Are Ideas Getting Harder to Find?

Bloom, Jones, Van Reenen, and Webb

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Overview

• New stylized fact:

Exponential growth is getting harder to achieve.

\[
\text{Economic growth} = \text{Research productivity} \times \text{Number of researchers}
\]

  e.g. 2% or 5%

\[\downarrow \text{ (falling)} \quad \uparrow \text{ (rising)}\]

• Aggregate evidence: well-known (Jones 1995)

• This paper: micro evidence
  
  ○ Moore’s law, Agricultural productivity, Medical innovations
  ○ Firm-level data from Compustat

Exponential growth results from the rising research effort that offsets declining research productivity.
Basic Framework

- Key equation in many growth models:

\[
\frac{\dot{A}_t}{A_t} = \alpha S_t
\]

where \( \dot{A}_t / A_t = \) TFP growth
and \( S_t = \) the number of researchers

- Define ideas to be proportional improvements in productivity.
  - Since we don’t observe ideas directly \( \Rightarrow \) just a normalization
  - Quality ladder models assume this

- TFP of the Idea Production Function:

\[
\text{Research Productivity} := \frac{\dot{A}_t / A_t}{S_t} = \frac{\# \text{ of new ideas}}{\# \text{ of researchers}}
\]
Null hypothesis: Research productivity $= \alpha \Rightarrow \text{constant!}$

- Standard endogenous growth $\iff$ constant research productivity
  - Permanent research subsidy $\Rightarrow$ permanent $\uparrow$ growth

- Motivations for the paper
  - Inherently interesting: Is exponential growth getting harder to achieve?
  - Can a constant number of researchers generate constant exponential growth?
  - Informative about the growth models we write down
Aggregate Evidence

- What if research productivity declines sharply *within* every product line, but growth proceeds by developing new products?
  - Steam, electricity, internal combustion, semiconductors, gene editing, etc.
  - Maybe research productivity is constant via the discovery of new products?

- But the extreme of this $\Rightarrow$ Romer (1990)!

- Standard problem:
  - Growth is steady or declining (here BLS TFP growth)
  - Aggregate R&D rises sharply (here NIPA IPP deflated by the nominal wage for 4+ years of college/postgrad education)
Aggregate Evidence

Research: 23x (+4.3% per year)
Idea TFP: 41x (-5.1% per year)
The Importance of Micro Data

• In response to the “scale effects” critique:
  
  o Howitt (1999), Peretto (1998), Young (1998) and others
  
  o **Composition bias**: perhaps research productivity *within* every quality ladder is constant, e.g. if number of products $N_t$ grows at the right rate:

    \[
    \frac{\dot{A}_{it}}{A_{it}} = \alpha S_{it} \quad (\star)
    \]

    \[\Rightarrow S_{it} = \frac{S_t}{N_t} \text{ invariant to scale, but responds to subsidies}
    
    \quad - \text{Aggregate evidence would then be misleading}
    
    \quad - \text{Permanent subsidies would still have growth effects.}
    
• Key to addressing this concern:

  **Study (\star) directly ⇒ research productivity within a variety!**
The “Lab Equipment” Approach

- Setup
  
  Goods production
  \[ Y_t = K_t^\theta (A_t L)^{1-\theta} \]
  
  Resource constraint
  \[ Y_t = C_t + I_t + R_t \]
  
  Idea production
  \[ \dot{A}_t = \alpha R_t \]

- Solution, with \( s_t := R_t / Y_t \)

  \[
  Y_t = \left( \frac{K_t}{Y_t} \right)^{\frac{\theta}{1-\theta}} A_t L \\
  \dot{A}_t = \alpha R_t = \alpha s_t Y_t = \alpha s_t \left( \frac{K_t}{Y_t} \right)^{\frac{\theta}{1-\theta}} A_t L.
  \]

- Therefore:

  \[
  \frac{\dot{A}_t}{A_t} = \alpha \left( \frac{K_t}{Y_t} \right)^{\frac{\theta}{1-\theta}} \times s_t L
  \]

  research productivity \quad “researchers”
What if the R&D input is expenditures instead of people?

- **Key:** Deflate R&D spending by the nominal wage to get the "effective" number of researchers.
  - Gives the "researchers" term in lab equipment model
  - Additionally allows heterogeneous researchers — weights by their wage $\Rightarrow$ efficiency units

- The maintains the appropriate null hypothesis:
  - Constant "effective" research generates constant exponential growth
  - Constant research productivity $\iff$ fully endogenous growth

- Empirically: the nominal wage = mean personal income from CPS for males with 4 or more years of college/post education
Stepping on Toes?

- Perhaps the idea production function depends on $S_t^\lambda$ rather than on $S_t$?

- We focus on $\lambda = 1$ for three reasons:
  - Only affects the magnitude of whatever trend we find — easy to multiply by your preferred value (appendix table $\lambda = 3/4$)
  - R&D spending already controls for heterogeneity in talent
  - No consensus on the right value of $\lambda$

- Statements like “we have to double research every $T$ years to maintain constant growth” are invariant to $\lambda$
Moore’s Law
The Steady Exponential Growth of Moore’s Law

curve shows transistor count doubling every two years
Moore’s Law and Measurement

• **Idea output:** Constant exponential growth at 35% per year

\[
\frac{\dot{A}_{it}}{A_{it}} = 35\%
\]

• **Idea input:** R&D spending by Intel, Fairchild, National Semiconductor, TI, Motorola (and 25+ others) from Compustat

  ○ Pay close attention to measurement in the 1970s, where omissions would be a problem...

  ○ Use fraction of patents in IPC group H01L ("semiconductors") to allocate to Moore’s Law
Evidence on Moore’s Law

GROWTH RATE

FACTOR INCREASE SINCE 1971

Effective number of researchers (right scale)

$\hat{A}_{it}/A_{it}$ (left scale)
## Research Productivity for Moore’s Law – Robustness

<table>
<thead>
<tr>
<th>R&amp;D measure</th>
<th>Factor decrease</th>
<th>Average growth</th>
<th>Half-life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>18</td>
<td>-6.8%</td>
<td>10.3</td>
</tr>
<tr>
<td>(a) Narrow</td>
<td>8</td>
<td>-4.8%</td>
<td>14.5</td>
</tr>
<tr>
<td>(b) Narrow (adj. congl.)</td>
<td>11</td>
<td>-5.6%</td>
<td>12.3</td>
</tr>
<tr>
<td>(c) Broad (adj congl.)</td>
<td>26</td>
<td>-7.6%</td>
<td>9.1</td>
</tr>
<tr>
<td>(d) Intel only (narrow)</td>
<td>347</td>
<td>-13.6%</td>
<td>5.1</td>
</tr>
<tr>
<td>(e) Intel+AMD (narrow)</td>
<td>352</td>
<td>-13.6%</td>
<td>5.1</td>
</tr>
</tbody>
</table>

*We have to double our research effort every decade just to keep up with declining research productivity!*
Agricultural Innovation
Seed Yields for Corn, Soybeans, Cotton, Wheat

- **Idea output:**
  - Realized yields per acre on U.S. farms
  - Approximately doubles since 1960
    \[ \frac{A_{it}}{A_{it}} \approx 2\% \text{ (stable, or even declining slightly)} \]

- **Idea input:** two measures, both show large increases
  - Narrow: public and private R&D to increase biological efficiency (cross-breeding, genetic modification, insect/herbicide resistance, nutrient uptake)
  - Broader: Also add in crop protection and maintenance R&D (developing better herbicides and pesticides).
Yield Growth and Research: Corn

Yield growth (left scale) and effective number of researchers (right scale) since 1969.
Yield Growth and Research: Soybeans

GROWTH RATE

Yield growth, left scale (moving average)

FACTOR INCREASE SINCE 1969

Effective number of researchers (right scale)

0% 4% 8% 12% 16%


19 / 46
# Research Productivity for Agriculture: 1969–2010

<table>
<thead>
<tr>
<th>Crop</th>
<th>Effective research factor increase</th>
<th>Average growth</th>
<th>Research productivity factor decrease</th>
<th>Average growth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Seed efficiency only</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>23.0</td>
<td>7.8%</td>
<td>52.2</td>
<td>-9.9%</td>
</tr>
<tr>
<td>Soybeans</td>
<td>23.4</td>
<td>7.9%</td>
<td>18.7</td>
<td>-7.3%</td>
</tr>
<tr>
<td>Cotton</td>
<td>10.6</td>
<td>5.9%</td>
<td>3.8</td>
<td>-3.4%</td>
</tr>
<tr>
<td>Wheat</td>
<td>6.1</td>
<td>4.5%</td>
<td>11.7</td>
<td>-6.1%</td>
</tr>
<tr>
<td><strong>+ crop protection</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>5.3</td>
<td>4.2%</td>
<td>12.0</td>
<td>-6.2%</td>
</tr>
<tr>
<td>Soybeans</td>
<td>7.3</td>
<td>5.0%</td>
<td>5.8</td>
<td>-4.4%</td>
</tr>
<tr>
<td>Cotton</td>
<td>1.7</td>
<td>1.3%</td>
<td>0.6</td>
<td>+1.3%</td>
</tr>
<tr>
<td>Wheat</td>
<td>2.0</td>
<td>1.7%</td>
<td>3.8</td>
<td>-3.3%</td>
</tr>
</tbody>
</table>
Medical Innovation
U.S. Life Expectancy Rises Linearly

At birth (left scale)

At age 65 (right scale)
New Molecular Entities Approved by the FDA

NUMBER OF NMES APPROVED

YEAR

NUMBER OF NMES APPROVED

New Molecular Entities

- **Idea output:** FDA approvals of new molecular entities. Usually 2 or 3 of these become blockbuster drugs
  - Limitation: Simple counts do not adjust for quality

- **Idea input:** R&D spending measured by the Pharmaceutical Researchers and Manufacturers of America survey.
  - Includes research performed abroad by U.S. companies and research performed in the U.S. by foreign companies.
  - But not research performed abroad by foreign companies.
Research Productivity for New Molecular Entities

Research productivity (left scale)

Effective number of researchers (right scale)
Better Micro Data? Disease Mortality

- **Idea output**: Years of life saved per 1000 people
  - Based on declines in mortality
  - Three diseases: all cancers, breast cancer, heart disease

- **Idea input**: Scientific publications with the relevant Medical Subject Heading (e.g. “Neoplasms”)
  - Two approaches: all publications versus those documenting clinical trials
Mortality and Years of Life Saved: All Cancers

Years of life saved per 1000 people (right scale)

Mortality rate (left scale)
## Research Productivity for Medical Research

<table>
<thead>
<tr>
<th>Category</th>
<th>Effective research Factor increase</th>
<th>Average growth</th>
<th>Research productivity Factor decrease</th>
<th>Average growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>New molecular entities</td>
<td>14.8</td>
<td>6.0%</td>
<td>4.9</td>
<td>-3.5%</td>
</tr>
<tr>
<td><strong>All publications</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cancer, all types</td>
<td>3.5</td>
<td>4.0%</td>
<td>1.2</td>
<td>-0.6%</td>
</tr>
<tr>
<td>Breast cancer</td>
<td>5.9</td>
<td>5.7%</td>
<td>8.2</td>
<td>-6.8%</td>
</tr>
<tr>
<td>Heart disease</td>
<td>5.1</td>
<td>3.6%</td>
<td>5.3</td>
<td>-3.7%</td>
</tr>
<tr>
<td><strong>Clinical trials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cancer, all types</td>
<td>14.1</td>
<td>8.5%</td>
<td>4.8</td>
<td>-5.1%</td>
</tr>
<tr>
<td>Breast cancer</td>
<td>16.3</td>
<td>9.0%</td>
<td>22.6</td>
<td>-10.1%</td>
</tr>
<tr>
<td>Heart disease</td>
<td>24.2</td>
<td>7.1%</td>
<td>25.3</td>
<td>-7.2%</td>
</tr>
</tbody>
</table>
Firm-Level Data from Compustat
Firm-Level Data from Compustat

- Compute research productivity for each firm in Compustat since 1980

- Idea output:
  - Decadal growth rates of sales revenue, market capitalization, or employment

- Idea input: R&D expenditures

- Various robustness checks for sample selection (below)
Compustat Distributions, Sales Revenue (2 Decades)

Only 3% of firms have roughly constant research productivity.
## Research Productivity using Compustat Data (weighted averages)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Effective research factor increase</th>
<th>Average growth</th>
<th>Research productivity factor decrease</th>
<th>Average growth</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sales Revenue</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 dec. (1712 firms)</td>
<td>2.0</td>
<td>6.8%</td>
<td>3.9</td>
<td>-13.6%</td>
</tr>
<tr>
<td>3 dec. (469 firms)</td>
<td>3.8</td>
<td>6.7%</td>
<td>9.2</td>
<td>-11.1%</td>
</tr>
<tr>
<td>4 dec. (149 firms)</td>
<td>13.7</td>
<td>8.7%</td>
<td>40.3</td>
<td>-12.3%</td>
</tr>
<tr>
<td><strong>Market Cap</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 dec. (1124 firms)</td>
<td>2.2</td>
<td>8.0%</td>
<td>3.4</td>
<td>-12.2%</td>
</tr>
<tr>
<td>3 dec. (335 firms)</td>
<td>3.1</td>
<td>5.6%</td>
<td>6.3</td>
<td>-9.2%</td>
</tr>
<tr>
<td>4 dec. (125 firms)</td>
<td>7.9</td>
<td>6.9%</td>
<td>14.0</td>
<td>-8.8%</td>
</tr>
<tr>
<td><strong>Employment</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 dec. (1395 firms)</td>
<td>2.2</td>
<td>8.0%</td>
<td>2.8</td>
<td>-10.3%</td>
</tr>
<tr>
<td>3 dec. (319 firms)</td>
<td>4.0</td>
<td>6.9%</td>
<td>18.2</td>
<td>-14.5%</td>
</tr>
<tr>
<td>4 dec. (101 firms)</td>
<td>13.9</td>
<td>8.8%</td>
<td>31.5</td>
<td>-11.5%</td>
</tr>
</tbody>
</table>
### Compustat Sales Data across 3 Decades: Robustness

<table>
<thead>
<tr>
<th>Case</th>
<th>Research productivity</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Factor decrease</td>
<td>Average</td>
<td></td>
</tr>
<tr>
<td>Benchmark (469 firms)</td>
<td>9.2</td>
<td>-11.1%</td>
<td></td>
</tr>
<tr>
<td>Winsorize $g &lt; .01$ (986 firms)</td>
<td>7.9</td>
<td>-10.3%</td>
<td></td>
</tr>
<tr>
<td>Winsorize top/bottom (986 firms)</td>
<td>6.0</td>
<td>-8.9%</td>
<td></td>
</tr>
<tr>
<td>Research must increase (356 firms)</td>
<td>11.6</td>
<td>-12.3%</td>
<td></td>
</tr>
<tr>
<td>Drop if <em>any</em> negative growth (367 firms)</td>
<td>17.9</td>
<td>-14.4%</td>
<td></td>
</tr>
<tr>
<td>Median sales growth (586 firms)</td>
<td>6.3</td>
<td>-9.2%</td>
<td></td>
</tr>
<tr>
<td>Unweighted averages (469 firms)</td>
<td>9.2</td>
<td>-11.1%</td>
<td></td>
</tr>
<tr>
<td>Revenue labor productivity (337 firms)</td>
<td>2.5</td>
<td>-4.5%</td>
<td></td>
</tr>
</tbody>
</table>
Discussion
## Summary: Evidence on Research Productivity

<table>
<thead>
<tr>
<th>Scope</th>
<th>Average annual growth rate</th>
<th>Half-life (years)</th>
<th>Extent of Diminishing Returns, $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregate economy</td>
<td>-5.3%</td>
<td>13</td>
<td>3.4</td>
</tr>
<tr>
<td>Moore’s law</td>
<td>-6.8%</td>
<td>10</td>
<td>0.2</td>
</tr>
<tr>
<td>Agriculture (seeds)</td>
<td>-5.5%</td>
<td>13</td>
<td>4.8</td>
</tr>
<tr>
<td>New molecular entities</td>
<td>-3.5%</td>
<td>20</td>
<td>...</td>
</tr>
<tr>
<td>Disease mortality</td>
<td>-5.6%</td>
<td>12</td>
<td>...</td>
</tr>
<tr>
<td>Compustat firms</td>
<td>-11.1%</td>
<td>6</td>
<td>1.1</td>
</tr>
</tbody>
</table>
Implications for Economic Growth

- Ideas are getting harder to find!
  - Exponential growth is getting harder to achieve
  - We have to double research effort every 13 years to maintain constant growth.

- “Red Queen” result
  - We have to “run” faster and faster to stay in the same place (i.e. to maintain a constant growth rate)
  - If the growth rate of research effort slows, economic growth may slow
Caveats: How could this interpretation be wrong?

- Composition bias: increase in R&D occurs within varieties, but R&D toward inventing *new* varieties is constant and faces constant research productivity?
  - The one place where research productivity is constant is the one place where R&D is not growing??? In equilibrium?

- Composition bias II: Even more varieties (e.g. within firms, within corn, within computer chips) so that true research per variety is actually constant?

- Mismeasured growth? Are growth rates actually increasing? Would have to be substantial...

- Other factors? Rising regulation? Changing emphasis away from chip speed or yield per acre or years of life?
Why does research productivity fall so quickly for semiconductors?

- Consider Jones / Kortum / Segerstrom framework:

\[
\frac{\dot{A}_t}{A_t} = (\alpha A_t^{-\beta}) \cdot S_t
\]

which implies

\[
g_A = \frac{g_S}{\beta}
\]

*LR growth = the growth rate of researchers deflated by the extent of diminishing returns, \( \beta \)*

- Can measure \( \beta \equiv \text{extent of diminishing returns} \)

- Semiconductors has the least diminishing returns!
  - It is just that we’ve expanded R&D so quickly...
A clarification of endogenous growth theory, not a critique!

- Naive reading is that this is a criticism of endogenous growth

- Instead, I think it strongly supports the key insight: nonrivalry
  - If you are satisfied with constant research productivity, there is no need for nonrivalry!
  - Fully rivalrous ideas can lead to constant exponential growth with perfect competition (Akcigit, Celik, Greenwood 2016)
  - But with declining research productivity, the increasing returns implied by nonrivalry becomes essential

\[
\text{Exponential growth in research } \Rightarrow \text{ exponential growth of ideas.}
\]
\[
\text{Increasing returns implied by nonrivalry } \Rightarrow \text{ exponential growth in per capita income.}
\]
Extra Slides
U.S. Total Factor Productivity

PRIVATE BUSINESS SECTOR
1990-2003: 1.2%
2003-2015: 0.7%

MANUFACTURING
1990-2003: 1.6%
2003-2014: 0.2%
Research Employment in Select Economies

European Union (15 countries)
- 1981-2002: 3.7%
- 2002-2015: 3.1%

United States
- 1981-2002: 3.2%
- 2002-2014: 2.1%

Japan
- 1981-2002: 3.3%
- 2002-2015: 0.5%
U.S. Crop Yields: Corn

BUSHELS/ACRE


40 60 80 100 120 140 160 180