The Innovation/Complexity Trade-off: How Bottlenecks Create Superstars and Constrain Growth

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Introduction

Over the last several decades (especially since mid-1980s)

- Growth has been disappointing (BLS, 2020)
- Real interest rates have decreased (Barkai, 2020)
- And firm entry has decreased (Haltiwanger, 2019)

Yet,

- Some ‘Superstar firms’ have done incredibly well (Autor et al., 2020)
- AI technologies are generating excitement and investment (Brynjolfsson, Syverson and Rock, 2019)
- The world’s economy is getting more complex, and countries with the best ability to handle complexity are the most productive (Hidalgo, 2009)

Too Few Ideas? Or Too Many?

Two related explanations

- We're running out of 'low hanging fruit' ideas (Bloom et al., 2020)
- We have to do more work to overcome the "Burden of Knowledge" (Jones, 2008)

But Weitzman (1998), observes that if new ideas are recombinations of old, the amount of good new ideas grows *extremely* rapidly

> *What does it feel like to live in a model world where the potential number of seed ideas floating around, per unit of anything else, is increasing without bound? In such a world the core of economic life could appear increasingly to be centered on the more and more intensive processing of ever-greater numbers of new seed ideas into workable innovations. – Weitzman, 1998*

The Downsides of Complexity

Why must modern chip fabs be "copied exactly"?

Result Preview

New ideas are increasingly complex in a way that skews the distribution of outcomes, and reduces overall productivity growth

- Combining multiple ideas creates additional fragility, while increasing maximum productivity
- Increased complexity **skews** the distribution of firm sizes, with a higher share of mediocre firms and more extreme superstars
- Whether complexity boosts growth is determined by the relative growth rates of maximum productivity less complexity.
- Strategies to reduce effective complexity, e.g. modularization, are as or more important than 'flashier' innovations

See Also:

- "Design Rules: The Power of Modularity" (Baldwin and Clark, 2000)
- Sah and Stiglitz (1988)

A Model of Production Complexity

An idea, i, has a complexity N.

- $M(N)$ is the multiplicity of "fail points" in a process of complexity N.
  - Steps in a production process
  - Ratios of ingredients in a stew
  - Relationships between team-mates
  - Arrangement of components in a Swiss watch
- $P(N)$ is the maximum productivity of an idea of complexity N

Each idea component is a Leontief complement to all others (recall O-ring production: Kremer, 1993), and success at each failpoint is uniformly iid distributed.

$$A_i = P(N) \min\{X_{i,1}, ..., X_{i,M}\} \tag{1}$$

$$X_{i,M} \sim U[0, 1] \tag{2}$$

Firms and Ideas

Anyone firm i can enter with frontier complexity N by paying fixed cost F

$$\pi_i = A_i\sqrt{K_i} - rK_i - F \tag{3}$$

Firms choose their size K_i **after** realizing A_i draws, meaning firm size is increasing in A_i draw.

$$K_i = \left(\frac{A_i}{2r}\right)^2 \tag{4}$$

Firms enter until **expected** profits are zero, e.g.

$$E[\pi_i] = 0 \tag{5}$$

Market Clearing Conditions

Total output is gross output less fixed cost of entry

$$Y = \sum^{I} C(N) A_i \sqrt{K_i} - F = rK \tag{6}$$

Capital rented by each firm sums to the total capital stock

$$K = \sum^{I} K_i \tag{7}$$

Capital does not depreciate and there is a constant saving rate

$$K_{t+1} = sY_t + K_t \tag{8}$$

Together these equations describe an AK growth economy in aggregate

$$g = Y_{t+1}/Y_t = sr \tag{9}$$

and take $F = \epsilon$ so there are lots of firms and LLN holds

Two Sets of Results

- Complexity and Firm Size Distribution

- Four Solutions to Complexity, and Implications Long Term Growth
  1. Replicate what works
     "Copy exactly"
  2. Brute Force
     Apply Moore's Law to sift through more and more solutions
  3. Copernican Revolution
     Reduce the complexity with a new paradigm
  4. Modularization
     Encapsulate complexity

Firm Size Distribution

Average firm size $E[K_i]$is increasing in $E[A_i]$ for FIXED r (i.e. open economy)

$$E[K_i] = \left(\frac{E[A_i]}{2r}\right)^2 \tag{10}$$

For fixed K (i.e. closed economy), higher $E[A_i]$ induces more entry, raising r and lowering average firm size

$$r = \left(1 - \sqrt{1 - 2F\frac{(M(N)+1)(M(N)+2)}{P(N)^2}}\right)^{-1} \tag{11}$$

Note: for sufficiently large F no firms enter and r is undefined. For $F = 0$ there is infinite entry and r is undefined.

Firm Size Distribution in Closed Economy

Holding $E[A_i]$ constant, an increase in the number of fail points M

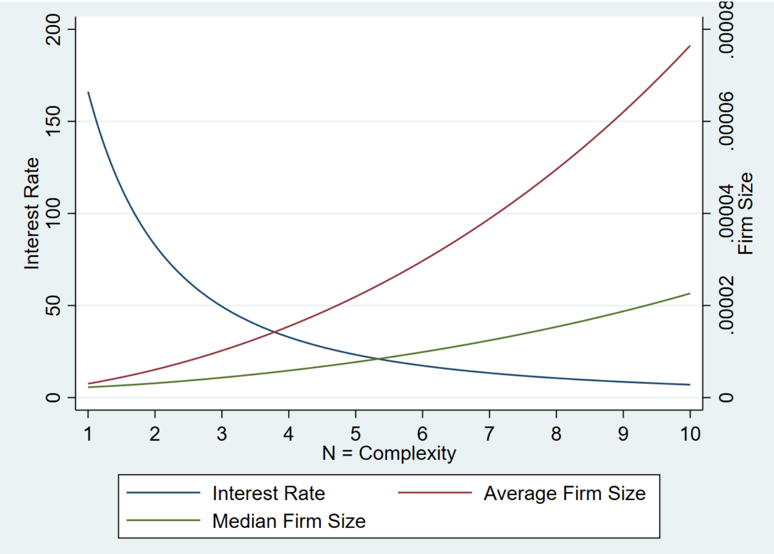
- Requires an increase in P, increasing maximum firm size
- Holds interest rate and average firm size constant
- Reduces median firm size
- Increases firm size distribution skewness

$$Max[K_i] = \frac{P^2}{2r} \quad (12)$$

$$median[K_i] = \frac{median[A_i^2]}{4r^2} \quad (13)$$

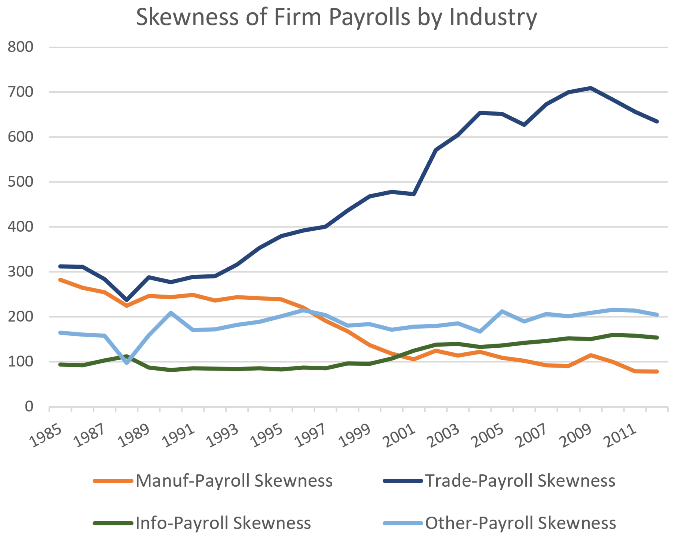
$$median[A_i^2] = P^2 2^{\frac{-2}{M}} (2^{1/M} - 1)^2 \quad (14)$$

Complexity and Firm Size Distribution



$$K = 1;\ F = .001;\ P(N) = 1;\ M(N) = N$$

Complexity and Firm Size Distribution



thanks to Xiupeng Wang for this LBD data

Recall that in this AK economy, growth is constant in percent terms for a constant r

$$g = Y_{t+1}/Y_t = sr \tag{15}$$

So understanding the impact of increasing complexity on growth is equivalent to finding the sign of $\frac{\partial r}{\partial N}$. Recall,

$$r = \left(1 - \sqrt{1 - 2F\frac{(M(N)+1)(M(N)+2)}{P(N)^2}}\right)^{-1} \tag{16}$$

So r is monotonically decreasing in $\frac{(M(N)+1)(M(N)+2)}{(P(N)^2)}$.

Taking M as large (i.e. ignore the $+1$ and $+2$), we have:

$$\text{sgn}\left(\frac{\partial g}{\partial N}\right) = \text{sgn}\left(\frac{\frac{\partial P}{\partial N}}{P} - \frac{\frac{\partial M}{\partial N}}{M}\right) \tag{17}$$

Whether additional complexity increases or decreases economic growth is a function of the *difference* in

- The growth rate of maximum productivity $P(N)$
- The growth rate of fail-points/effective complexity $M(N)$

But how fast does $M(N)$ grow? And what should we do if it grows too fast?

The Watchmaker

The Swiss watchmaker makes artisinal watches with N elements. To work perfectly, each element needs to be put into perfect pair-wise alignment with each other. $M(N)$ grows exponentially fast:

$$M(N) = \frac{N(N-1)}{2} = O(N^2) \tag{18}$$

Suppose that adding an additional feature requires increases maximum productivity by a fixed amount a. Then,

$$P(N) = aN = O(N) \tag{19}$$

Adding additional complexity will eventually reduce the watchmaker's expected productivity

The watchmaker may give up on more complexity and replicate what works, the economy growing with capital accumulation, until forced to adopt more complexity (e.g. as non-complex ideas are used up).

Solution 2: Brute Force

The watchmaker goes to training at "Moore's Gym" and improves his ability to design watches of increased complexity at an exponential rate. Then:

$$M(N) = \frac{N(N-1)}{2} = O(N^2) \tag{20}$$

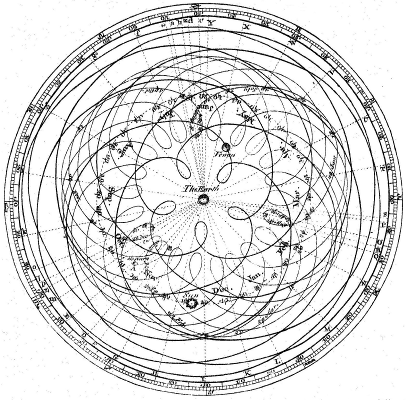
$$P(N) = Ba^N = O(a^N) \tag{21}$$

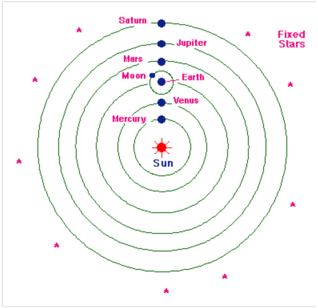
For some settings, exponential growth in computing power is enough to overwhelm polynomially increased complexity. In these settings, skewness will increase but so will average productivity.

If complexity grows exponentially (i.e. $M(N) = O(a^N)$), then it will be locked in a 'race' with Moore's Law.

Solution 3: Copernican Revolution

Adding and calibrating additional epicylces becomes increasingly difficult and decreasingly rewarding

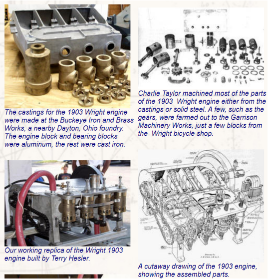




Using Copernican revolutions to reduce complexity may be necessary if $M(N) = N!$, which occurs if there are fail points for each possible ordering of N

Complexity and Revolution: Plane Engines

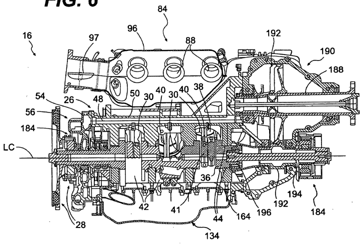
"We didn't make any drawings. One of us would sketch out the part we were talking about on a piece of scratch paper, and I'd spike the sketch over my bench. It took me six weeks to make that engine. The only metal-working machines we had were a lathe and a drill press, run by belts from the stationary gas engine." – Charlie Taylor, Wright Brothers' Mechanic

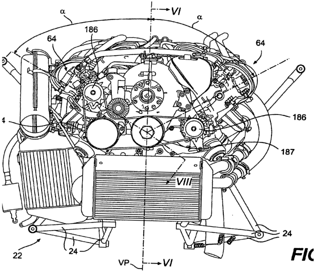


Wright Flyer Engine: 180 pounds, 12 horsepower

Modern propeller plane engines achieve better thrust, but require more parts and more precise tolerances

FIG. 6

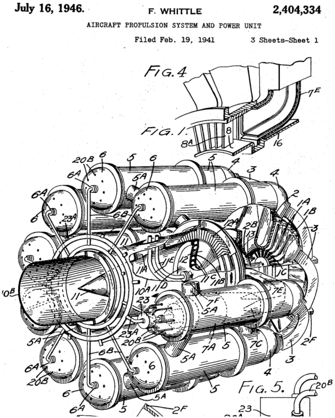




Modern propeller plane engine: 660 pounds, 600 horsepower, 196 labeled parts

Complexity and Revolution: Plane Engines

Even early jet engines provided superior thrust, with *fewer* parts, making additional innovations easier



Whittle's 1940 Engine: 950 pounds, 2187 horsepower, about 50 labeled parts

Solution 4: The Smarter Watchmaker: Hora and Modularization

"There once were two *watchmakers...*

The watches consisted of about 1000 parts each. The watches that [the first watchmaker] made were designed such that, when he had to put down a partly assembled watch, it immediately fell into pieces and had to be reassembled from the basic elements. [The second watchmaker,] Hora had designed his watches so that he could put together sub-assemblies of about ten components each, and each sub-assembly could be put down without falling apart. Ten of these subassemblies could be put together to make a larger sub-assembly, and ten of the larger sub-assemblies constituted the whole watch."
- Herbert Simon, 1962

Modularization and Complexity

Modularization, in the limit as $\mu \to N$, can transform $M = O(N^2)$ complexity to $M = O(N)$

- A task has N elements
- If each element must be perfectly synced with each other, there are $\frac{N(N-1)}{2}$ interactions to manage
- If the N elements can be compartmentalized into μ modules, then there are only $\frac{N(N/\mu-1)}{2} + \frac{\mu(\mu-1)}{2}$
- If the modules don't need to interact then there are only $\frac{N(N/\mu-1)}{2}$ elements

$$M(N,\mu) = \underbrace{\frac{N(N-1)}{2}}_{\textit{Naive}} \geq \underbrace{\frac{N(N/\mu-1)}{2} + \frac{\mu(\mu-1)}{2}}_{\text{Interacting Modules}} \geq \underbrace{\frac{N(N/\mu-1)}{2}}_{\text{Full Compartmentalization}} \tag{22}$$

Conclusion

"We have accumulated stupendous know-how... accomplished extraordinary things. Nonetheless, that know-how is often unmanageable. Avoidable failures are common and persistent, not to mention demoralizing and frustrating, across many fields—from medicine to finance, business to government... Knowledge has both saved us and burdened us." – Atul Gawande, Checklist Manifesto, 2020

1. It is expensive to sift through ideas, so as we learn more, managing complexity is increasingly important
2. It's not innovation alone that matters for growth, but rather the ratio of innovation/complexity
3. We need to focus on the denominator as much as the numerator
4. Firms and countries that are best at managing complexity (or luckiest) thrive, while a growing mass of mediocre firms drag down interest rates and growth
5. Is commodification a dirty word in some quarters, but perhaps unjustly

Modularization and Commodification Across Firms

Parable of the Pencil

1. Modularization can also happen *across* firms through commodification
2. Many highly successful platforms are mediators who commoditize a previously frictional or risky transaction, or difficult to internally generate complement
3. When you modularize within the firm, you can also export the new commodity – See Amazon's API strategy