Short Course: Exploring Complexity in Social Systems and Economics
January 5 – January 7, 2016

Technological Change: An Evolutionary Process?

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What is *technological change?*

Technological change is the story of how we create and transform the world around us. How we go from:

Children in the Philippines scavenging for recyclable materials

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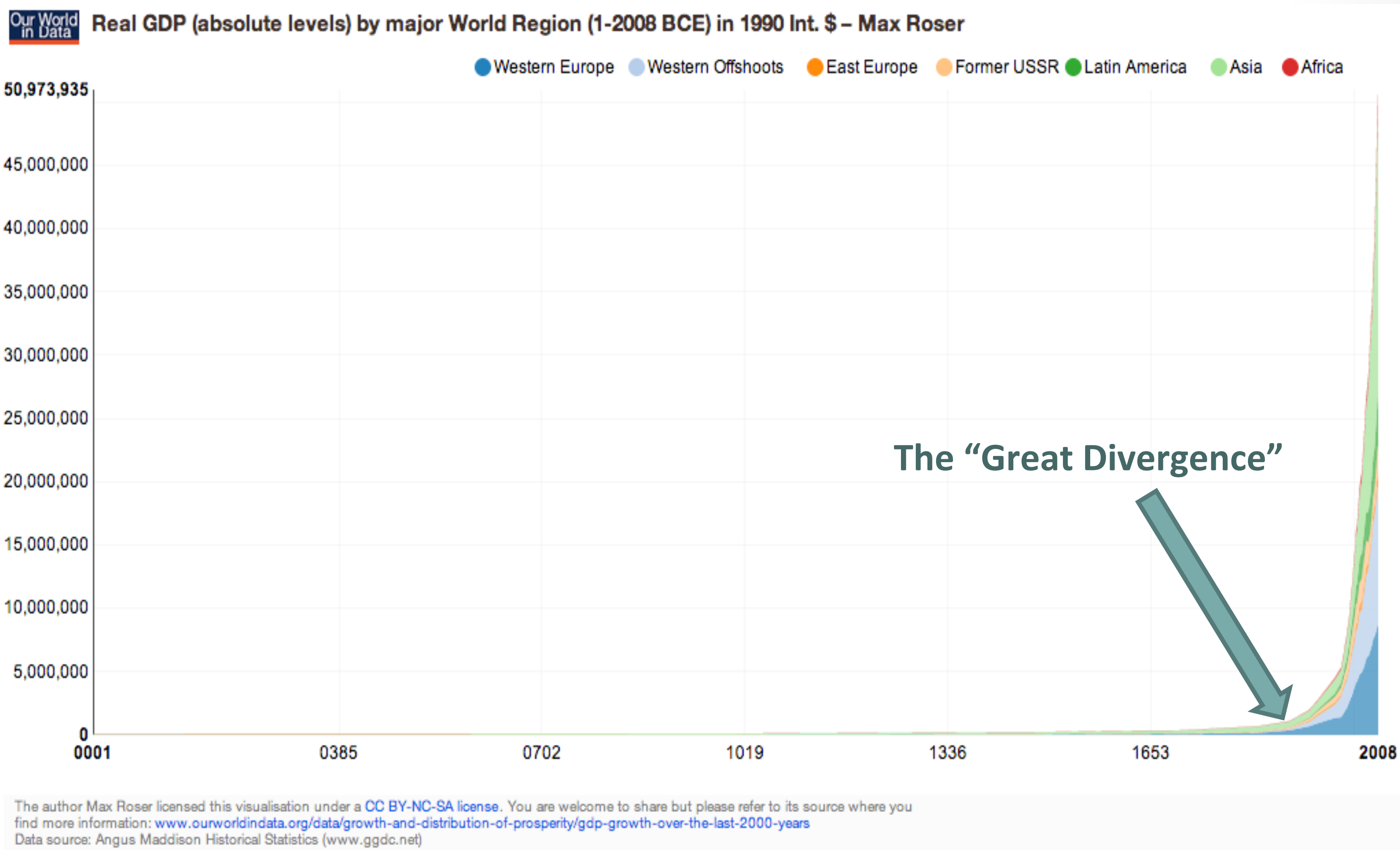
Modern "Directed" Technological Change

When think of *"technological change"* we picture the application of science to the process of invention, but this is a very recent phenomena in human history.



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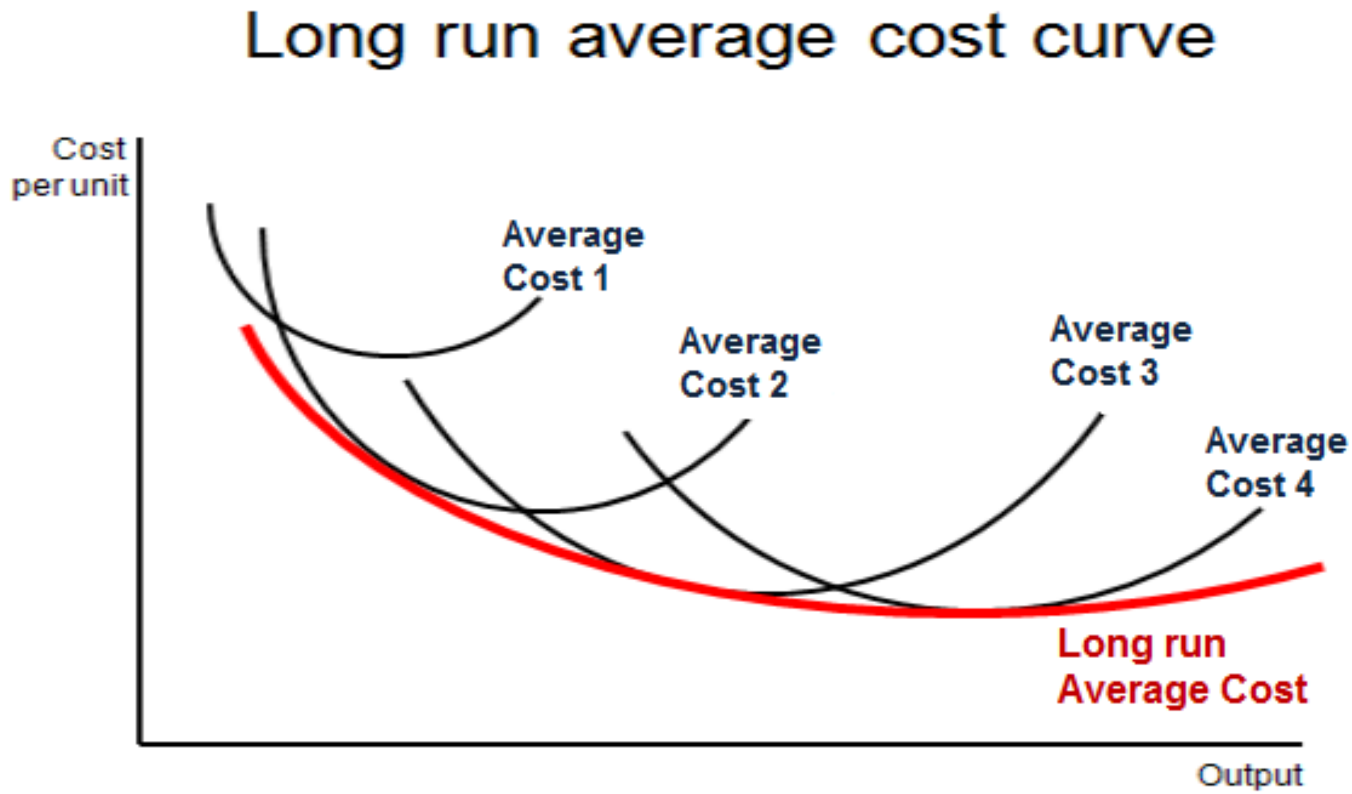
The Neoclassical framework.



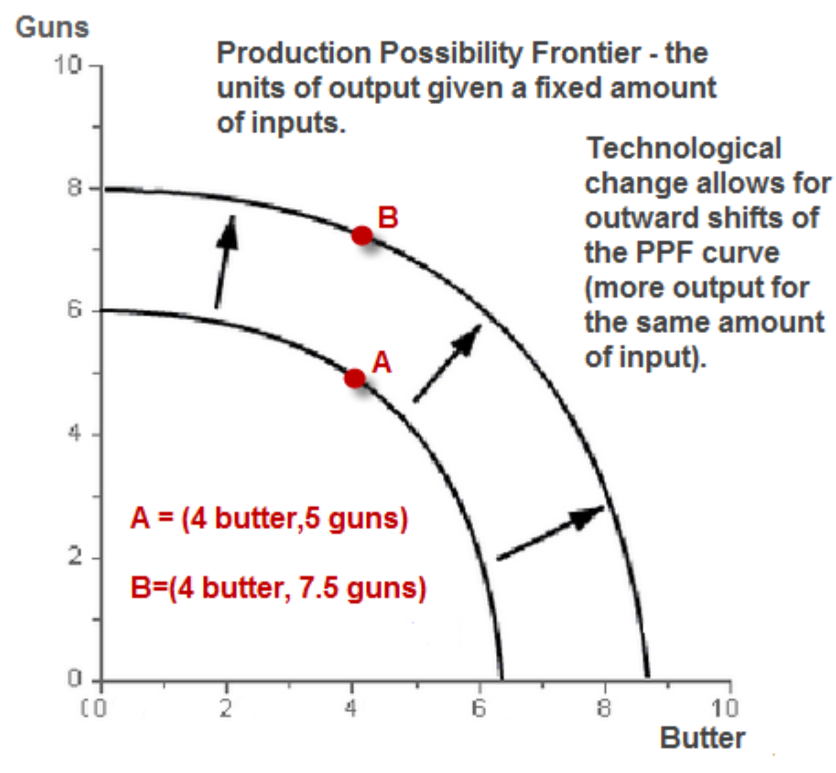
Sophisticated economic models have existed for decades to understand the role of technological change in the economy.
The Neoclassical approach optimizes the investment decision for the firm for both the short run and long run.

Production Possibility Frontier

T(Y, I, t) ≤ 0

Where Y = f(K, L, E; t)

- Y a vector of outputs
- I represents a vector of inputs
- E is a composite of K & L augmenting inputs
- t is time

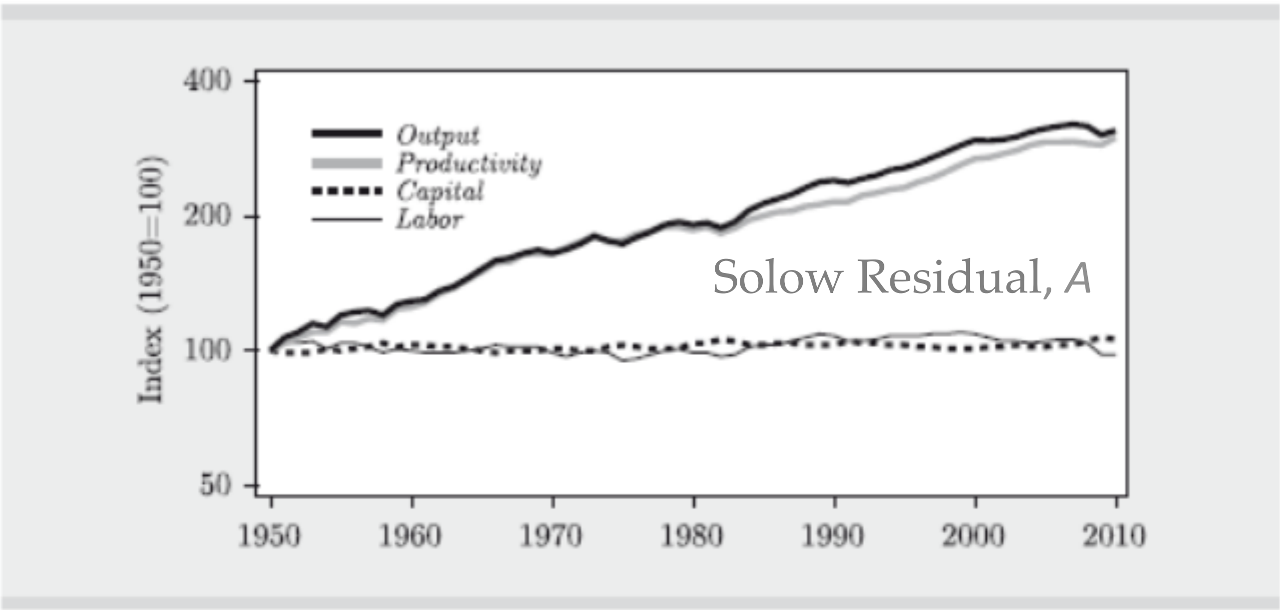


- Technological change modeled as the outward movement of the *Production Possibility Frontier*, illustrates the change in the productive capacity of an economy when new technology becomes available or economically feasible.

New Growth Theory

$$Y(t) = BK(t)^{\alpha} L(t)^{1-\alpha} \longrightarrow Y(t) = A(t)\,BK(t)^{\alpha} L(t)^{1-\alpha},$$

Growth accounting for the United States



Even, New Growth Theory, with its great contribution of modeling endogenous technological change, suffered from an incorrect central prediction in which GDP growth is a function of the stock of ideas, which must be proportional to the population. However, what we observe are increases in economic growth, increases in the rate of innovation, and slowing population growth.

Romer, Paul (1986) "Increasing Returns and Long-Run Growth". *The Journal of Political Economy*, Vol. 94, No. 5, pp. 1002-1037.

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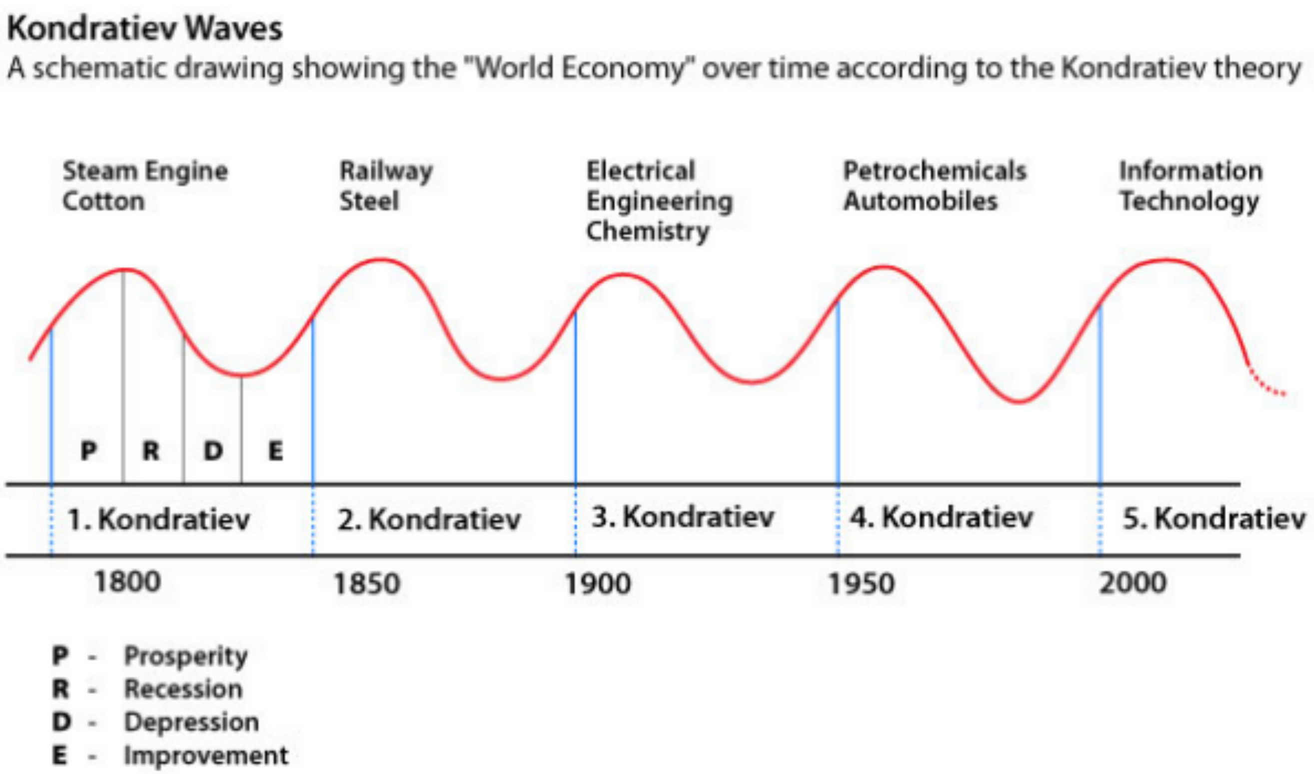
Schumpeter – Creative Destruction

Economic theories of the process of technological change can be traced back to the ideas of Nikolai Kondratiev (1922) and Josef Schumpeter (1942).

They hypothesized technological change was the cause of business cycles, Kondratiev through periodic waves and Schumpeter through a process of continuous creative destruction.



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Problem?

- Technological change is treated as an exogenous shock, with the exception of New Growth Theory (even New Growth Theory's causal relationship is highly abstract).
- The models were designed to inform economic decision making on the part of the an agent or the firm, and do not *explain* technological change.

All of them treat technology is a big black box!

Rosenberg, Nathan (1983) *Inside the Black Box: Technology and Economics*.
Rosenberg, Nathan (1994) *Exploring the Black Box: Technology, Economics, and History*

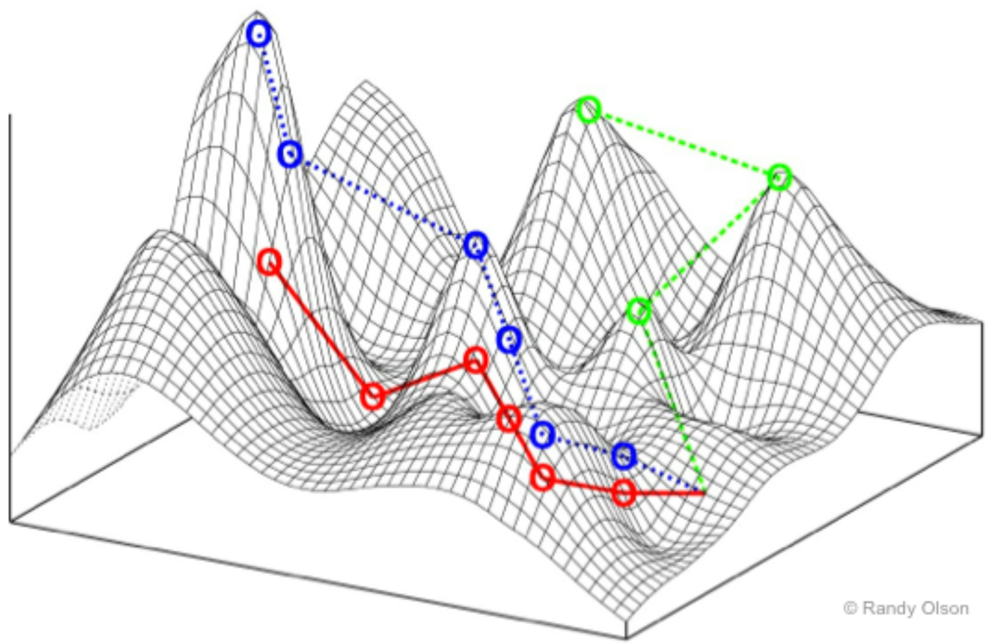
Complex System: Search Theory meets NK Landscapes

Since the 1960's technological change was modelled as a probabilistic search by sampling from a fixed population of possibilities.

Nelson and Winter's 1982 text was a watershed moment for evolutionary models in economics.

The marriage of evolutionary economics and search theory recognized that a firm's search for technological improvements is affected by:

1) The "properties of the search space"
2) The location of the searcher in that space.
3) How good the agent is at searching (aka. the "search strategy")



Richard Nelson and Sidney Winter (1982) An Evolutionary Theory of Economic Change

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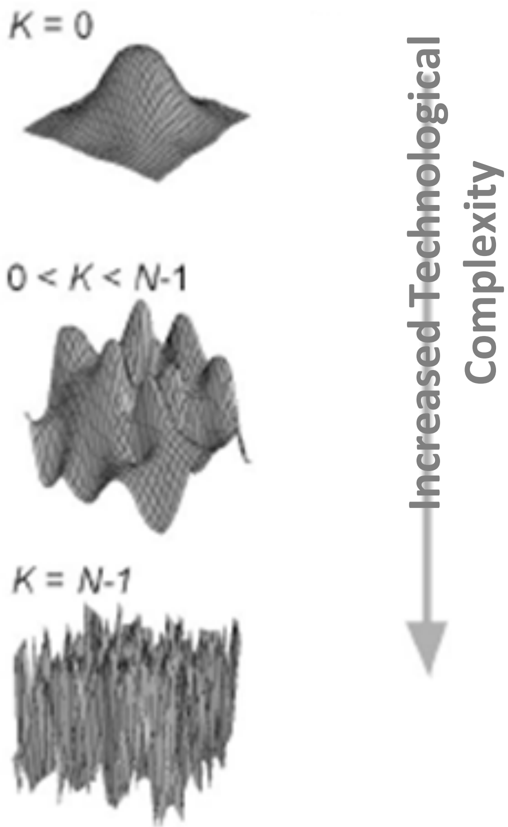
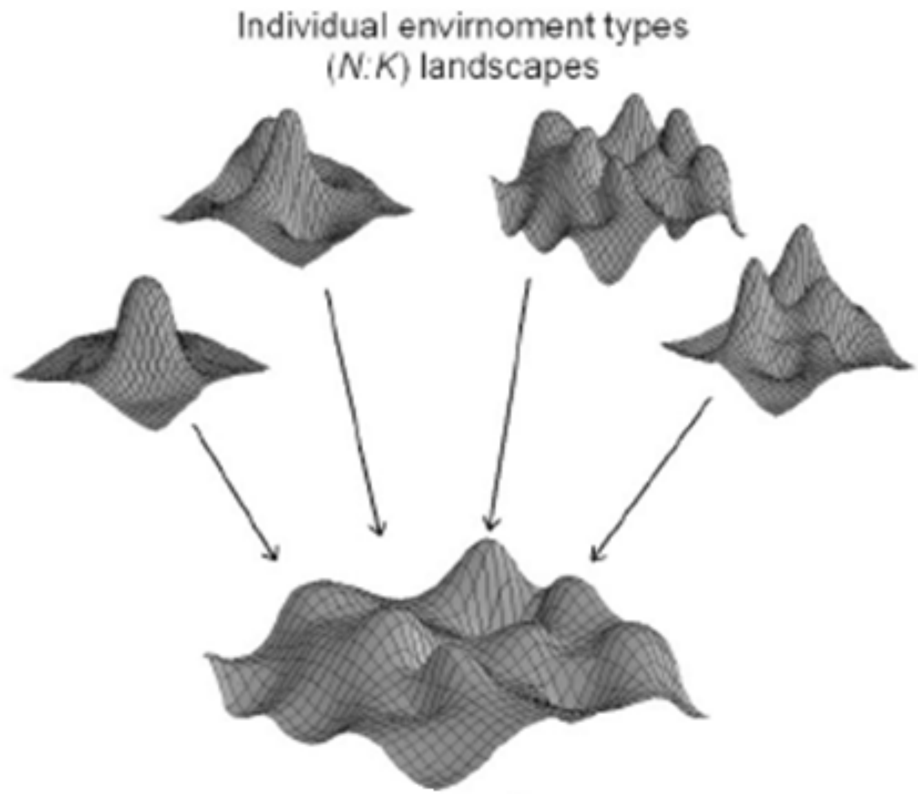
Complex System: Search Theory meets NK Landscapes

NK Landscape models (and earlier "spin glass" models) had been used in biological modeling and physics for decades. NK Landscapes allowed the modeler to "tune" the model to reflect the difficulty of the search problem. The "*tunable ruggedness*" of the NK Landscape framework was a significant advancement. Perhaps more important, NK models invoked "*production recipes*" as a way to open the black box of technological change.





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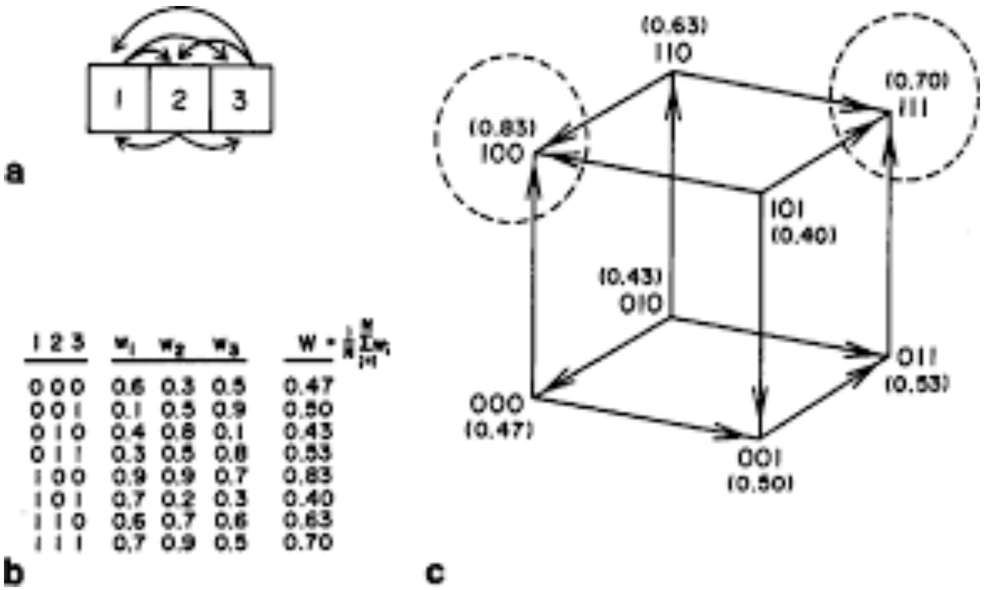
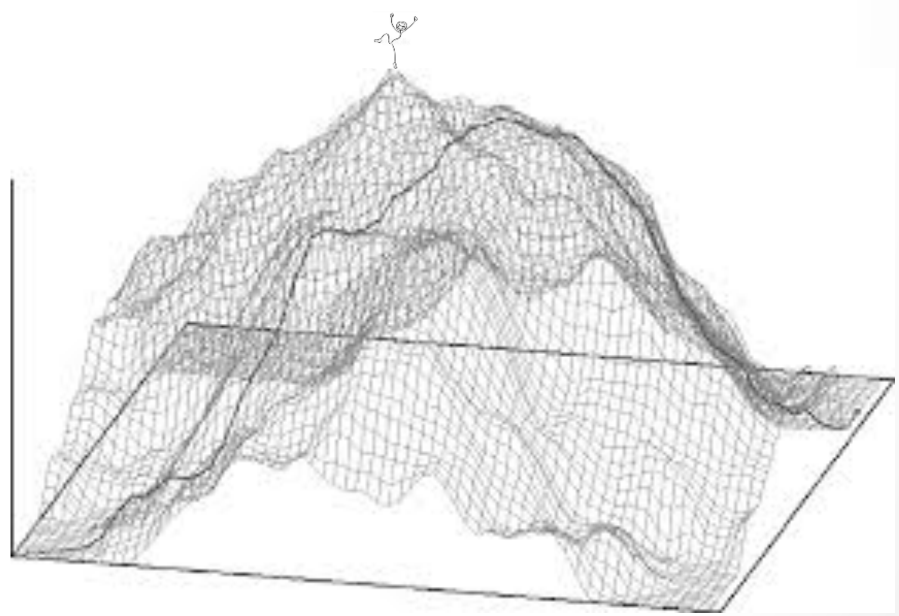
NK Landscapes – a stochastic combinatorial search problem



1 2 3	w_1	w_2	w_3	$W = \frac{1}{N}\sum_{i=1}^{N} w_i$
0 0 0	0.6	0.3	0.5	0.47
0 0 1	0.1	0.5	0.9	0.50
0 1 0	0.4	0.8	0.1	0.43
0 1 1	0.3	0.5	0.8	0.53
1 0 0	0.9	0.9	0.7	0.83
1 0 1	0.7	0.2	0.3	0.40
1 1 0	0.6	0.7	0.6	0.63
1 1 1	0.7	0.9	0.5	0.70

An NK Landscape is basically a hypercube with a fitness or payoff function. The hypercube includes all the possible ways to produce some good. While this may look simple these are extraordinarily large, high dimensional search spaces.

When a fitness function is applied the search is often portrayed as a surface, akin to a physical landscape, with a searcher trying to climb to the highest fitness peak.



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What we learned from NK

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NK Landscape models we wonderful, because we were able to replication of well known findings from empirical and theoretical literature, such as:

- diminishing marginal returns to search
- the existence of reservation prices for search
- the generation of learning curves

We gained a few new insights, for example:

- Depending on the structure of the search space, firms can easily get stuck without ever finding the optimal variant of their technology, and no amount of the same investment in R&D would allow them to identify the optima.
- There is an optimal search distance at which firms should search based on the correlation structure of the landscape.
  - In a smooth, highly correlated landscape (ρ=0.9) large jumps (bigger riskier projects) are more likely to increase profits.
  - If the landscape is rugged and correlation is low, then all search distances are equivalent, there is no topological information to exploit, thus cautious, incremental, low risk projects are better.
- Despite all this information we were still left asking:

Search where? Jump to what?

Exactly what technology are they talking about!

Literature on Landscapes

- **The Origins of Order: Self Organization and Selection in Evolution,** Stuart A. Kauffman (1993). http://www.amazon.com/Origins-Order-Self-Organization-Selection-Evolution/dp/0195079515/ref=sr_1_1?ie=UTF8&qid=1440790572&sr=8-1&keywords=origins+of+order
- **"Technological evolution and adaptive organizations: Ideas from biology may find applications in economics"** Stuart Kauffman and William Macready, Complexity. http://onlinelibrary.wiley.com/doi/10.1002/cplx.6130010208/abstract"
- "**Navigating the Technology Landscape of Innovation**" Lee Fleming and Olav Sorenson. (2003) MIT Sloan Management Review, Vol. 44, No. 2, pages 15-24
- "**Manufacturing strategy: understanding the fitness landscape**", Ian P. McCarthy, (2004) *International Journal of Operations & Production Management*, Vol. 24, No. 2, pages 124 – 150. http://www.emeraldinsight.com/doi/abs/10.1108/01443570410514858
- "**Organizational sticking points on NK Landscapes**" Jan W. Rivkin and Nicolaj Siggelkow, *Complexity*, Volume 7, Issue 5, pages 31–43, May/June 2002. http://onlinelibrary.wiley.com/doi/10.1002/cplx.10037/abstract
- "**Strategy-making in novel and complex worlds: The power of analogy**" Giovanni Gavetti, Dan Levinthal, Jan W. Rivkin, (2005) Strategic Management Journal, Volume 26, pages 691 – 712. http://www.researchgate.net/profile/Daniel_Levinthal/publication/227658558_Strategy_making_in_novel_and_complex_worlds_the_power_of_analogy/links/0fcfd5142b6a7a8ca7000000.pdf

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Become this?

Where are we now?

Let's start with 2 important points:

Technological change is a product human activity.

New Growth Theory is a good reminder that technologies do not invent themselves. New technologies are the result of human social processes, and the relationship between human activity, technological change and economic growth is not simple.

Invention is a combinatorial process.

NK Landscape models and the production recipe approach brought us tantalizingly close to actual materials and processes that people and firms actually use and how those technologies are related to one another. Still, we need a technique that is less theoretical, a model where it is easier/possible to invokes real technologies and how those technologies interact.

Asking this…

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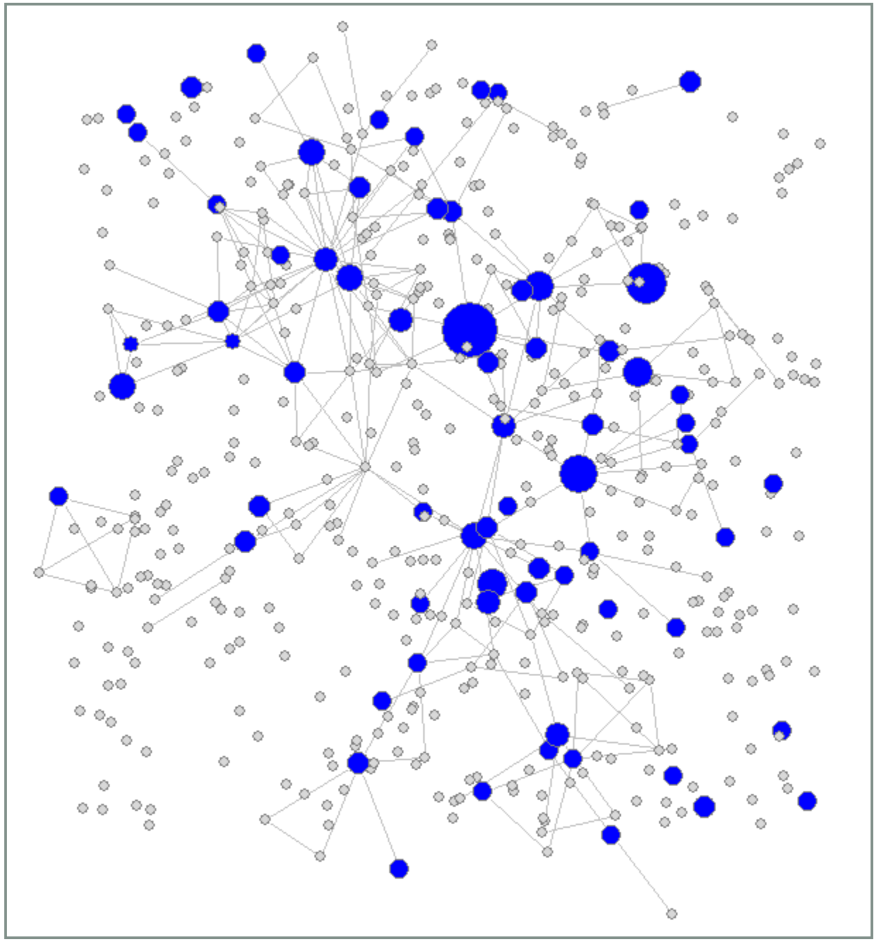
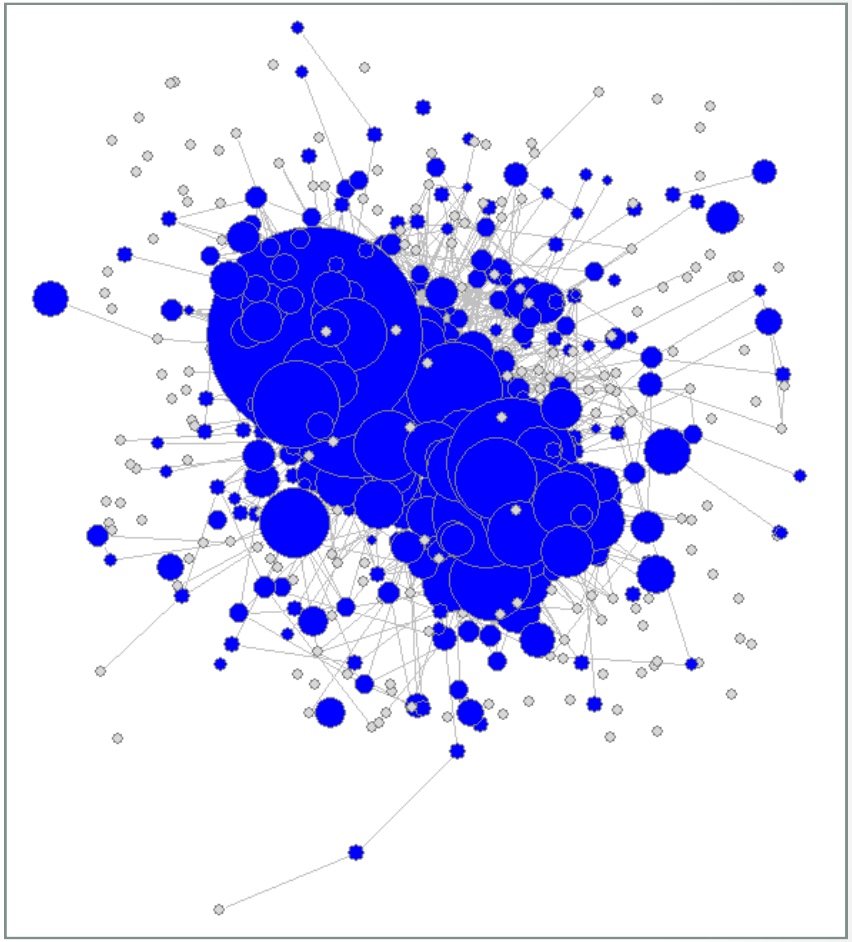
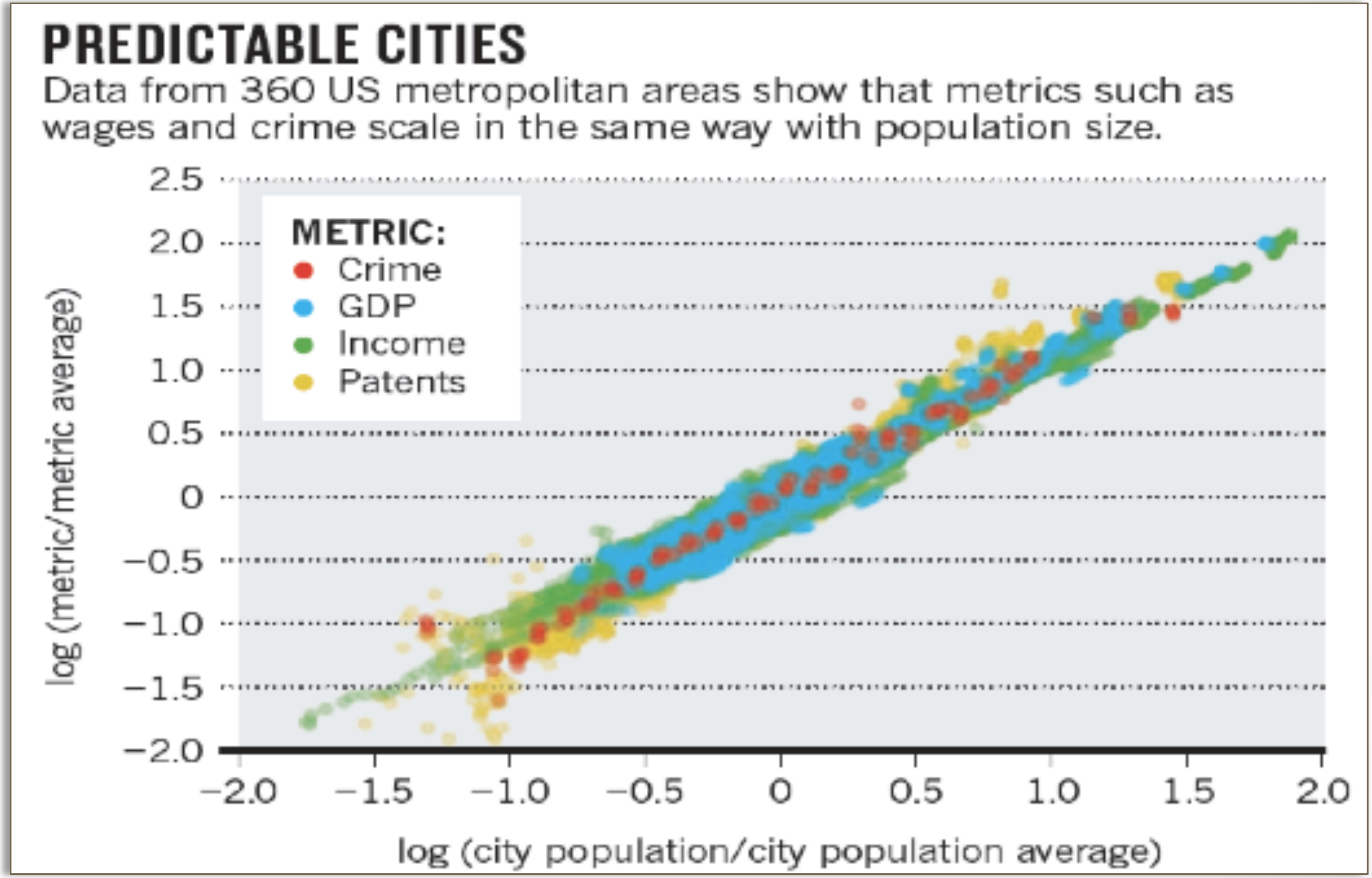
Is equivalent to asking how the network on the left becomes the network on the right….



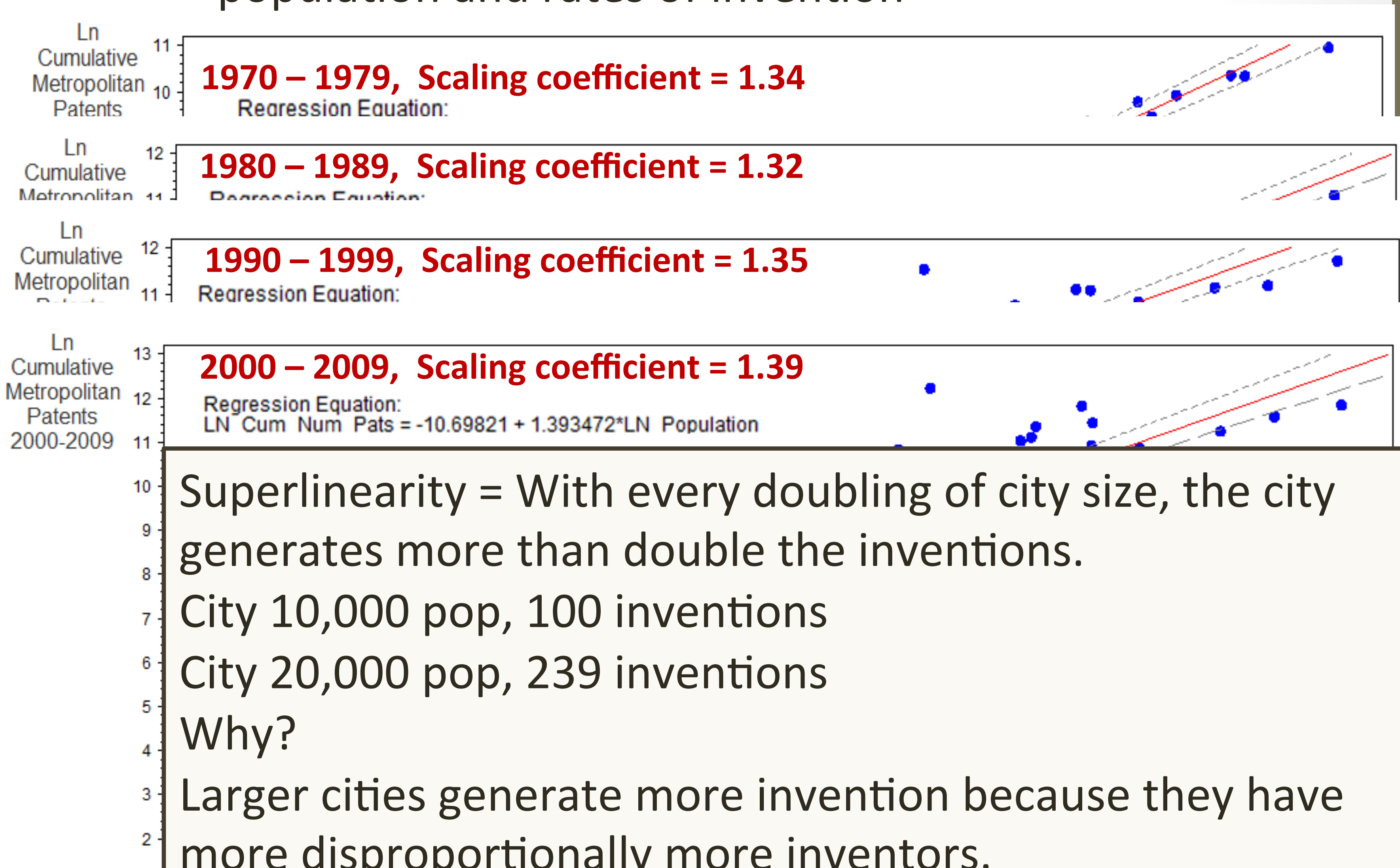


That process begins with Urban Scaling

- The lesson from urban scaling is that the larger the city the disproportionately more that city gets of the good stuff and the bad.



Consider the simple scaling relationship between population and rates of invention



Superlinearity = With every doubling of city size, the city generates more than double the inventions.

City 10,000 pop, 100 inventions

City 20,000 pop, 239 inventions

Why?

Larger cities generate more invention because they have more disproportionally more inventors.

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We already learned from growth theory that "stocks of knowledge" and pure counts of people are not sufficient to explain technological change and economic growth.

The claim that larger cities have more inventions and more people can not be the explain why the superlinearity occurs…

Are inventions in larger cities different?

Are inventors in larger cities different?

Are all inventions created equal?
Or does invention come in flavors?

The first cellular phone

New operating system for mobile devices

First cell phone with a camera

Origination

Novel Combination

Combination

Refinement

Taxonomy of Invention

W. Brian Arthur (2009) “The Nature of Technology: What it Is and How it Evolves”

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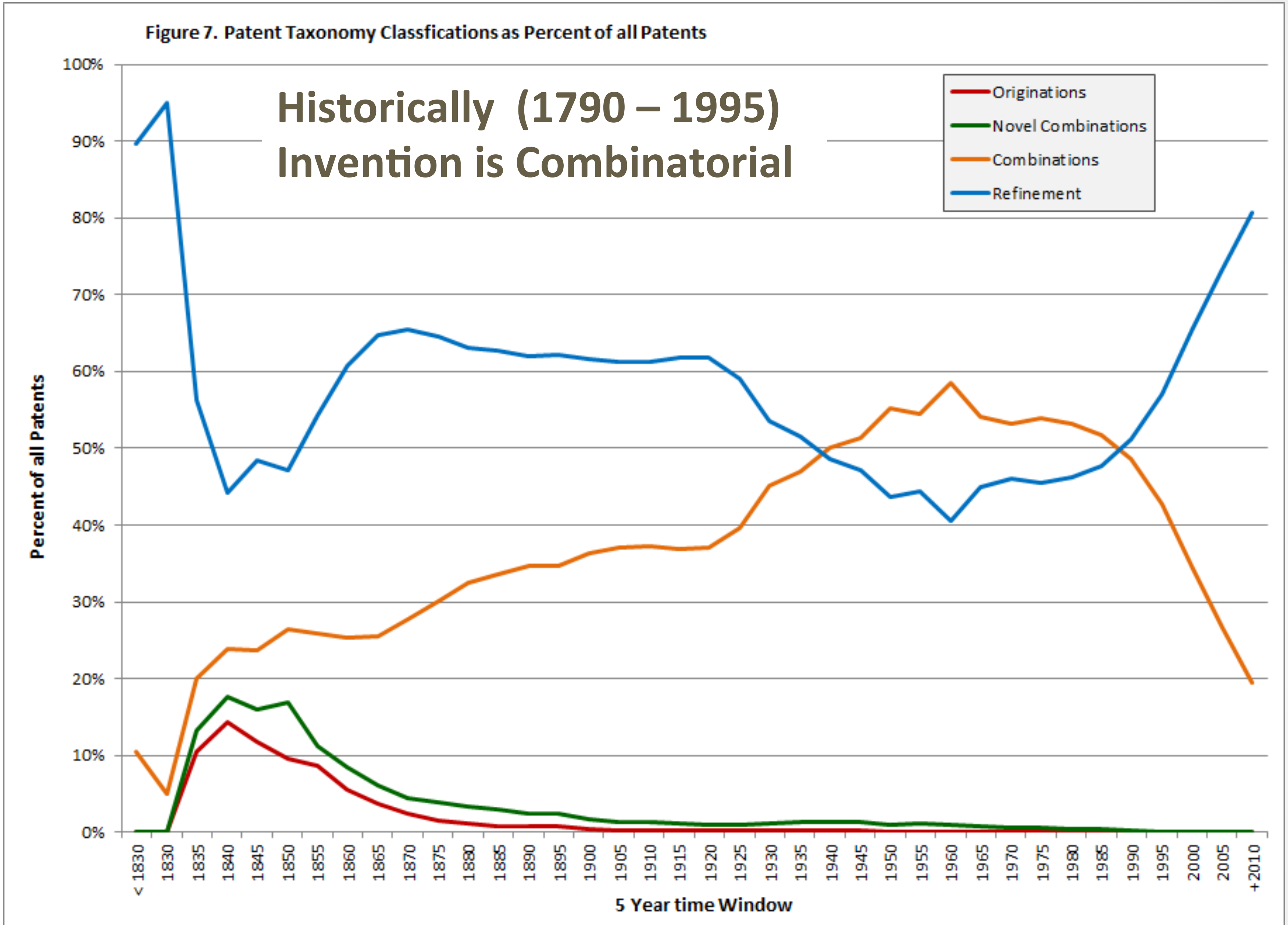

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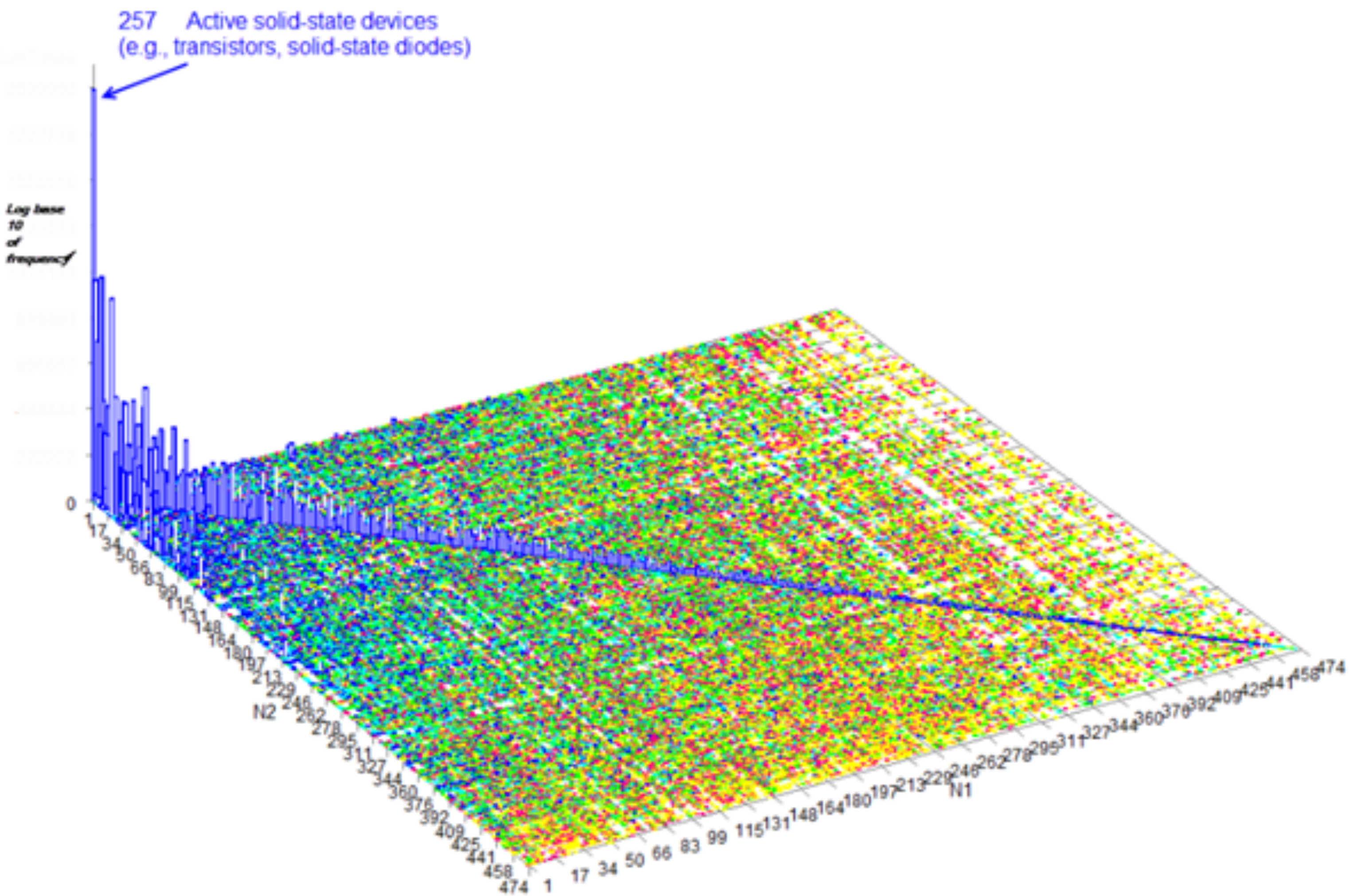
When a new technology is born (an origination or novel combination),
it is available to combine with all the existing technologies already in existence.

This is the process of selection.

Those technologies that are selected for combine often.



A typical patent

United States Patent **6,637,349**
Lafferty **October 28, 2003**

Motorized picnic table

Abstract

A motorized picnic table having a drive mechanism, wheels connected to and driven by the drive mechanism, a table mounted above the drive mechanism, and at least one seat adjacent the table. In the preferred embodiment, the seats are bench-type seats and flank the drive mechanism. The motorized table includes fenders covering at least a portion of the wheels to protect the feet and legs of picnickers using the table from the wheels when the table is in motion. A foot platform is provided for picnickers to rest their feet upon. The table has a roof and a roof mounting frame for mounting said roof above said table. The roof may be removable. The motorized table has open sides. The motorized table includes a steering mechanism wherein the steering mechanism can be operated by a picnicker seated on one of the seats. In the preferred embodiment, the steering mechanism extends through an aperture in the picnic table. The drive mechanism has a hydrostatic transmission. The operating control for the hydrostatic transmission may be provided with a biasing mechanism for biasing the control in a neutral position when not actively engaged by the operator.

Inventors: **Lafferty; Gregory A.** (Plymouth, IN)
Family ID: **29251384**
Appl. No.: **09/644,598**
Filed: **August 23, 2000**

Current U.S. Class: **108/20**; 180/305; 280/30; 296/22

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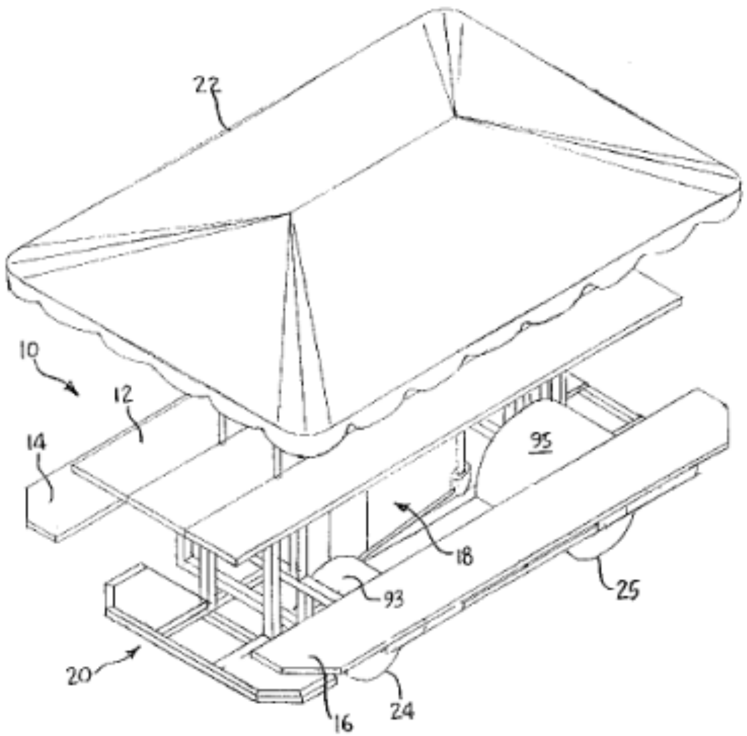
Motorized Picnic Table



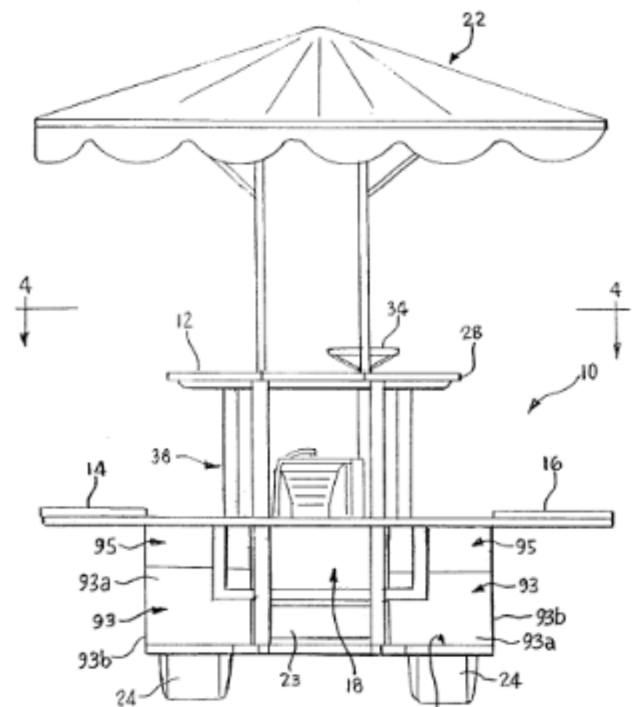


FIG.3

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United States Patent	**6,637,349**
Lafferty	**October 28, 2003**

Motorized picnic table

Current U.S. Class:	**108/20**; 180/305; 280/30; 296/22

Class 108 HORIZONTALLY SUPPORTED PLANAR SURFACES

- A P 20 POWER DRIVEN

Class 180 MOTOR VEHICLES

A P 305 · Including traction motor of kind driven by noncompressible fluid received under pressure from a pump

Class 280 LAND VEHICLES

A P 30 · Convertible

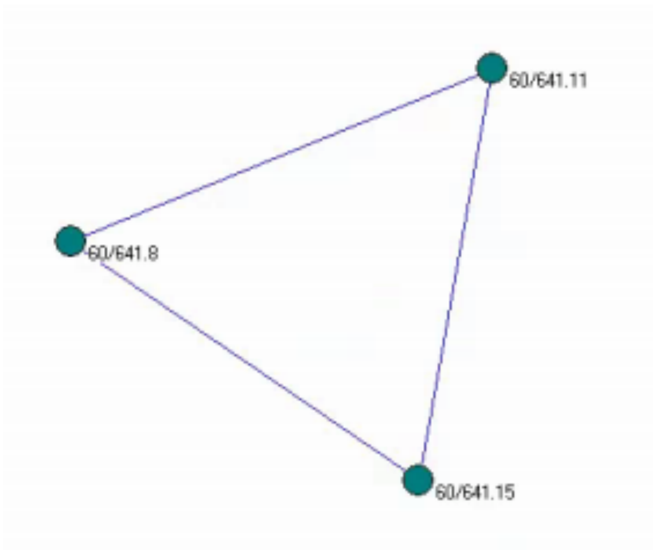
Class 296 LAND VEHICLES: BODIES AND TOPS

A P 22 · Lunch wagons

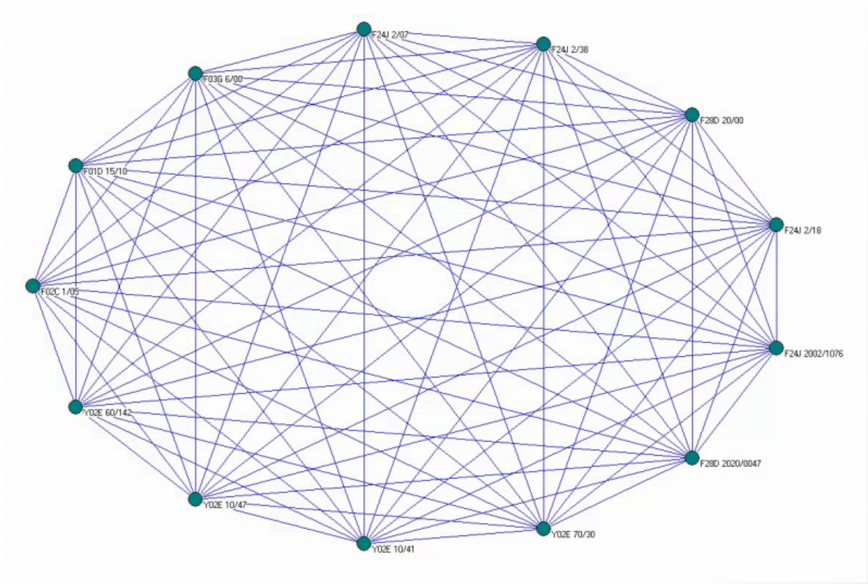
Technology graphs

- Each node is a single technology
- An edge connects 2 nodes when two technology codes appear on the same patent.

60/641.8; 60/641.11; 60/641.15



F02C 1/05; F01D 15/10; F03G 6/00; F24J 2/07; F24J 2/38; F28D 20/00; F24J 2/18; F24J 2002/1076; F28D 2020/0047; Y02E 70/30; Y02E 10/41; Y02E 10/47; Y02E 60/142



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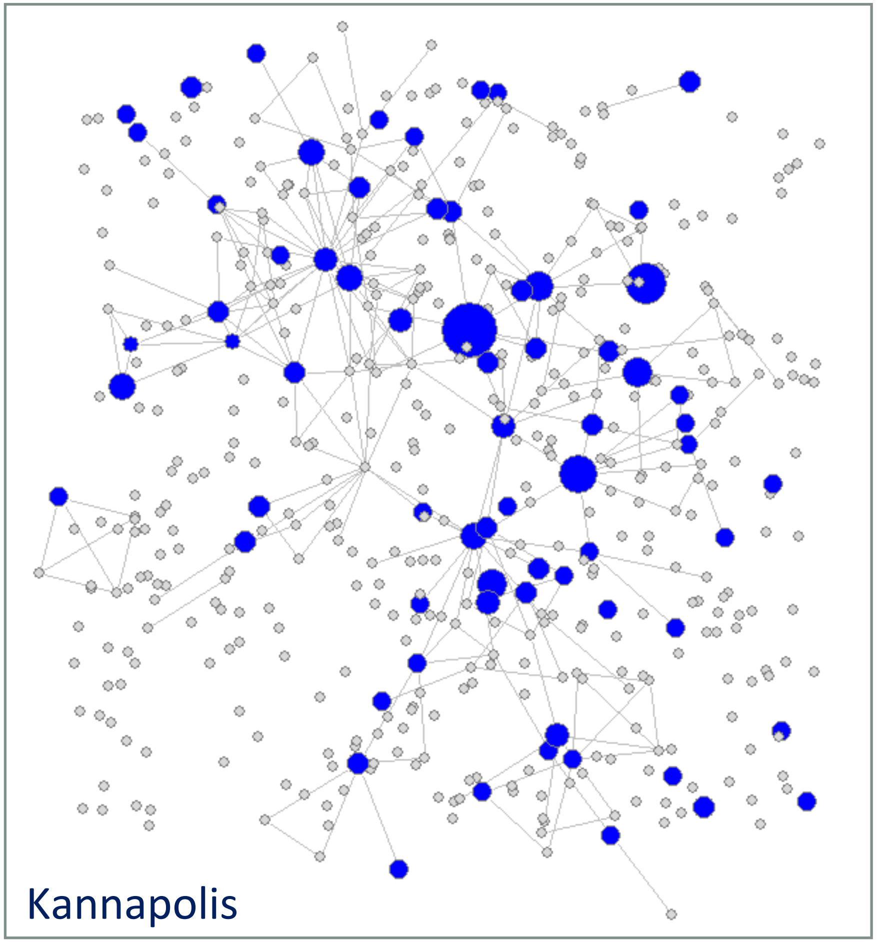
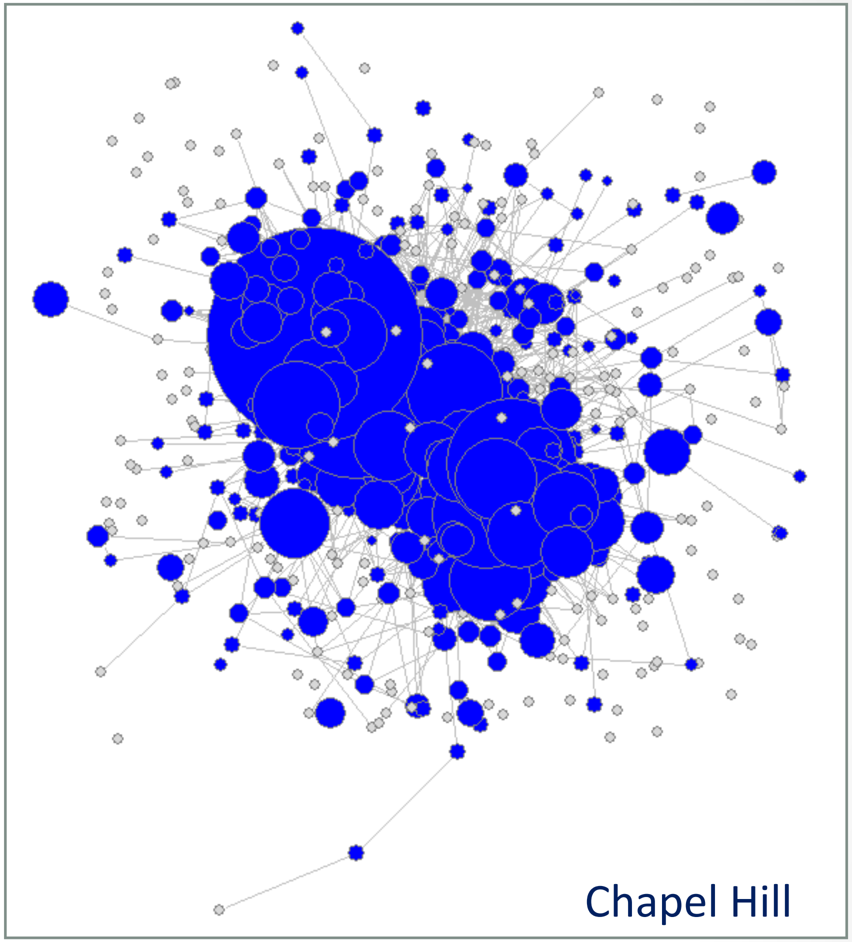
Technology Graphs (2000 – 2005)

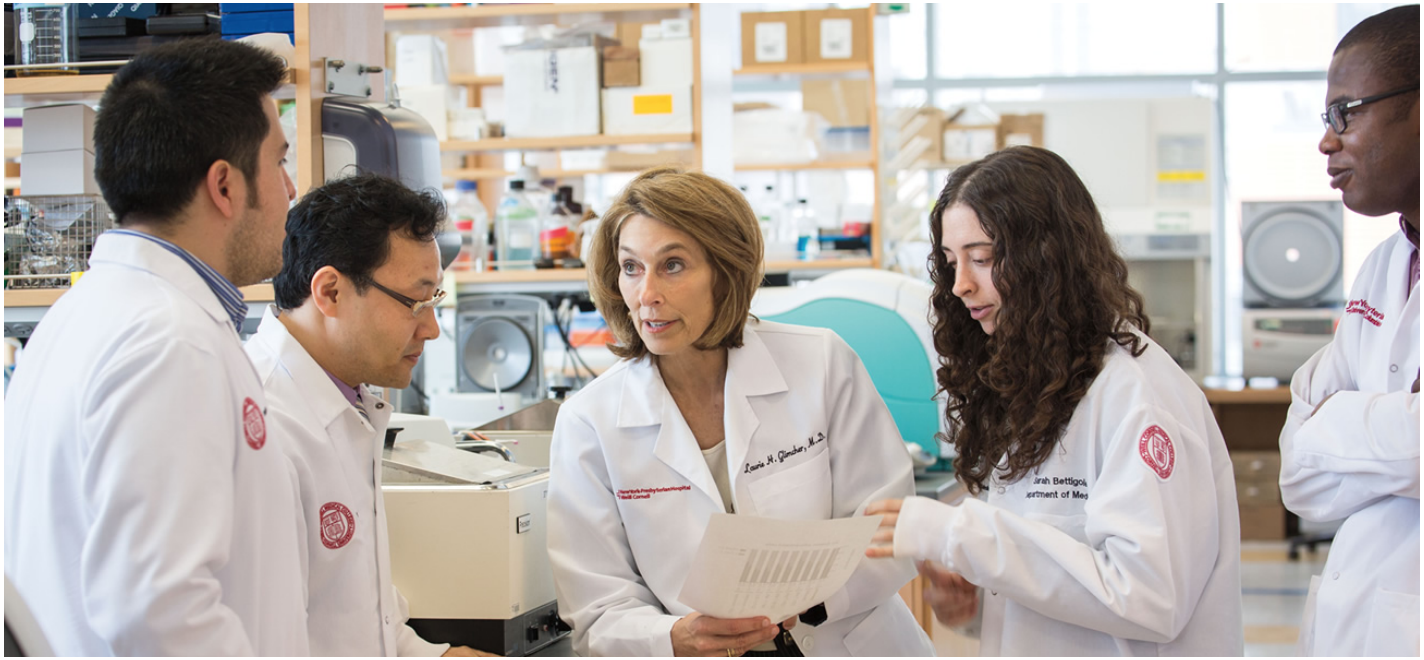




Chapel Hill covers a much larger portion of the technology space, so almost all technologies are "nearby" and the technologies are connected by edges demonstrating Chapel Hill is very successful at combinatorial invention. Kannapolis most technologies are not nearby, occupies less of the technology space, most nodes are not connected, so most technologies are very far away.

Remind ourselves:

- Invention occurs in place
- Technologies are representations of the skill sets of the people that invent them.



Source: Scientists from Weill Cornell Medical College

So, how is this even possible?

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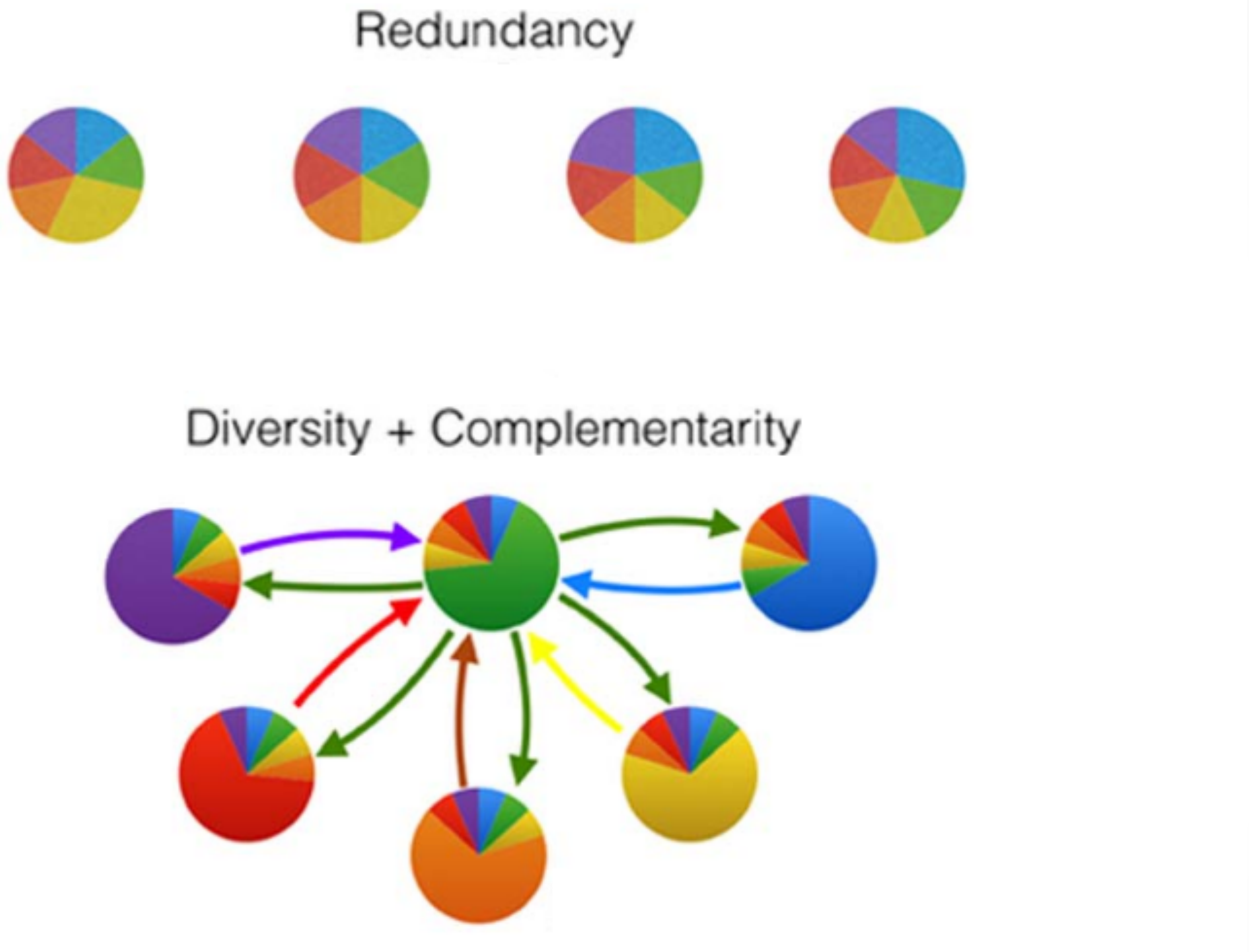

Source: Bettencourt (2014) "Impact of changing technology on the evolution of complex informational networks", Proceedings of the IEEE.

Exotic Dishes in NYC

What: Live Octopus

Where: Sik Gaek

What: Kangaroo Loin

Where: Burke and Wills

What: Chapulines Taco

(Toasted Grasshopper Tacos)

Where: Toloache

What: Pickled Raw Mussels

Where: Take Root

What: Pez Globo

(Crispy Moroccan Blowfish Tails)

Where: Toro

What: Smoked Whole Neck of Goat

Where: Ducks Eatery

What: Foie Gras Doughnuts

Where: Do or Dine

Exotic Dishes in NYC

What: Zillion Dollar Lobster Frittata

(which boasts 10 ounces of caviar

and a $1,000 price tag)

Where: Norma’s

What: Huarache de Nopal

(Cactus Mushroom Stew)

Where: The Black Ant

What: Extra Virgin Olive Oil Ice Cream:

Where: Oddfellows

Wiscasset is charming.
Wiscasset is not culinary center of innovation.
Wiscasset will not transform how or what we eat.

Conclusion: Technologies as Capabilities

Underlying each invention is a team of inventors, as such technologies are actually proxies for human skills sets.

Larger cities do not just get more inventors, they get more KINDS of inventors. The diversity of skills make combining technologies (even Toasted Grasshopper Tacos or Crispy Moroccan Blowfish Tails) easier. New combinations are all “nearby” in technology space, because diverse sets of complementary skills are local.

Originations and novel combinations are spatially concentrated in the largest cities, because the greater information content and diversity of knowledge exist in those locations.

Highly novel inventions require that diversity of knowledge to bring them about, and for selection act upon them.

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Relevant Recent Research:

"Identifying the sources of technological novelty in the process of Invention"
Authors: Deborah Strumsky and José Lobo
Research Policy, Volume 44, Issue 8, October 2015, Pages 1445-1461
http://www.sciencedirect.com/science/article/pii/S0048733315000840

"Invention as a combinatorial process: evidence from US patents"
Authors: Hyejin Youn, Deborah Strumsky, Luis M. A. Bettencourt, José Lobo
The Royal Society: Interface, May 2015, Volume: 12 Issue: 106
http://rsif.royalsocietypublishing.org/content/12/106/20150272
MIT Technology Review article about the paper:
http://www.technologyreview.com/view/528436/data-mining-200-years-of-patent-office-records-to-reveal-the-nature-of-invention/

"Impact of changing technology on the evolution of complex informational networks"
Author: Luis M Bettencourt
Proceedings of the IEEE 102 (12), 1878-1891

"Complexity and the productivity of innovation"
Authors: Deborah Strumsky, José Lobo, Joseph A Tainter
Publication Date: September 2001
Journal Systems Research and Behavioral Science Volume 27, Issue 5, Pages 496-509, Publisher: John Wiley & Sons, Ltd.

Thank you for you attention.

Questions and comments welcome!

Technological Evolution: Not just a metaphor

- ***Evolutionary processes*** require a process of selection.
- Selection mandates a measure of fitness.

Fitness

- *n* different *types* of individuals in a population
- The relative frequency of each type is q_i
- Each type has R_i offspring (*R* being reproductive success)
- Average reproductive success $R = \sum q_i R_i$
- Fitness: $w_i = R_i / R$

Here fitness is relative reproductive success.

(Based on the Price Equation Framework)

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V. Technological Evolution: Not just a metaphor

Question: Can a measure of "fitness" be defined for Technologies.

Are there "*offspring*" of a technology?

Perhaps, once a new technology is invented, in how many inventions does it appear in subsequently?

The demand for a new technology seems like a reason measure of fitness.

So, let's assume just for a few minutes we have a correct measure of fitness (i.e. its frequency of use over time), then we can consider the process of selection.

V. Technological Evolution: Not just a metaphor

Selection

Population of replicating units

1. The units expressing a trait vary in their reproductive success.
2. The trait(s) vary among the units of the population.
3. The correlation between the trait and a unit's reproductive success is non-zero.
4. For a response to occur the trait must be heritable.

A very similar alternative statement on selection lists necessary and sufficient conditions as:

1. <u>Variation</u>: differences among individuals
2. <u>Heritability</u>: heritable variation is essential as a mechanism of transmission
3. <u>Differential Reproduction</u>: "success" is measured in terms of the number of copies.

V. Technological Evolution: Not just a metaphor

Under this abstract perspective on selection:

- Selection essentially compares variants within a population.
- Selection is a statistical process: the change in the distribution of a trait within a population.
- Selection is essentially trial-and-error learning
- Selection *is* the source of change, *not* novelty

Important: the appearance of new inventions (instances of novelty) does not allow for technological change, it is only when those inventions are *selected for* that the change takes place.

You can consider this in cases of latency, when a technology is introduced before its time and is not selected for, so the technological change does not take until much later.

Consider the following examples…

What is a technology?

Well established definitions from economic theory:

Technologies: ideas or knowledge about the manipulation of matter, energy or information

Technologies: the application of science and engineering to the development of machines and procedures

US Patent Office

Formal definitions from the US Patent office:

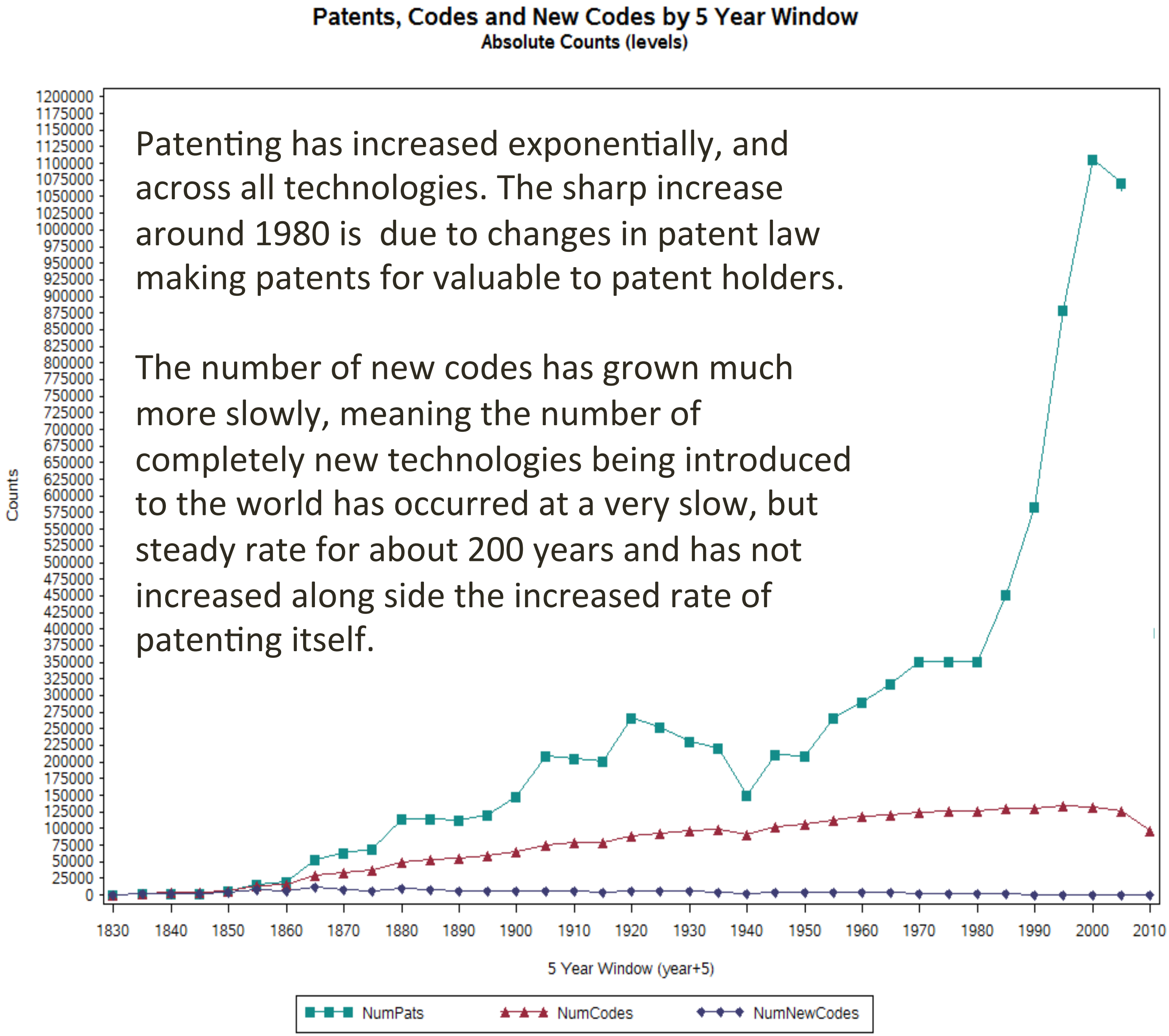
Patented Inventions: new and useful processes, machines, artifacts and compositions (also ornamental designs & plants)

Inventions: unique and novel devices, methods, processes or compositions that represent solutions to technical problems

Technologies: devices, apparatus, processes, methods, compositions, machines, measurement, testing, use of signals, nanotechnology, land vehicles, surgical devices…

Patenting has increased exponentially, and across all technologies. The sharp increase around 1980 is due to changes in patent law making patents for valuable to patent holders.

The number of new codes has grown much more slowly, meaning the number of completely new technologies being introduced to the world has occurred at a very slow, but steady rate for about 200 years and has not increased along side the increased rate of patenting itself.



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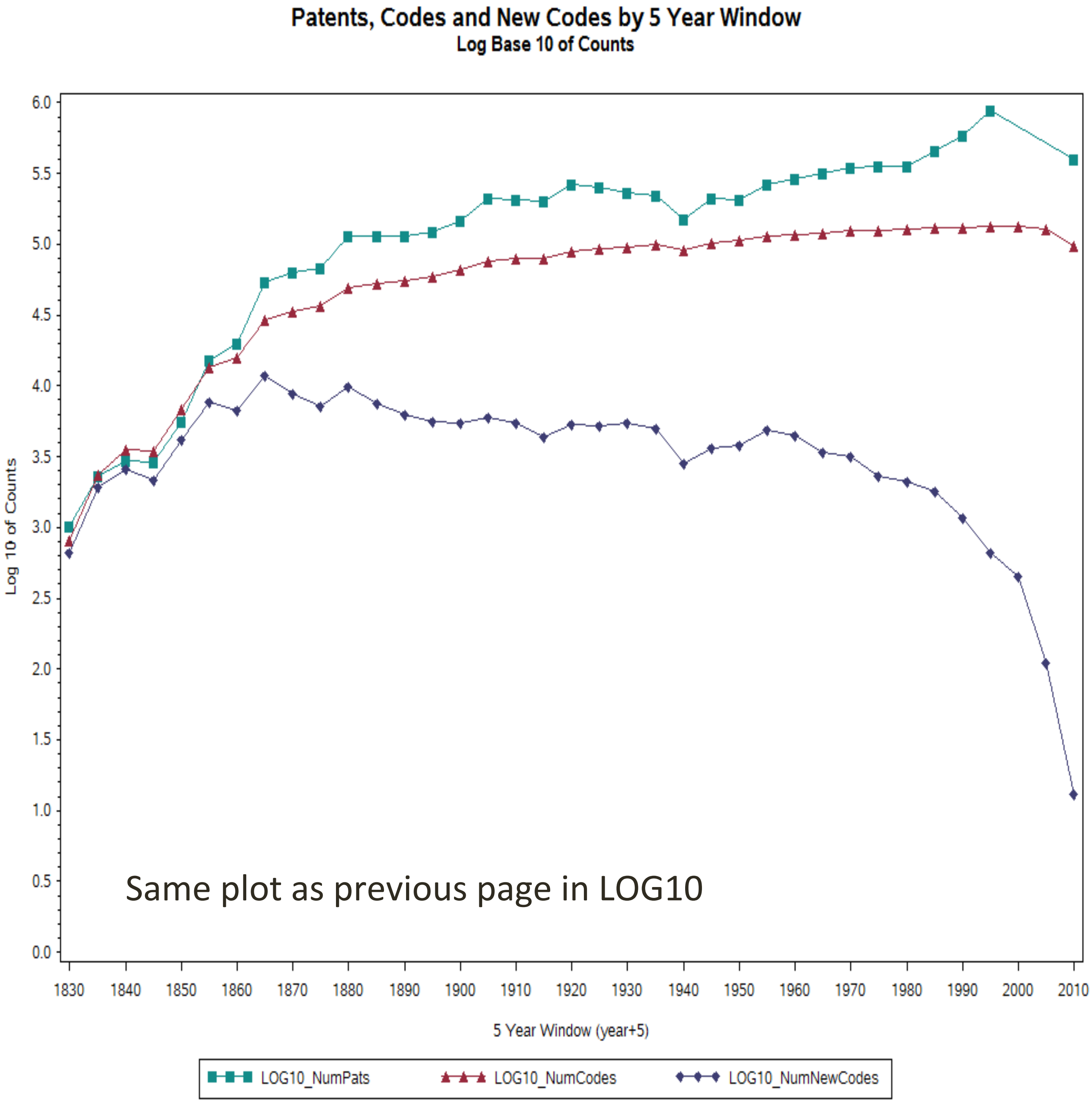


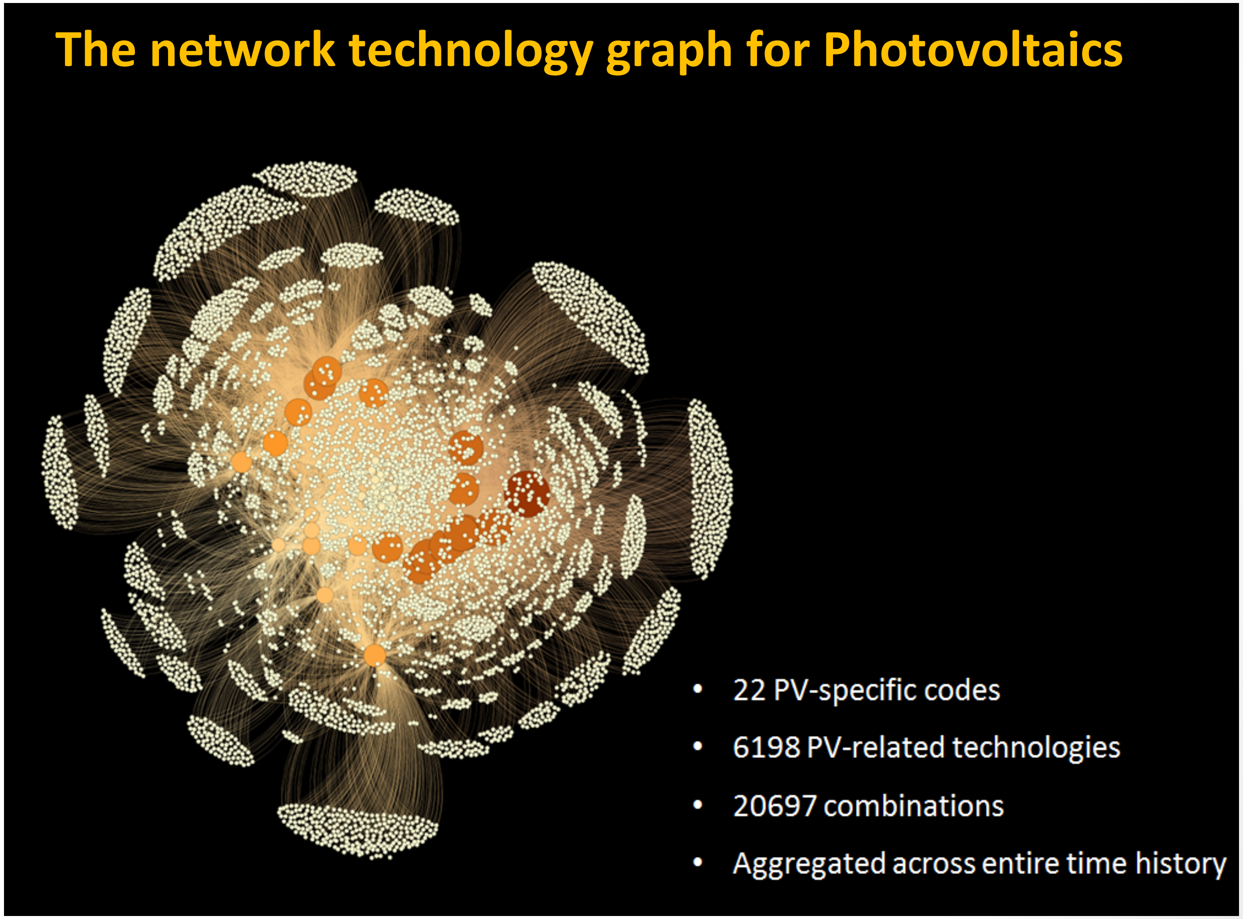
Same plot as previous page in LOG10

Can we define a "Technology Space"

Not mathematically formally…Recall from the NK Model, we would need a distance metric and a fitness or cost function. We are still struggling with the distance metric across technologies. For example, exactly how many units away is my toaster from a cancer drug?

We can define a technology network (technology graph), which is slightly less mathematically formal.

Each "technology" represented as a patent code is a node in the network graph. Network edges are formed when two codes co-occur on a patent.



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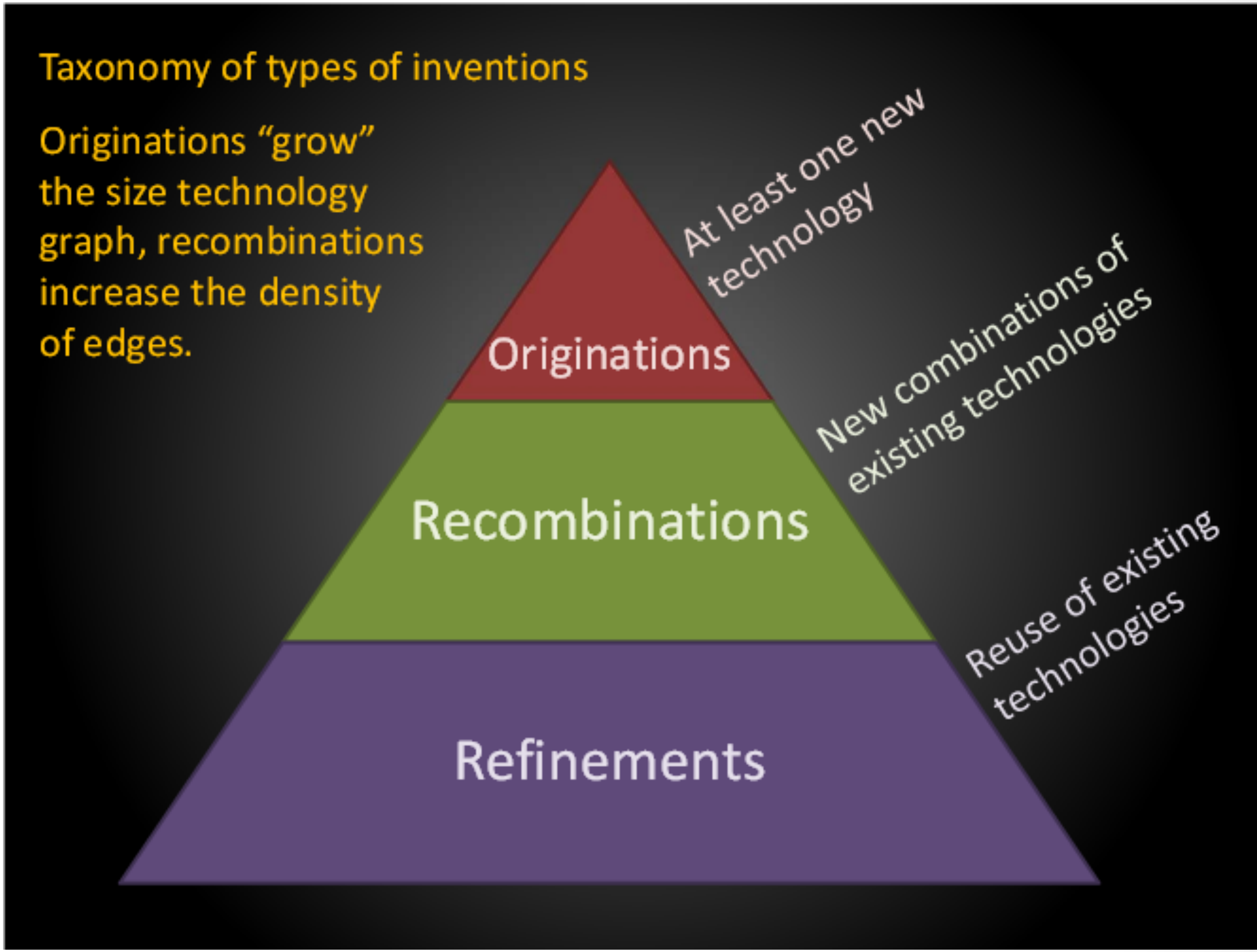

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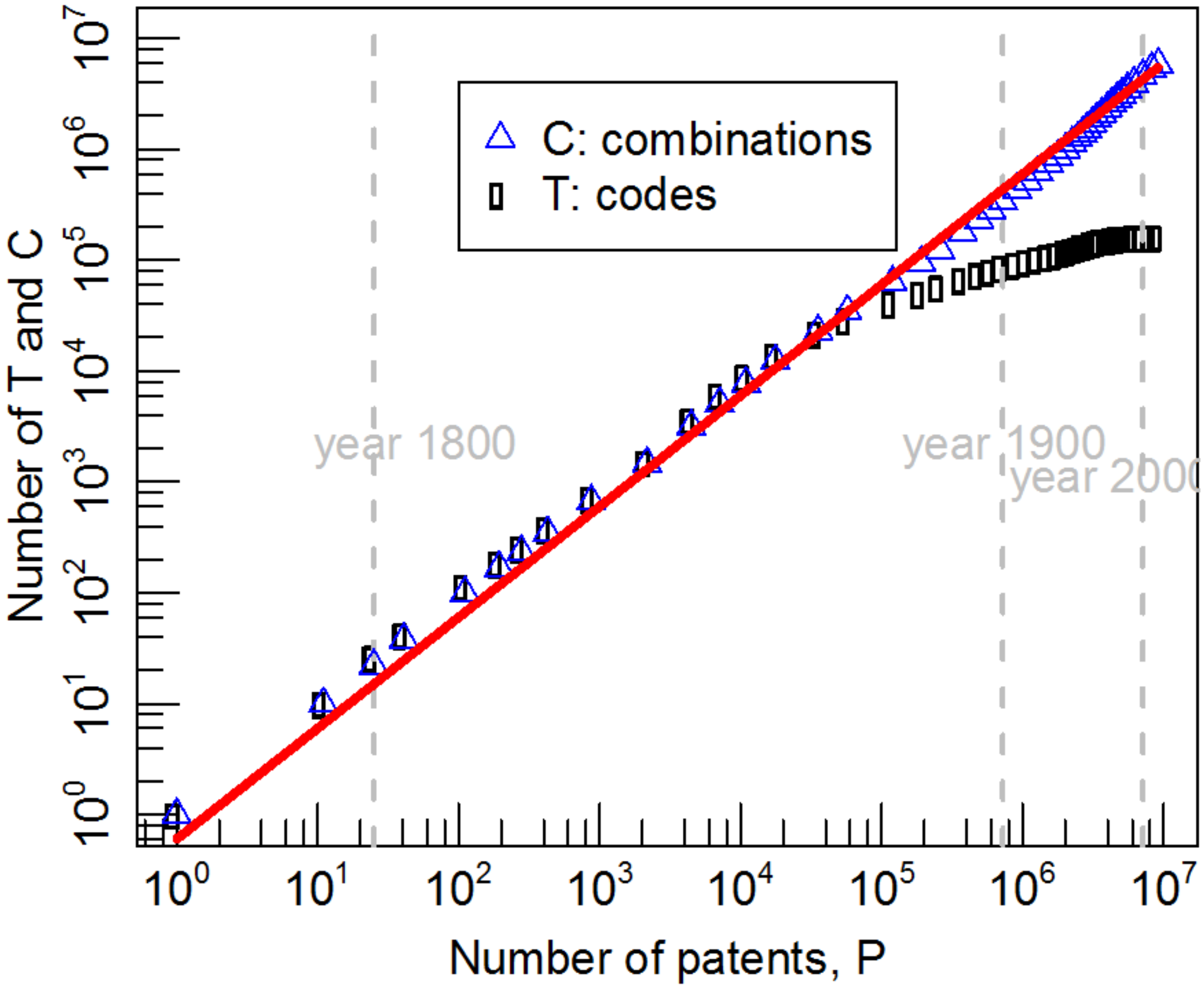
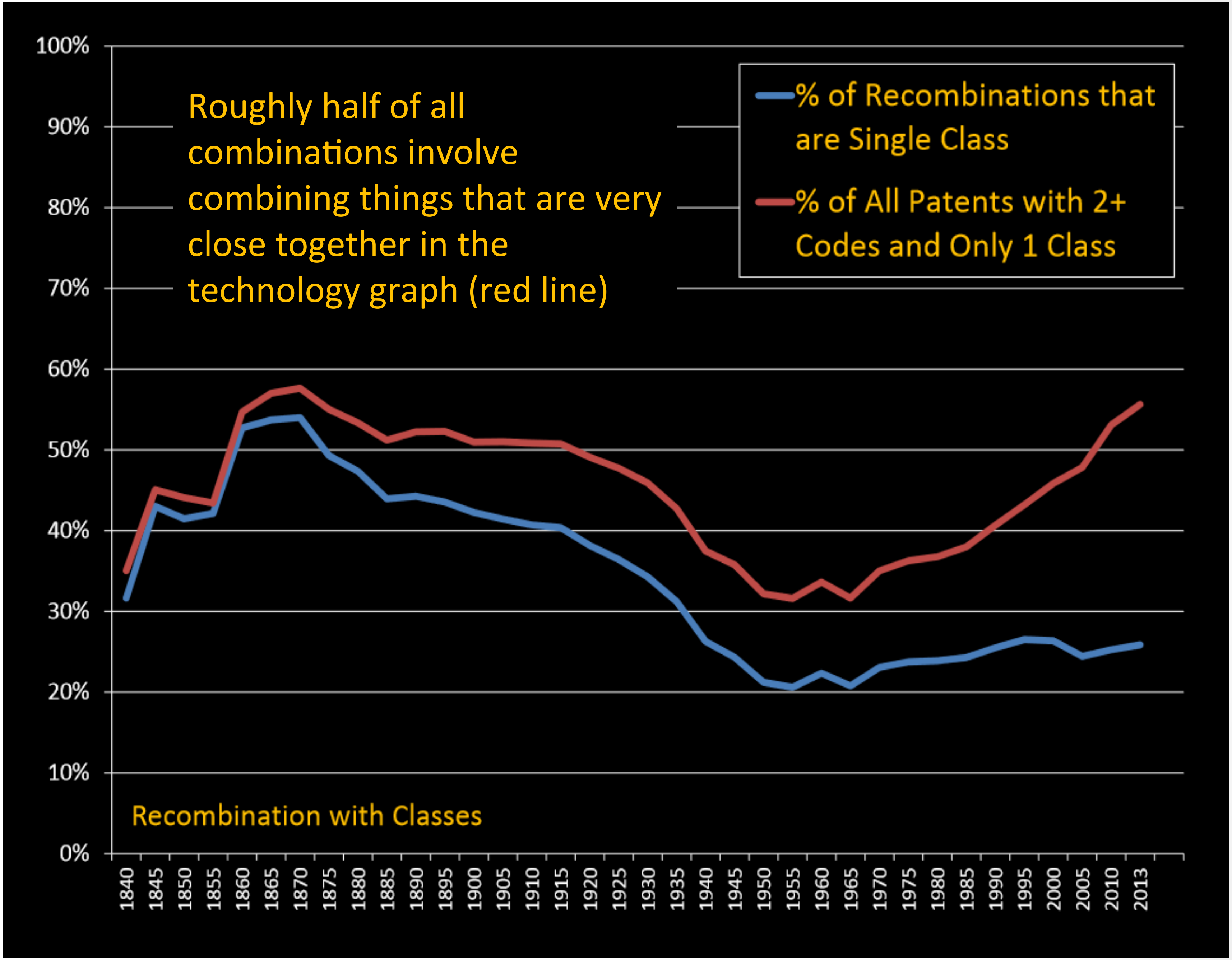
How Fast is the "technology space" growing?
With the increase in patents, are we keeping up searching it?



The space is expanding at the rate of the red line, and the rate at which technology is searching that space is the black line.
We are searching less and less of the total space over time.

Hyejin Youn, Deborah Strumsky, Luis M. A. Bettencourt, and José Lobo (2014) **Invention as a Combinatorial Process: Evidence from U.S. Patents, in review *Journal of the Royal Society Interface***



Deborah Strumsky

Technological Combinations

- On average, technologies that are closer together combine more often. Technologies that are farther apart combine less frequently.
- This might be because some technologies are harder to combine, or require special skill sets to combine successfully, therefore they combine less often. Of course some technologies make no sense to combine at all – exploding toothbrushes would be a bad combination.

An important note about combinations in the technology graph:

- Combinations form the edges in the network, so combinations account for the "density" of the technology graph.
- Historically, from 1790 – 1970 combinations were the primary driver of technological change in the US.
- In approximately 1970, Combinations peaked as a percent of patents and have been falling as a share ever since, refinements are now the primary driver.
  - Exploration = Combinations
  - Exploitation = Refinements

- What about those unusual combination?
- Where are they done well or more often?

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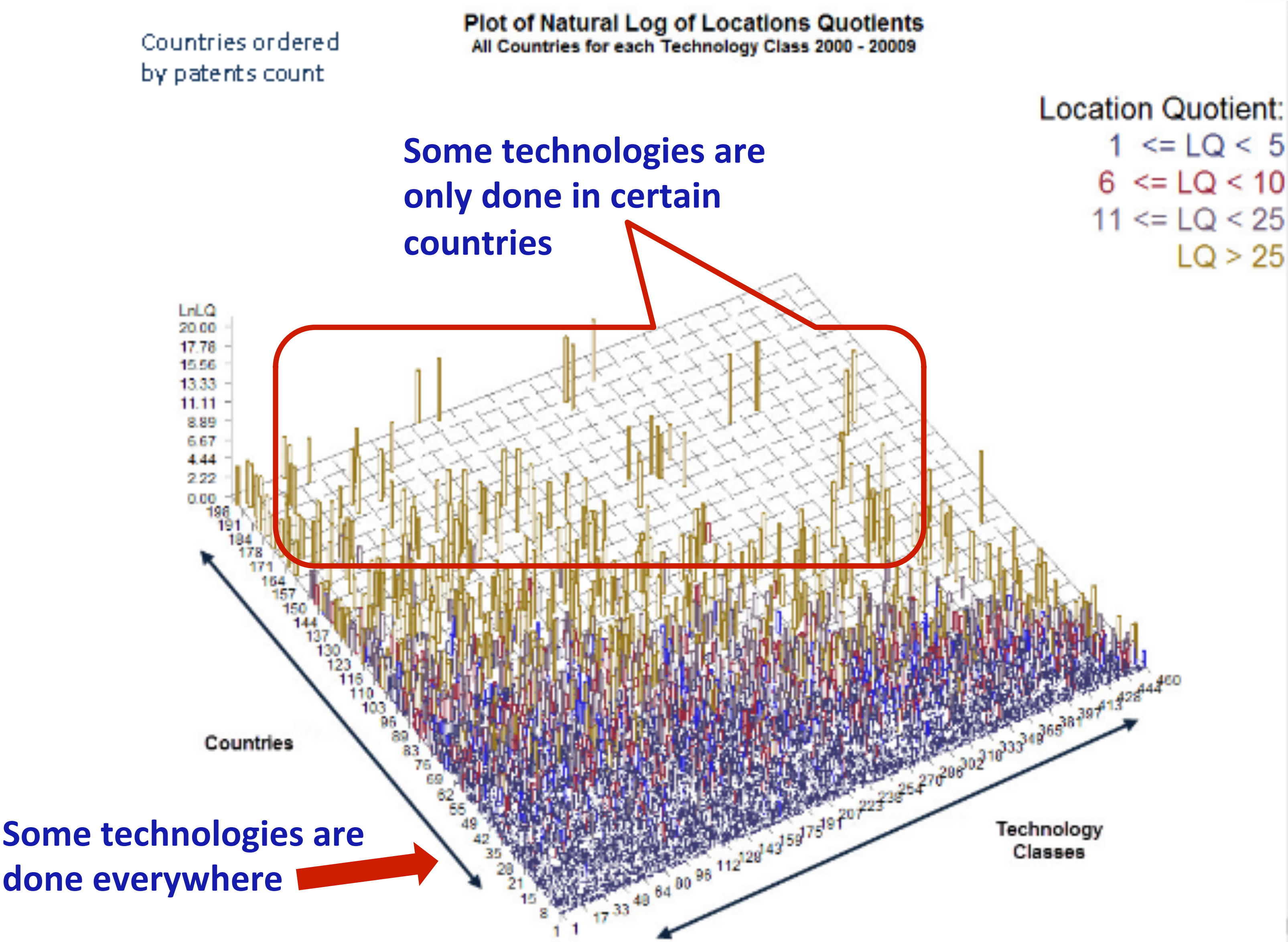
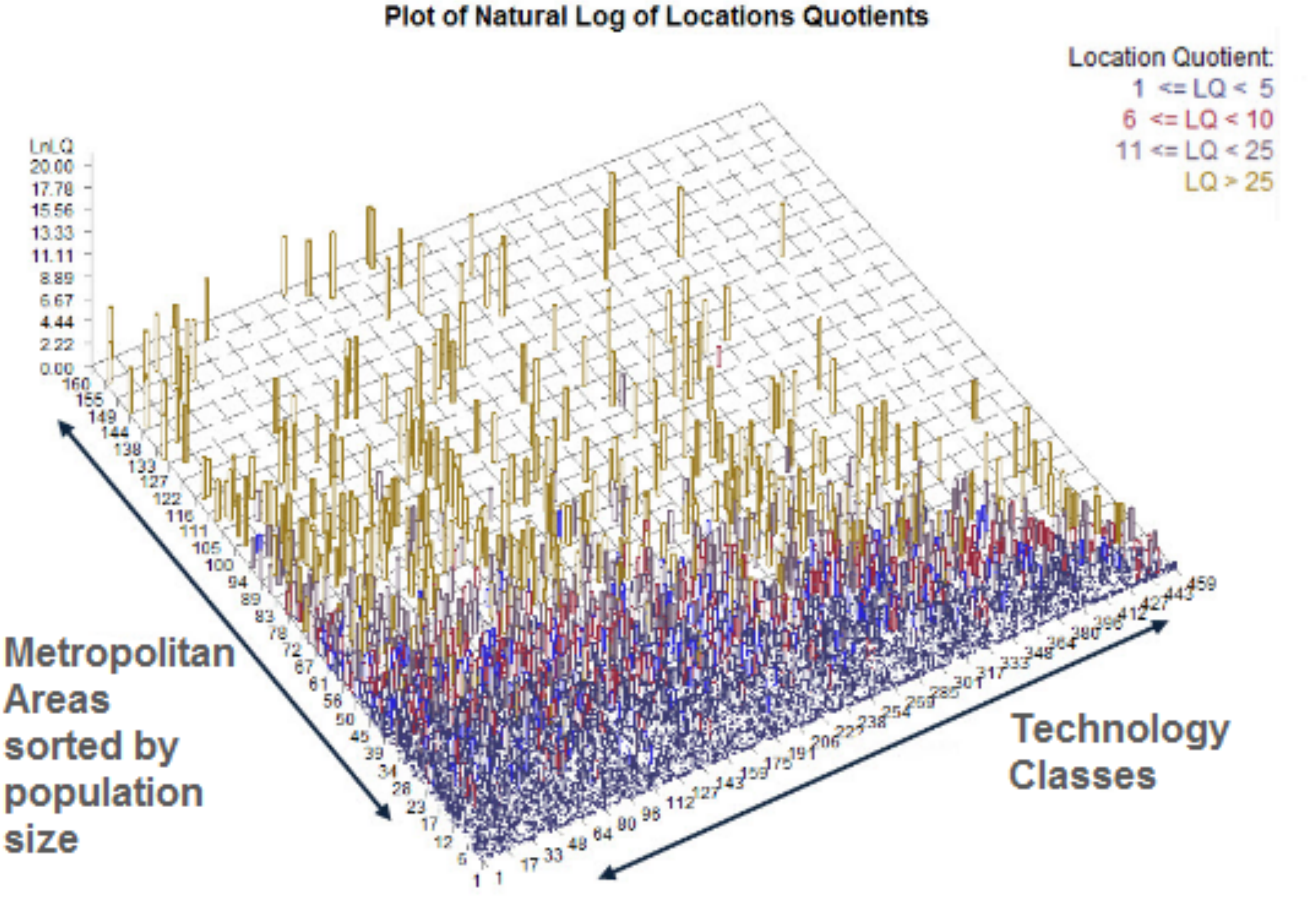
Technological Combinations



Similarly within the US, some technologies are observed in almost every city, while some technology only seem to be attainable in a few locations.



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Scaling and Innovation

- Larger cities produce disproportionately more patents per capita, and scaling coefficient of about 1.35 to 1.4.
  - For every doubling of population size there is, on average, more than a doubling of patents you get an extra 35% to 40% increase in inventions per capita.
  - This strength of the superlinear scaling relationship has been increasing over time.

Scaling and Innovation

- Larger cities produce disproportionately more patents per capita, and scaling coefficient of about 1.35 to 1.4.
- Larger cities disproportionately account for originations and inter-class combinations. What makes larger cities so special?
- Why?

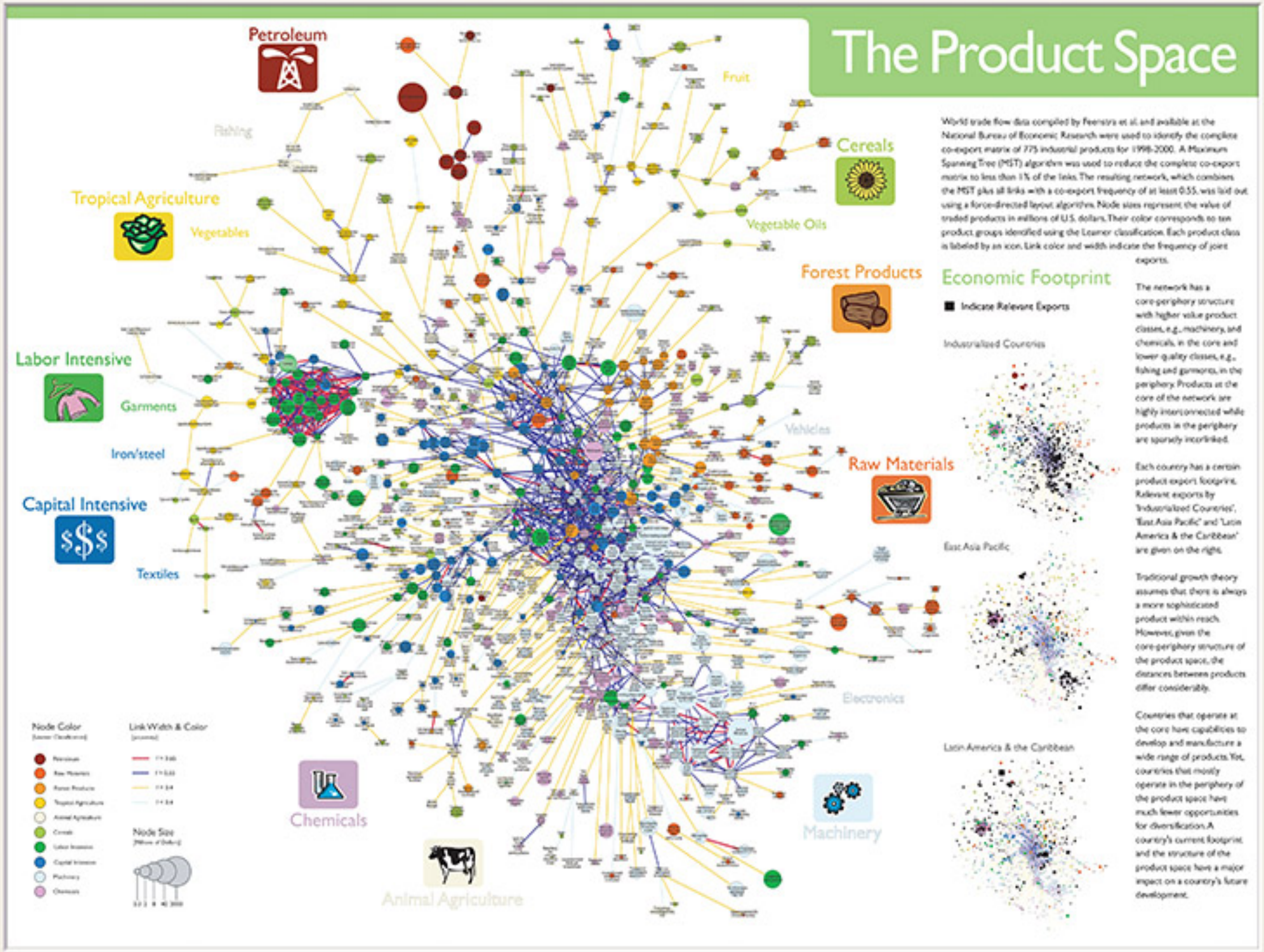
1. On average, rare/unusual things are produced in larger cities, because I can not combine what I do not know about. Social interaction is more frequent in larger cities.
2. Social interactions between very different ideas is more frequent in larger cities.
3. More collaborators are available, and better matchescan be identified between people and firms.

Innovation and technological change is *ultimately a social process*.

- Recall, Robert Boyd and Maxime Derex Totem project.
- Luis Bettencourt (resident faculty) has shown that diversity and complementarity increases with the size of the network.

Bettencourt, L.M.A. (2014) "Impact of Changing Technology on the Evolution of Complex Informational Networks." *Proceedings of the IEEE,* Vol. 102, No. 12 , p. 1878 – 1891.

Ricardo Hausmann (SFI External Faculty) on Economic Complexity



Similar work on product spaces has been done by Pr. Hausmann.
You may want to take the opportunity to explore his “Atlas of Complexity” book and interactive website link here: http://atlas.cid.harvard.edu/

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- Thank you very much for your patience and attention!
- I welcome any and all questions, comments and critiques. My contact info is:

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