Are Ideas Getting Harder to Find?

Bloom, Jones, Van Reenen, and Webb

March 2018
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.*
Conceptual Framework
Basic Framework

- Key equation in many growth models:

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

where \( \frac{\dot{A}_t}{A_t} = \) 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

- Productivity in 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 ⇒ 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

U.S. TFP Growth
(left scale)

Effective number of
researchers (right scale)

GROWTH RATE

FACTOR INCREASE SINCE 1930

0% 5% 10% 15% 20% 25%

0 5 10 15 20 25

1930s 1940s 1950s 1960s 1970s 1980s 1990s 2000s
Aggregate Research Productivity

Research effort: 23x (+4.3% per year)
Research productivity: 41x (-5.1% per year)

Effective number of researchers (right scale)
Research productivity (left scale)
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:

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

\[\Rightarrow S_{it} = \frac{S_{it}}{N_t}\] invariant to scale, but responds to subsidies
  
  – Aggregate evidence would then be misleading
  
  – Permanent subsidies would still have growth effects.

• Key to addressing this concern:

  *Study (*) directly ⇒ research productivity within a variety!*
Extensions to the basic framework
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
  - Additionaly allows heterogeneous researchers — weights by their wage ⇒ efficiency units

- The maintains the appropriate null hypothesis:
  - Constant “effective” research generates constant exponential growth ⇒ fully endogenous growth
  - **In contrast:** Naively dividing \( \frac{\dot{A}_t}{A_t} \) by \( R \) will incorrectly show a decline in “research productivity” even w/ endog. 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 $\lambda$
Selection of Our Cases and Measures

- How did we pick the cases to study and report?
  - Require good measures of idea output and research input
  - Also considered
    - internal combustion engine, airplane travel speed
    - Nordhaus (1997) price of light
    - solar panel efficiency
    - price of human genome sequencing
  - Problem: Could not measure research input...

- How do we choose our idea output measure?
  - Need to match up well with research input.
  - Highly robust — results driven by “no trend” versus “trend”
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
Research Productivity for Moore’s Law – Robustness

<table>
<thead>
<tr>
<th>Version</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 R&amp;D</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>(f) TFP growth (narrow)</td>
<td>5</td>
<td>-3.2%</td>
<td>21.4</td>
</tr>
<tr>
<td>(h) TFP growth (broad)</td>
<td>11</td>
<td>-5.6%</td>
<td>12.3</td>
</tr>
</tbody>
</table>

*We have to double our research effort every decade just to keep up with declining research productivity!*
Agricultural Innovation
TFP Growth and Research Effort in Agriculture

GROWTH RATE

FACTOR INCREASE

TFP growth, left scale
(next 5 years)

U.S. researchers
(1970=1, right scale)

Global researchers
(1980=1, right scale)
Seed Yields for Corn, Soybeans, Cotton, Wheat

- **Idea output:**
  - Realized yields per acre on U.S. farms (no TFP data)
  - Approximately doubles since 1960
    \[ \frac{\hat{A}_{it}}{A_{it}} \approx 2\% \] (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 (moving average)

Effective number of researchers (right scale)

Factor increase since 1969: 23 / 63
<table>
<thead>
<tr>
<th>Crop</th>
<th>Effective research factor increase</th>
<th>Research productivity factor decrease</th>
<th>Average growth</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>52.2</td>
<td>7.8%</td>
<td>-9.9%</td>
</tr>
<tr>
<td>Soybeans</td>
<td>23.4</td>
<td>18.7</td>
<td>7.9%</td>
<td>-7.3%</td>
</tr>
<tr>
<td>Cotton</td>
<td>10.6</td>
<td>3.8</td>
<td>5.9%</td>
<td>-3.4%</td>
</tr>
<tr>
<td>Wheat</td>
<td>6.1</td>
<td>11.7</td>
<td>4.5%</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>12.0</td>
<td>4.2%</td>
<td>-6.2%</td>
</tr>
<tr>
<td>Soybeans</td>
<td>7.3</td>
<td>5.8</td>
<td>5.0%</td>
<td>-4.4%</td>
</tr>
<tr>
<td>Cotton</td>
<td>1.7</td>
<td>0.6</td>
<td>1.3%</td>
<td>+1.3%</td>
</tr>
<tr>
<td>Wheat</td>
<td>2.0</td>
<td>3.8</td>
<td>1.7%</td>
<td>-3.3%</td>
</tr>
</tbody>
</table>
Yield Growth and Research: Cotton

Yield growth, left scale (moving average)

Effective number of researchers (right scale)

Factor increase since 1969

Growth rate

Yield growth, left scale (moving average)
Medical Innovation
New Molecular Entities Approved by the FDA

NUMBER OF NMES APPROVED

YEAR

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.
Better Micro Data? Disease Mortality

- **Idea output**: Years of life saved per 1000 people
  - Based on declines in mortality (Vaupel and Canudas 2003)
    
    \[ d \text{LE}(a) = \frac{\delta_i}{\delta_1 + \delta_2} \cdot \text{LE}(a) \cdot \left( -\frac{d\delta_i}{\delta_i} \right). \]
  
  - 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
U.S. Life Expectancy Rises Linearly

At birth (left scale)

At age 65 (right scale)
Medical Research Effort: All Cancers

- Number of publications
- Number for clinical trials
Research Productivity for Medical Research: All Cancers

YEARS OF LIFE SAVED PER 100,000 PEOPLE

Per 100 publications

Per clinical trial

YEAR

# 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)
Histogram of Research Productivity and Effort across Firms

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>Sales Revenue</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>Market Cap</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>Employment</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 Factor decrease</th>
<th>Average growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benchmark (469 firms)</td>
<td>9.2</td>
<td>-11.1%</td>
</tr>
<tr>
<td>Winsorize $g &lt; .01$ (986 firms)</td>
<td>7.9</td>
<td>-10.3%</td>
</tr>
<tr>
<td>Winsorize top/bottom (986 firms)</td>
<td>6.0</td>
<td>-8.9%</td>
</tr>
<tr>
<td>Research must increase (356 firms)</td>
<td>11.6</td>
<td>-12.3%</td>
</tr>
<tr>
<td>Drop if <em>any</em> negative growth (367 firms)</td>
<td>17.9</td>
<td>-14.4%</td>
</tr>
<tr>
<td>Median sales growth (586 firms)</td>
<td>6.3</td>
<td>-9.2%</td>
</tr>
<tr>
<td>Unweighted averages (469 firms)</td>
<td>9.2</td>
<td>-11.1%</td>
</tr>
<tr>
<td>Revenue labor productivity (337 firms)</td>
<td>2.5</td>
<td>-4.5%</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? Defensive R&D? 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

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

TOTAL FACTOR PRODUCTIVITY (2000=100)

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

180
160
140
120
100
80
60
40

Yield Growth and Research: Cotton

Yield growth, left scale
(moving average)

Effective number of researchers (right scale)

GROWTH RATE

FACTOR INCREASE SINCE 1969

Yield growth, left scale (moving average)
Medical Research Effort: Heart Disease

Number of publications

Number for clinical trials
Research Productivity for Medical Research: Heart Disease

YEARS OF LIFE SAVED PER 100,000 PEOPLE

Per clinical trial

Per 100 publications
Mortality and Years of Life Saved: Breast Cancers

- Years of life saved per 1000 people (right scale)
- Mortality rate (left scale)

Graph showing the mortality rate and years of life saved from 1975 to 2010.
Research Productivity for Medical Research: Breast Cancers

YEARS OF LIFE SAVED PER 100,000 PEOPLE

Per 100 publications

Per clinical trial

YEAR

Compustat Distributions, Sales Revenue (3 Decades)

Across 3 decades

NUMBER OF FIRMS

Research productivity

Number of Researchers

FACTOR CHANGE IN IDEA TFP AND # OF RESEARCHERS
Compustat Distributions, Sales Revenue (4 Decades)

NUMBER OF FIRMS

Factor change in idea TFP and # of researchers

Research productivity

Across 4 decades

Number of Researchers
Main Results from Compustat (Sales Revenue)

INDEX (INITIAL=1)

Idea TFP
(left scale)

Effective number of
researchers (right scale)

1st decade 2nd decade 3rd decade 4th decade

1/64 1/32 1/16 1/8 1/4 1/2 1

63 / 63