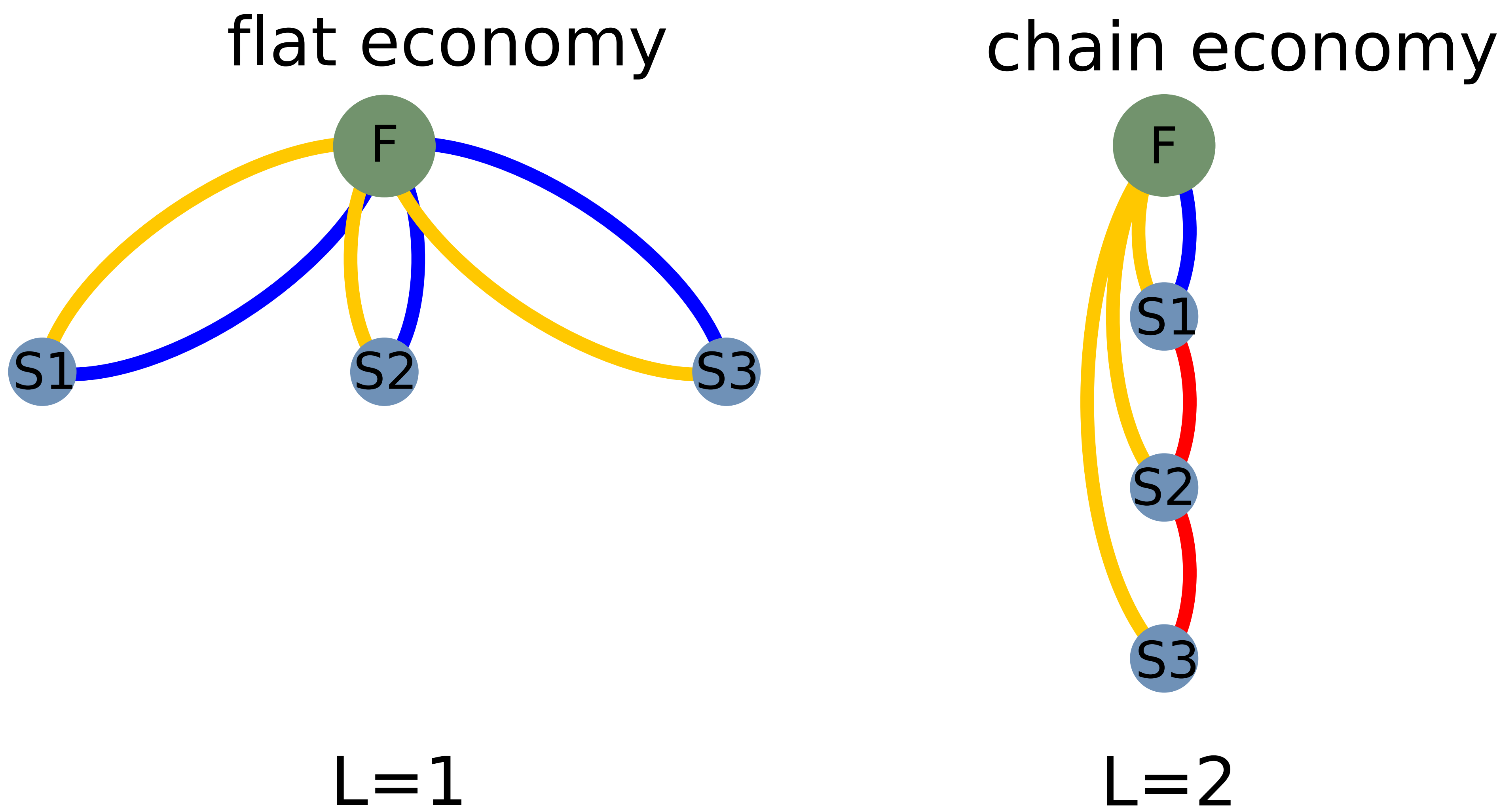

Trophic depth amplifies growth multiplicatively

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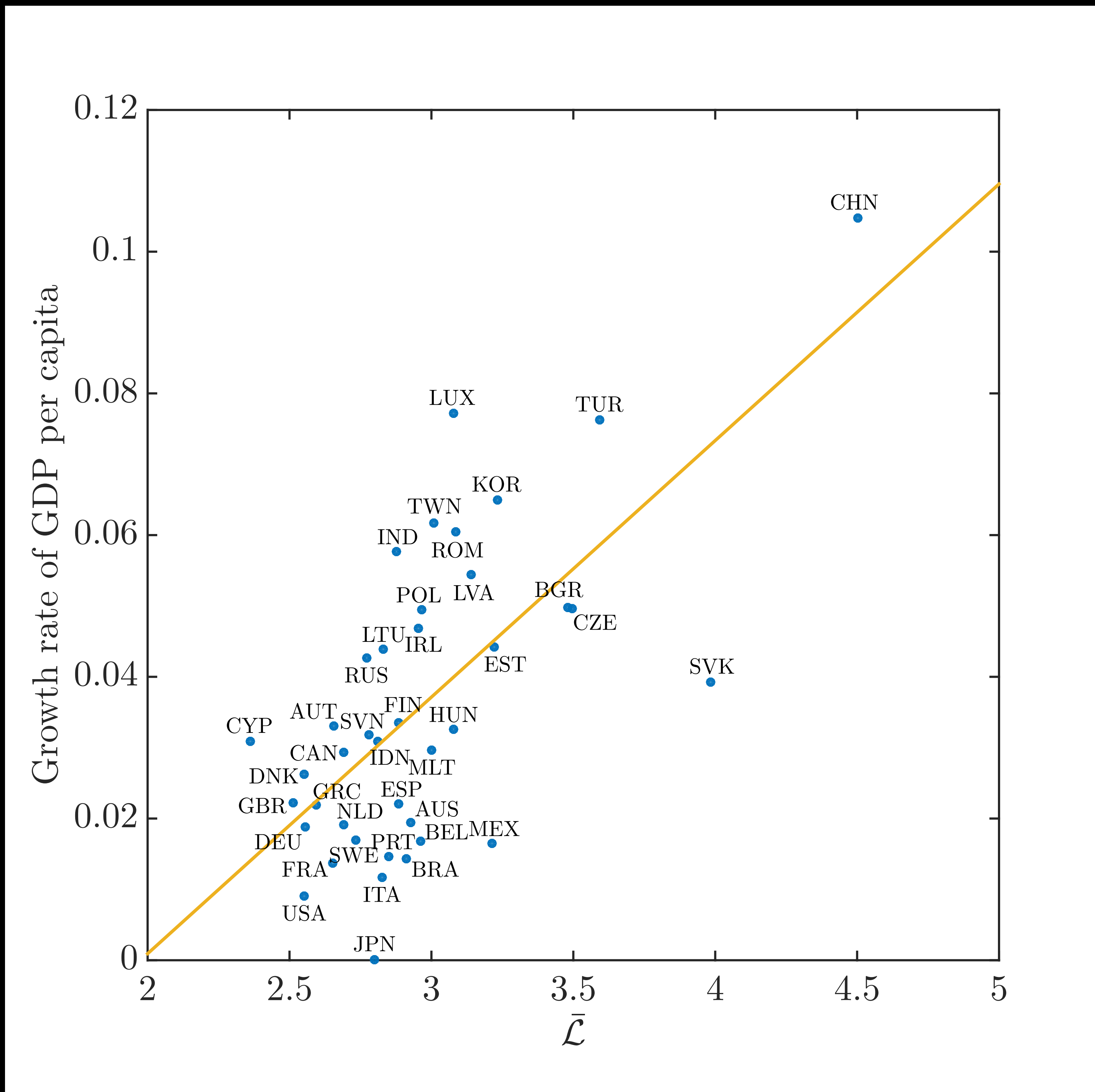
- Trophic depth $\bar{\mathcal{L}}$ is weighted by GDP in each sector

Growth rate and trophic depth



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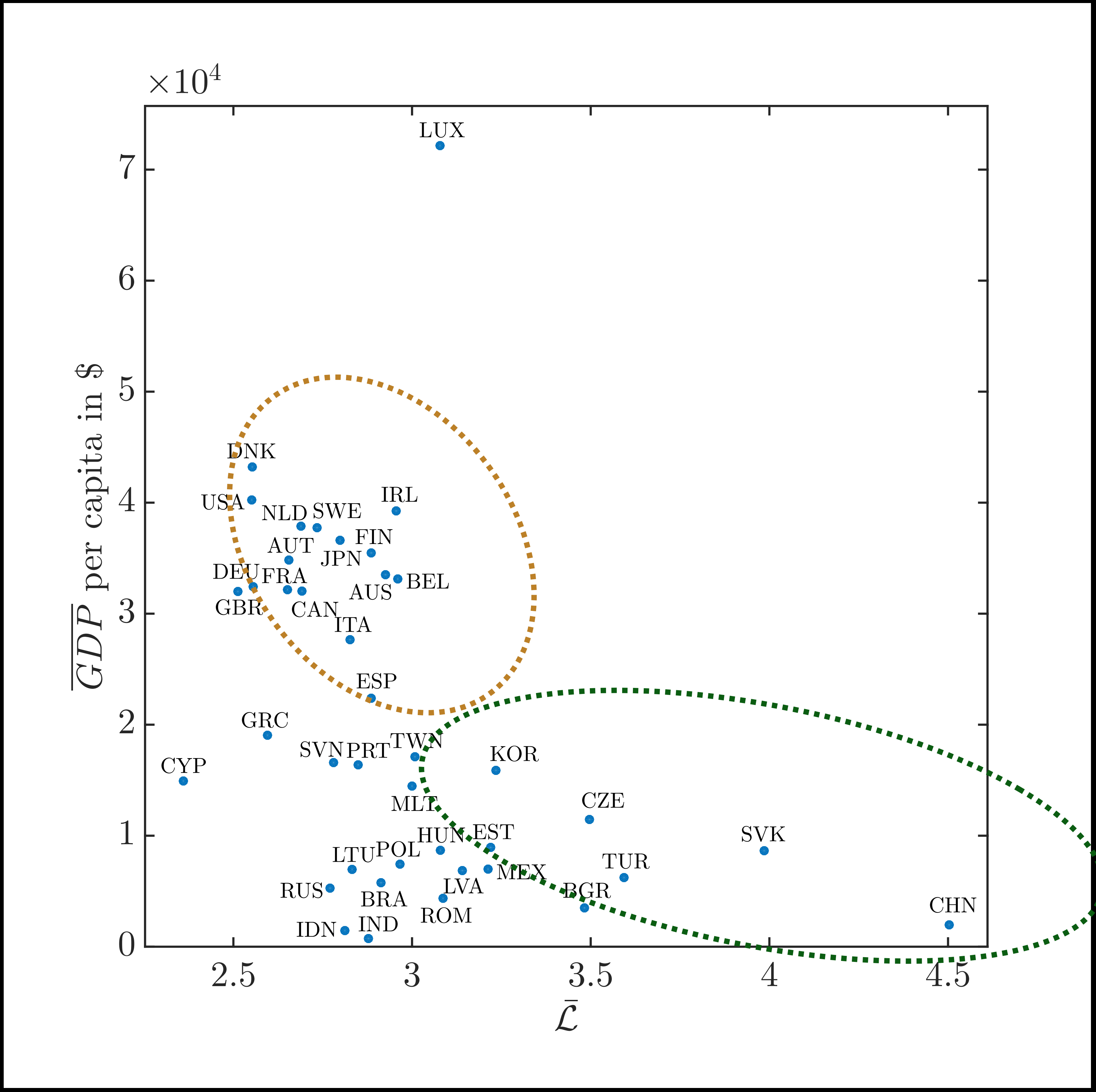
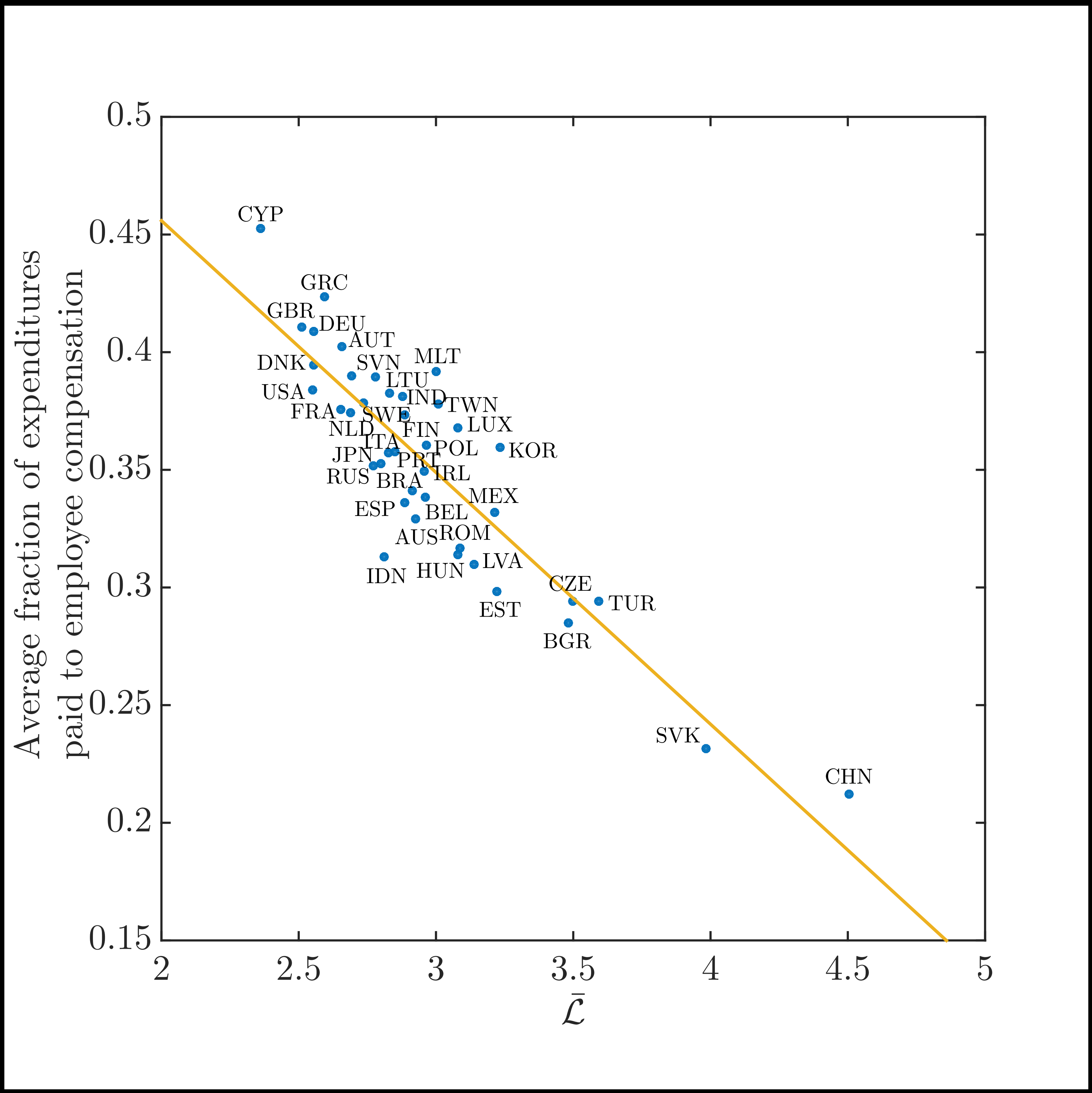


Expenditure share



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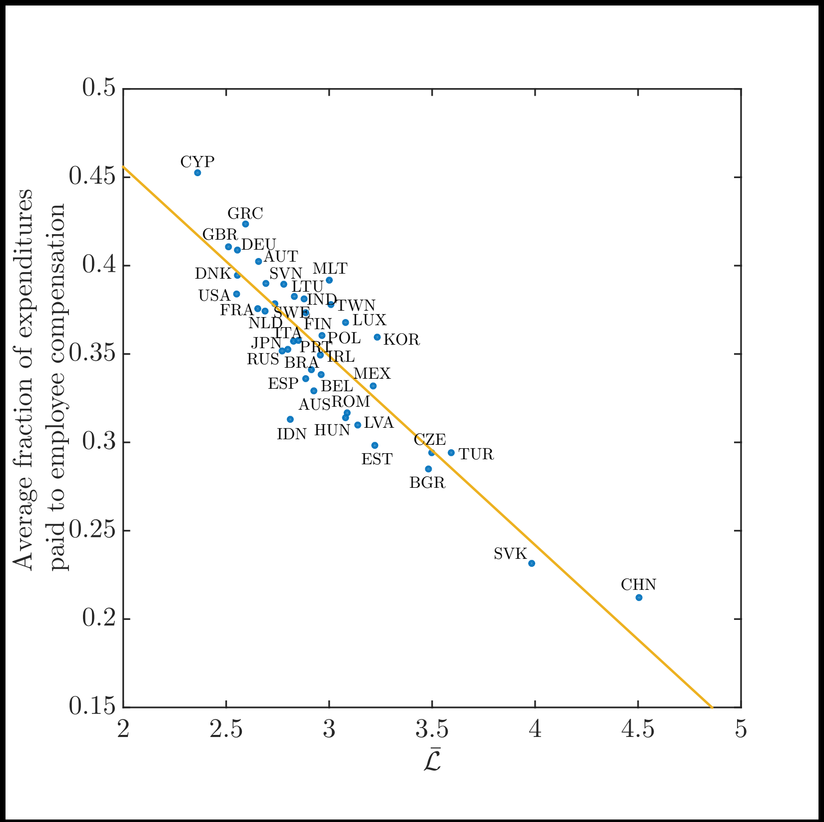

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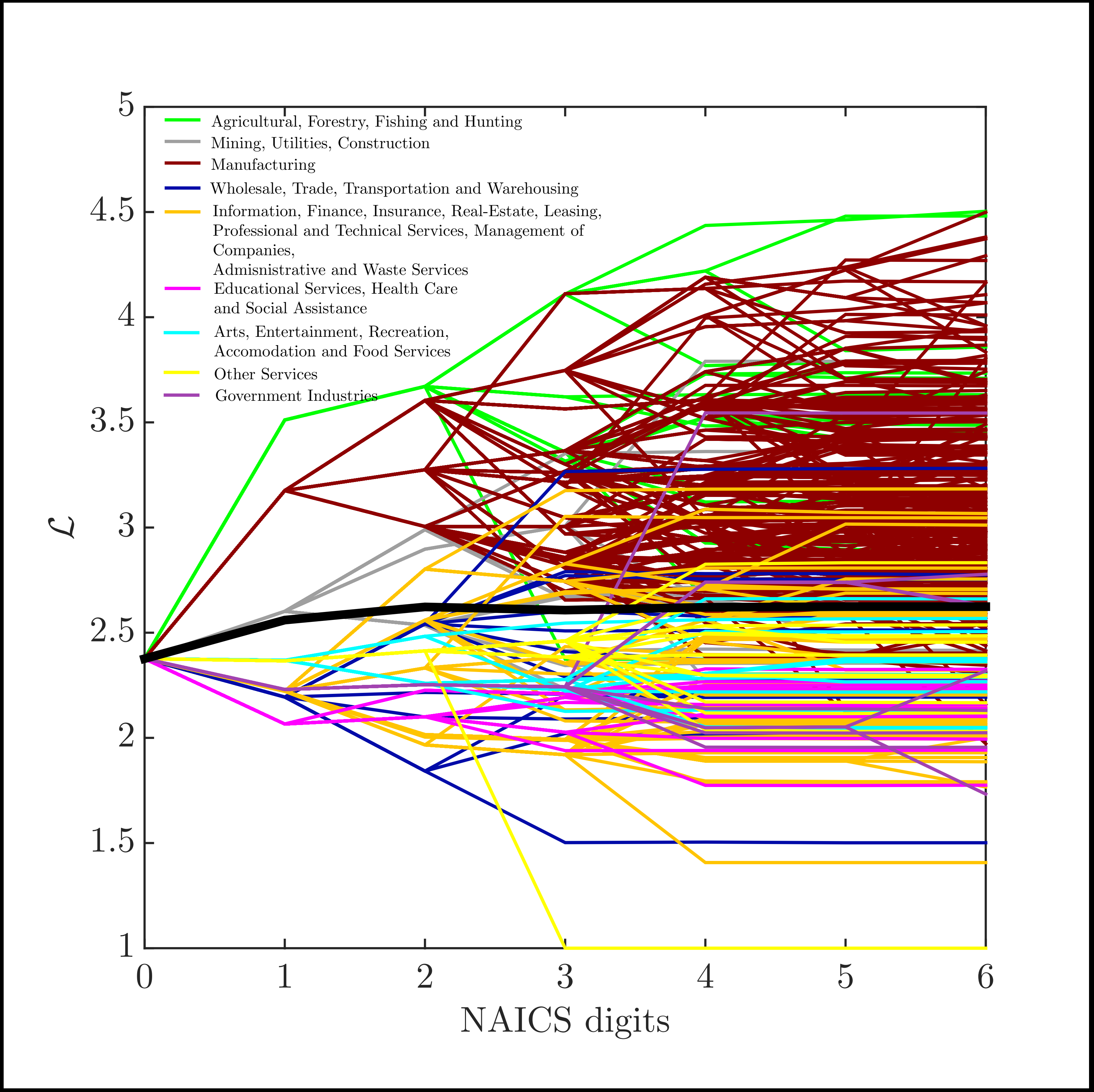


Provides alternate explanation for super-exponential population growth

- Paul Romer’s theory: population and technology co-evolved.
- Our theory: Growing trophic structure accelerates economic growth.

Analogy: Evolution of autocatalytic networks

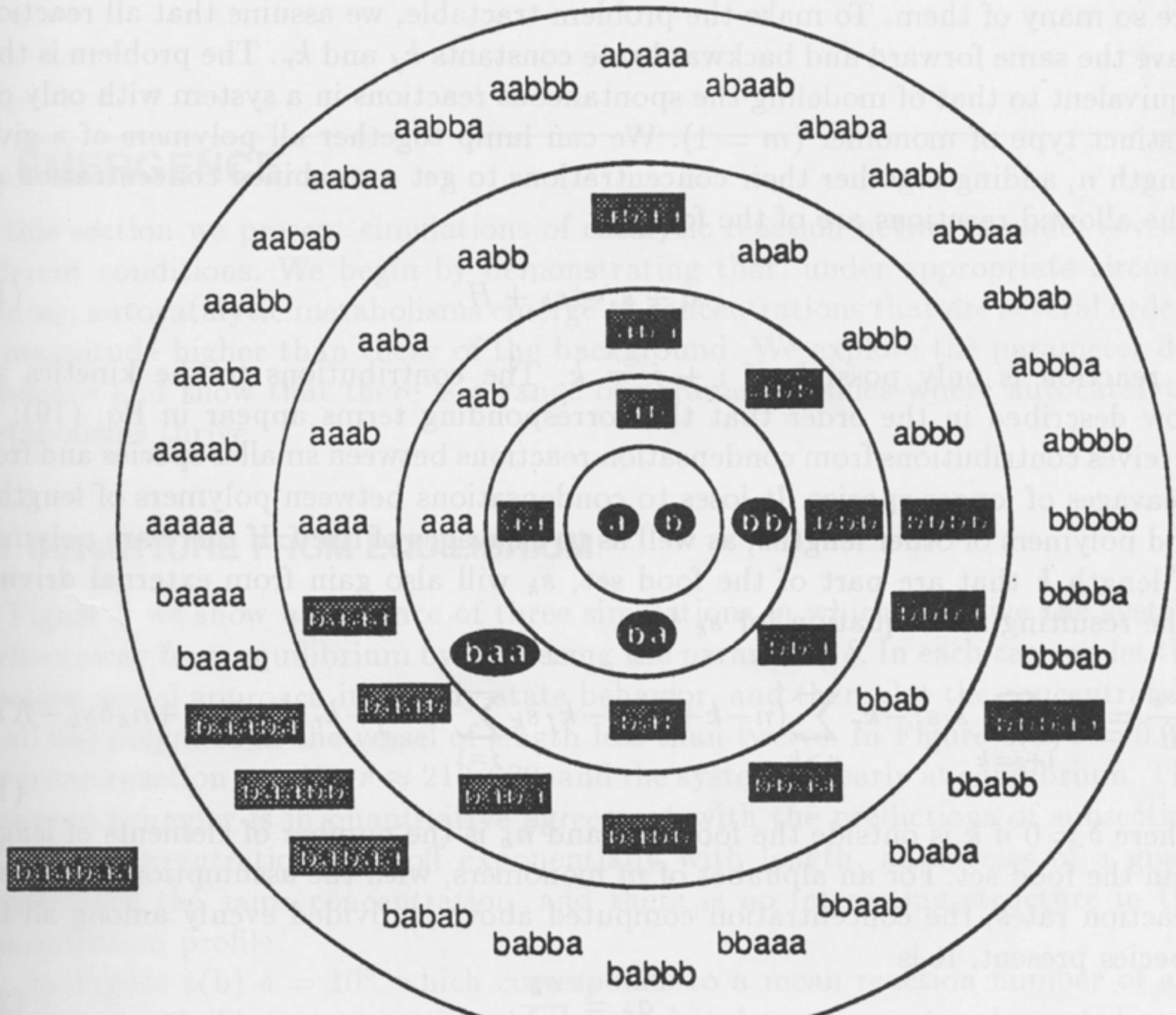
- Autocatalytic metabolism: Set of chemical species that jointly produce each other via catalyzed chemical reactions involving only other members of the set.

Metadynamics
(with Norman Packard)

- A *metadynamics* model is a dynamical systems model on a dynamic network. The dynamics induce changes in the network, which in turn induces changes in the dynamical system.
- For example, consider modeling a potentially infinite set of possible chemical reactions.
  - Chemical kinetics are solved on a network of dominant reactions. This network is defined by the set of existing chemical species, which can themselves change through time. As they change, they change the network.
- Key idea: Evolution toward the adjacent possible (Kauffman).

Metadynamics papers

- Farmer, J.D., S. Kauffman, N. Packard. "Autocatalytic Replication of Polymers." *Physica D* (1986).
- Farmer, J. D., N. H. Packard, A. Perelson. "The Immune System, Adaptation, and Machine Learning." *Physica D* (1986)
- Bagley, R. J., and J. D. Farmer. "Spontaneous Emergence of a Metabolism." In *Artificial Life II* (1991).
- Bagley, R. J., J. D. Farmer, and W. Fontana. "Evolution of a Metabolism." In *Artificial Life II* (1991).



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sense) under reasonably plausible prebiotic conditions.

There are three notions of the formation of autocatalytic sets, depending on what we mean by "produced by" in the definition given above:

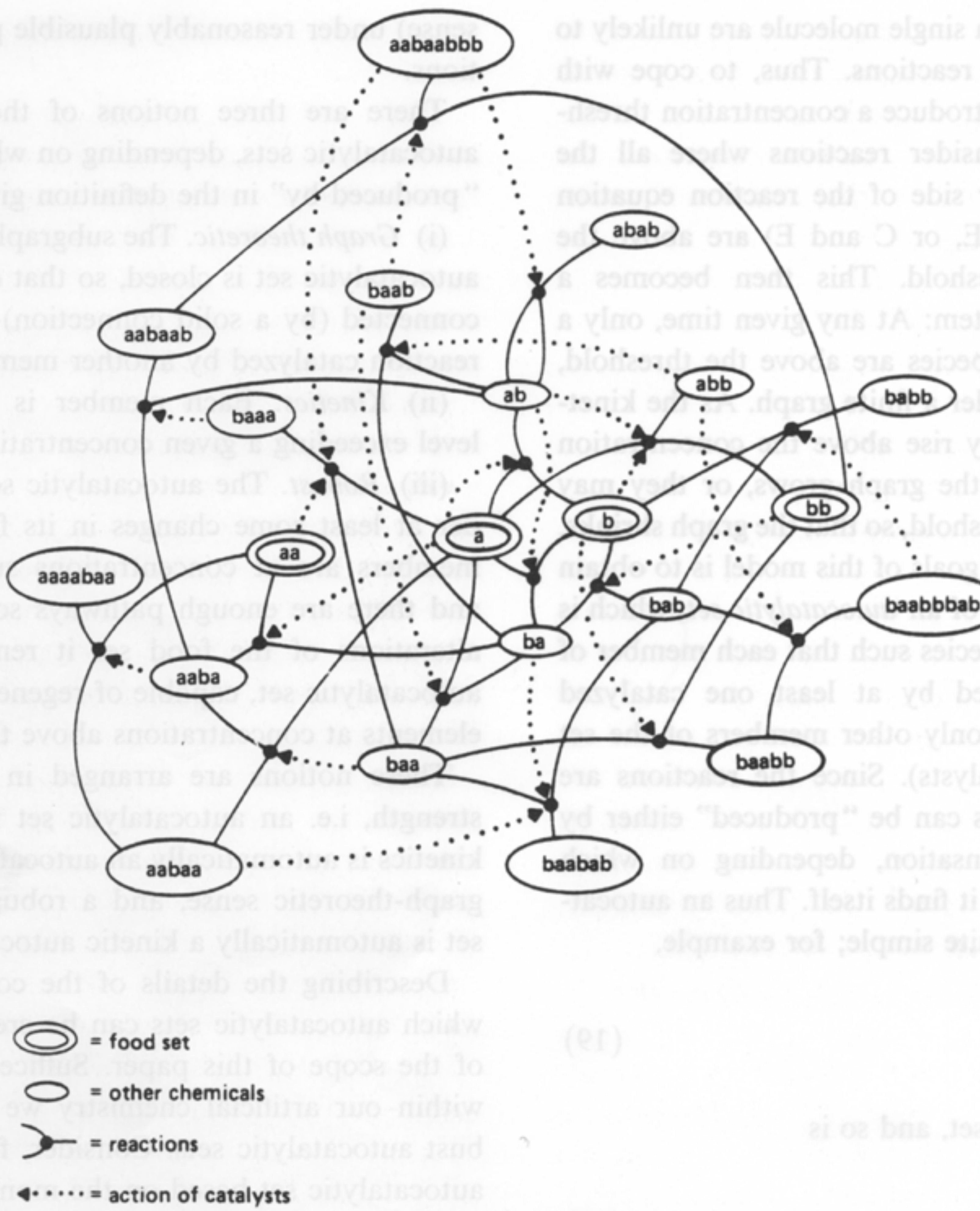
(i) *Graph theoretic.* The subgraph defined by the autocatalytic set is closed, so that each member is connected (by a solid connection) to at least one reaction catalyzed by another member.

(ii) *Kinetic.* Each member is produced at a level exceeding a given concentration threshold.

(iii) *Robust.* The autocatalytic set is robust under at least some changes in its food set, i.e. its members attain concentrations sufficiently large and there are enough pathways so that for some alterations of the food set it remains a kinetic autocatalytic set, capable of regenerating removed elements at concentrations above the threshold.

These notions are arranged in order of their strength, i.e. an autocatalytic set in the sense of kinetics is automatically an autocatalytic set in the graph-theoretic sense, and a robust autocatalytic set is automatically a kinetic autocatalytic set.

Describing the details of the conditions under which autocatalytic sets can be created is outside of the scope of this paper. Suffice it to say that, within our artificial chemistry we can create robust autocatalytic sets, consisting, for example, on autocatalytic set based on the monomers a and b,



to the presence of a single molecule are unlikely to participate in any reactions. Thus, to cope with this problem we introduce a concentration threshold, and only consider reactions where all the members on either side of the reaction equation (either A, B, and E, or C and E) are above the concentration threshold. This then becomes a metadynamical system: At any given time, only a finite number of species are above the threshold, and we only consider a finite graph. As the kinetics act, species may rise above the concentration threshold, so that the graph grows, or they may drop below the threshold, so that the graph shrinks.

One of the main goals of this model is to obtain closure in the form of an autocatalytic set, which is a set of polymer species such that each member of the set is produced by at least one catalyzed reaction involving only other members of the set (including the catalysts). Since the reactions are reversible, a species can be "produced" either by cleavage or condensation, depending on which side of equilibrium it finds itself. Thus an autocatalytic set can be quite simple; for example,

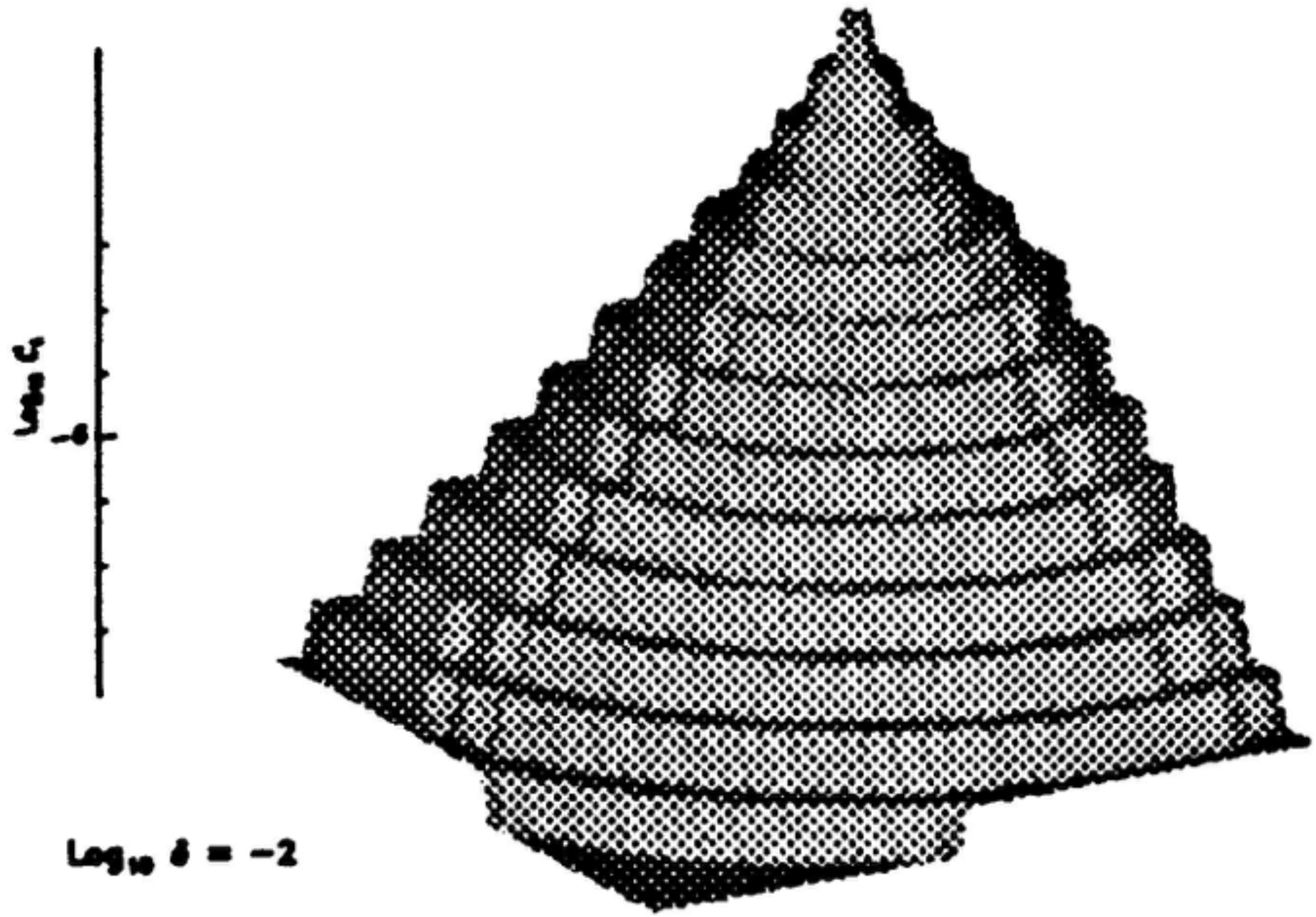
$$A + B \overset{\wedge}{\rightleftharpoons} C + H \quad (19)$$

is an autocatalytic set, and so is

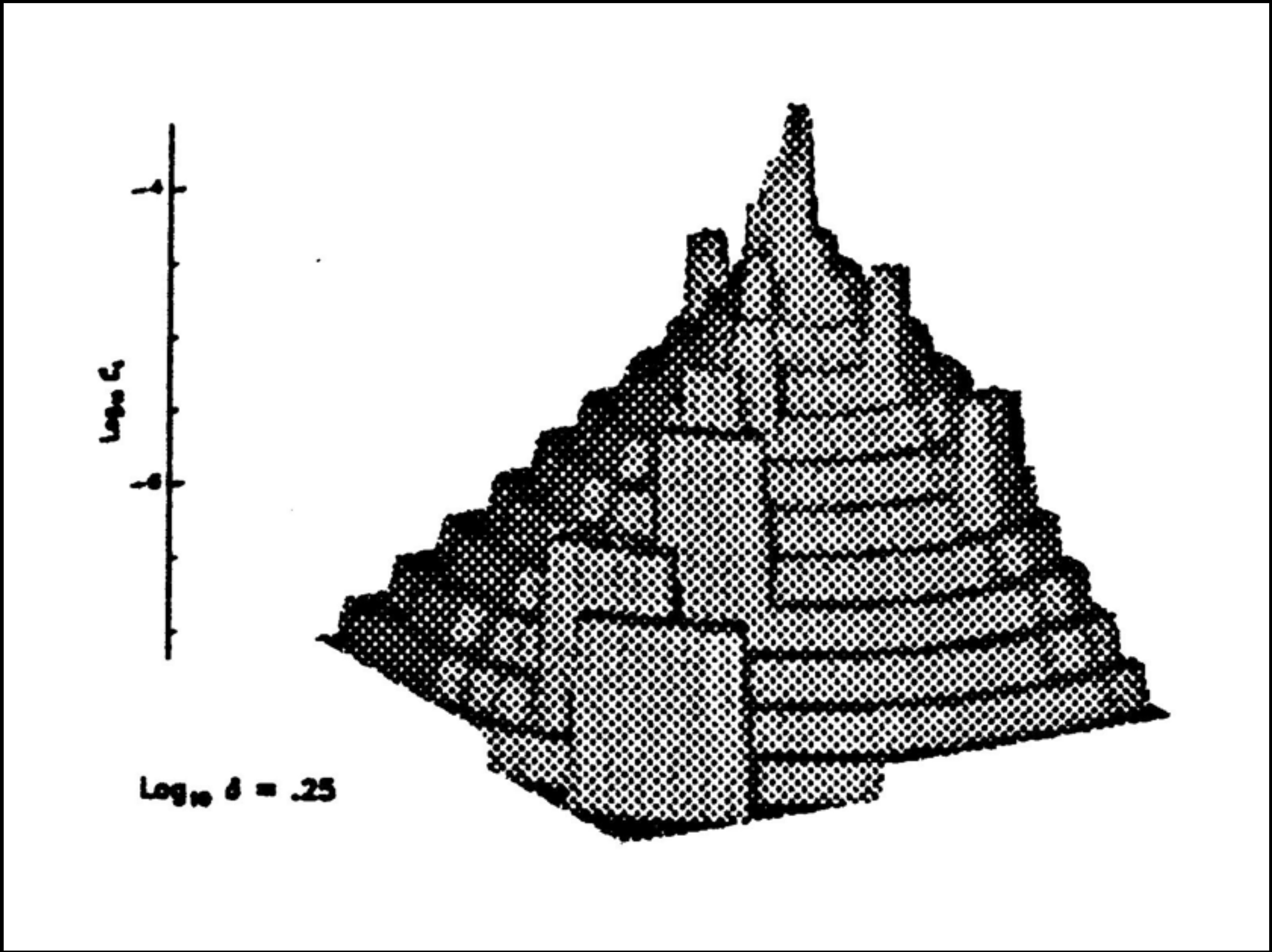
Simulation of an autocatalyic metabolism

- Start with simple food set (e.g. 5 species)
- Implement kinetics for catalyzed reactions among food set (which defines initial network).
- Define shadow set as species that can be reached by uncatalyzed reactions within network
- Create a new species from shadow set with probability depending on reaction rates.
- If this adds new catalyzed reaction, alter network of catalyzed reactions accordingly.
- Repeat.

equilibrium concentration with only uncatalyzed reactions



from: The Functional Self-Organization of Autocatalytic Networks In a Model of the Evolution of Biogenesis, Richard James Bagley, Ph.D. thesis (1991)



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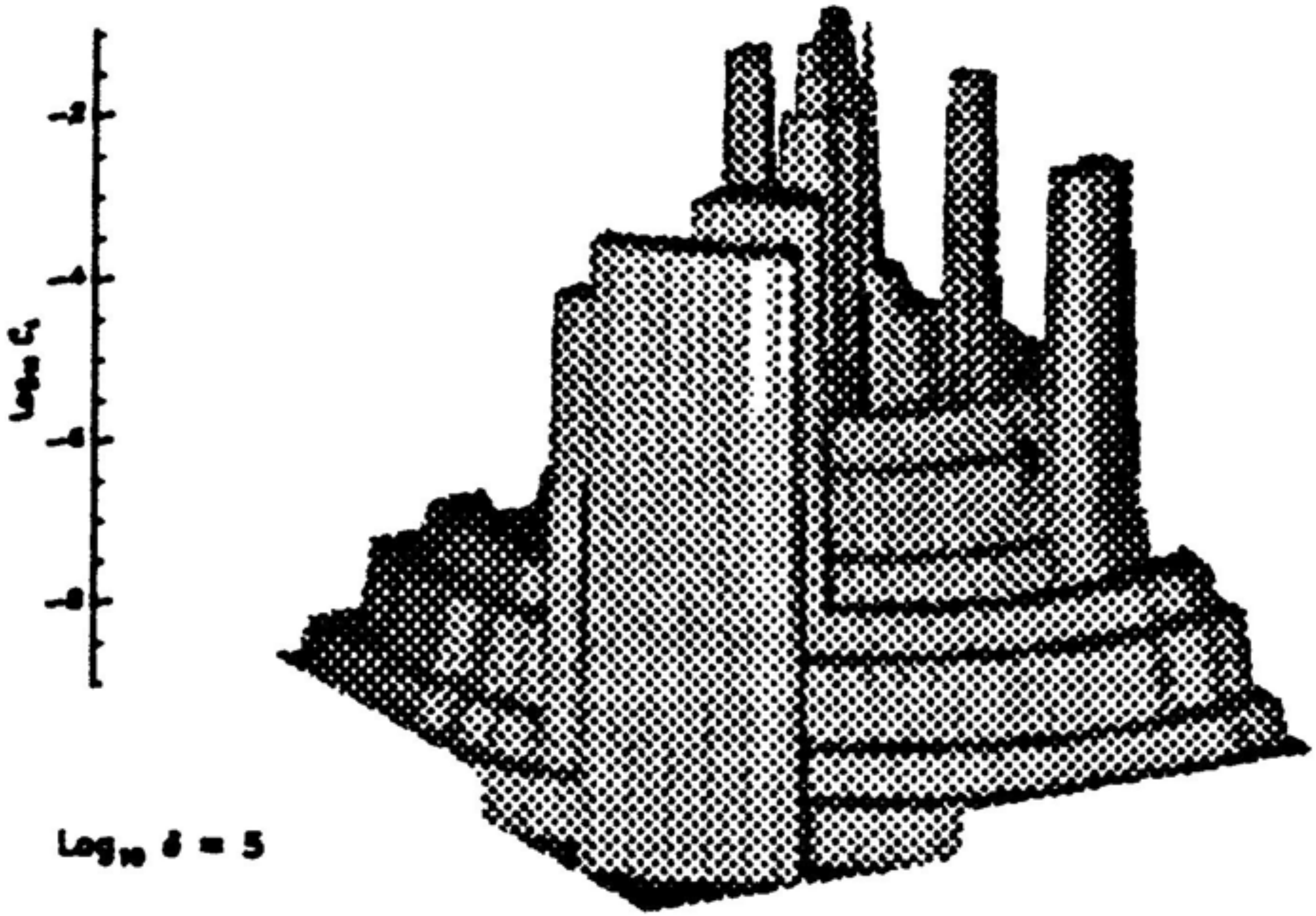

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Spontaneous emergence of an evolving metabolism (with R. Bagley, W. Fontana)

- Set of specific chemical species
- Capable of "digesting" many possible food sets
- Composition of of species evolves through time under random variation and selection.
- Metadynamic model generates network through dynamics of components of network.

How can we achieve sustainability?

- GDP grows exponentially
  - developing countries are increasing their standard of living
- Fortunately, GDP is also "dematerializing"
- With constant population, for sustainability rate of growth of GDP must be slower than rate of dematerialization.
- Need to selectively encourage rewiring of economy to make this happen.

Rebooting the economy?

- Suppose all technology were destroyed
  - Library with all explicit knowledge remains
  - All tacit knowledge remains (100M technicians?)
  - Century supply of freeze dried food
- Could we reboot the economy?
- How would we do it?

Economy is strongly autopoetic

Technology giveth, and technology taketh away

- Complex systems engineering is more like gardening than traditional engineering.

The noosphere is our garden, we must tend it.

Last Sander question

Did being a scientist change your view of the world in general, and in what sense?

Technological progress gives us a hint about purpose

- Aristotle's four types of causation
  - material
  - formal
  - efficient
  - final (telos)
- Telos is not primary, it is an emergent property of the world, driven by the nonlinear feedback of reproduction