CLASS I – ECONOMIC GROWTH THEORY AND THE INNOVATION SYSTEM

Innovation Systems for Science, Technology, Energy, Manufacturing and Health

Course STS.081;17.935

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Course Introduction -

- **Class Organization:** Aim of class – summary of syllabus
- Your backgrounds, interests; Mine
- What do you want to get from class?
- One Key – you talk, you don't learn unless you talk, and talk to each other not just me –
- have to read - need you in the discussion
- How the discussion leader system will work

- **Innovation is about people** – people not institutions innovate -

Class One Overview

- **<u>Points in Class One</u>**:
- Solow – "Technological and Related Innovation" - basic growth theory Factor 1;
- Romer – "human capital engaged in research" – Factor 2
- Jorgenson – role of innovation as the growth driver in 90's;
- Merrill Lynch – how investors look at innovation for investment
- Note emerging debate on comparative advantage of competitor nations
- Review 2 elements of DIRECT innovation policy – R&D and Education

Class 1 – Part 1: Economic Models of Innovation

General Background - Definitions

- Science – understanding the natural world – out of "natural philosophy" of the 16^{th}-19^{th} centuries – observes natural world – discovery oriented
- Technology – System to organize scientific and technical knowledge to achieve a practical purpose – "systems" include technical advance plus models to implement that advance – moves from observation to implementation
- Research – increasing scientific OR technical knowledge or both
- Invention – applying research knowledge to create a practical idea/device
- Innovation – built on scientific discovery and breakthrough invention(s) – is the system of Research, Invention, & Development using both science and technology to commercialize (spread advances into societal use) –
- or: "intersection of invention and insight leading to the creation of social and economic value" (NII)
- Innovation System – the ecosystem for developing innovation – operates at 2 levels: the institutional actors, and the face-to-face groups
- Innovation Wave – 40/50 year cycle of innovation based on radical, breakthrough, disruptive invention, then applications piled on this, productivity rises, then long period of incremental invention
- "Valley of Death" – where invention and innovation usually dies - gap between research and development – institutions often not in place to bridge this gap, and move idea into development prototyping and production, then invention into innovation

[source for some of these – Prof. Charles Weiss, Georgetown University]

Relationship Between Science and Technology:

* Before mid-19th century – technology based on "tinkering" not science – telegraph, RR - early technology gives rise to early technology

*Now: basic science gives rise to technology – lasers

- but Dr. Lee Buchannan, ex-DARPA Deputy Director– "I get nothing from basic science – could drop that science funding and never miss it"

* Now: technology gives rise to science – IBM scanning tunneling microscope, nanotechnology

Professor Robert Solow, MIT

Robert M. Solow – Growth Theory

(NY, Oxford Univ. Press 2000)

- Prof. of Eco., MIT, Nobel Prize 1987, Nat'l Medal Tech.

- Solow Attacks Classical Economic Theory – of

  Roy Harrod, Evsey Domar:
  - Q: When is an economy capable of steady growth?
  - Classical Answer: When national savings rate (income saved)= capital/output ratio + rate of labor force growth
    - Have to keep capital plant and equip. in balance with labor supply
    - Static view: 3 factors – labor supply/capital supply/savings rate – have to fix these ratios in balance
    - Capitalism: just periods of alternating worsening unemployment and labor shortages

2. Solow’s Rethinking:

- Solow: “the story told by these [Classical] models felt wrong”
- Harrod had a hint – vague generalizations about “entrepreneurial behavior”
- Classical Model: recipe for doubling rate of growth was simply to double the national savings rate, perhaps through the public budget (Keynes) – throw money at it
- Economic development: Classical: “key to transition from slow growth to fast growth was sustained growth in the savings rate”
- <u>But Solow: “ I thought about replacing the capital and labor output “with a richer and more realistic representation of technology” – a new theory of production not just output levels</u>

3. Solow’s Basic Finding:

- The Rate of growth is independent of the savings (investment) rate
- Old “growth theory was mechanical” – simply

  “a description of flows and stocks of goods”
- Solow’s finding of “technological flexibility…opened up growth theory to a wider variety of real world facts”

- Basic Growth theory – Solow in 1957:
  - “Gross output per hour of work in the US doubled between ’09 and ’49’ [productivity gain]
  - “7/8’s of that increase could be attributed to ‘technical change in the largest sense’ ”
  - “all the remaining 1/8 could be attributed to a conventional increase in capital intensity

4. Unpacking Solow – Dennison:

- Reviewed US growth '29-'82 to break out Solow's broad term "technical progress":
  - 25% increased labor output
  - 16% increased education qualification of average worker
  - 12% growth of capital [same as Solow]
  - 11% "improved allocation of resources" [ex.- shift of labor from agriculture to high productivity industry]
  - 11% economies of scale
  - 34% growth of knowledge or technical progress [Dennison's narrow definition]

Total: 109% [extra 9% is misc.factors that reduce growth]

Dennison basically confirms Solow's broad "technical progress" total

Solow reduces Dennison's factors to 3 broad factors

- "straight labor", "straight capital" and "technical change"
- argues that technology and related innovation is 2/3's of growth
- "technology remains the dominant engine of growth" – human capital (talent) is part of that and in second place

5. TRANSLATION OF SOLOW:

- Solow attacks classical economics and transforms growth theory – sees capitalism and growth as *dynamic* not in close and static equilibrium system
- We see his point – railroads, canals, electricity, telegraph, telephone, aerospace, computing, internet, all transform growth
- *Pattern*: initial technology advance – yields *new applications*, which pile on to broaden the advance – which yields productivity gains throughout economy – which yields real growth in wages, income
- Solow's basic point about classical economics: "No amount of statistical evidence will make a statement invulnerable to common sense"
- *The good news: you can increase your rate of economic growth through technological advance – you can improve real incomes/societal wellbeing*

6. Under Solow, what is the role of Capital? -- A Supporting Player

- "technological progress …could find its way into actual production only with the use of new and different capital equipment"
- Therefore the effectiveness of innovation in increasing output would be paced by the rate of gross investment"
- So: much faster transfer of new technology into production with investment

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- Comment: what kind of investment are most important to innovation? (Angel, Venture Capital IPO's, general equity, lending)
- Doesn't technical advance yield investment, not just the other way around?

- Comment: Boom & Bust: Periods of boom and stagnation can and do appear due to Keynesian and classical unemployment – Q: can accelerating the rate of technological advance/innovation reduce the "bust" period?
  - Implication: innovation capacity is a key
  - A healthy innovation system is a key to growth

7. Solow - Exogenous Growth

- Solow sees the power of technological advance as an economic force, but he doesn't see how to measure it
- He's stuck with the traditional toolset of both classical and neoclassical economics - capital supply and labor supply measures and market movements
- He's not ready to measure innovation system elements
- He therefore treats tech innovation as "*exogenous*" - as outside the understood economic system and outside of metrics

8. Solow's Warning:

* Ex. – there was little economic growth in medieval Europe because so little technical advance – economy was a capture economy -- piracy, war were ways to capture wealth
* Solow Quoting Frost:

  "Most of the change we think we see in life is due to truths being in and out of favor"
* p.xxvi: 'social institutions and social norms evolve… so economic behavior will surely evolve with them"
* So: "the permanent substructure of applicable economics cannot be so very large"

Paul M. Romer – Prof. of Economics, Stanford/NYU

"Endogenous Technological Change" (Journal of Political Economy, vol 98, pp. 72-102 (1990)

BASIC POINTS – Summary:

1. "Growth model" – growth is driven by technological change
   - which is driven by researchers who are profit maximizing agents at the immediate pre-commercial stage
   - Technology is not a conventional good and not a "public good" – it is a "non-rival" potentially excludable good, so it won't support price-taking competition, it's more like monopolistic competition
2. The stock of human capital (talent) determines the rate of growth
3. Given that role, too little human capital is devoted to research (the major input into technology, so behind growth)
4. Growth theory is therefore ENDOGENOUS - part of the economic system not outside it
5. Integration into world markets increases access to human capital and technology and therefore increases growth
6. A large population is not enough to generate growth, the key is the size of human capital (talent)

2. Romer's Growth Model

- Output per hour worked (productivity) now is 10x as valuable per hour worked 100 years ago
- Cause: <u>technological change</u>
- But: what other specific and measurable factors generate growth of output per worker?
  - **"<u>increase in the effective labor force</u>" &**
  - **<u>increase in effective stock of capital/worker</u>**

3. Romer’s 3 Premises

1) Technological change (“improvement in the instructions for mixing together raw materials” –ie, tech. is physical product-based, not process) “lies at the heart of economic growth”

   - technology provides the incentive for capital accumulation and both of these improve output per worker (of products)

2) Technological change occurs in large part because of people who respond to market incentives

   - academic scientists on gov’t grants don’t but when new knowledge is translated into practical goods, market incentives are key

3) Technological knowledge (ie, “instructions for working with raw materials”) is inherently different from other economic models:

   - developing new and better “instructions” is a fixed cost

   - this is the defining economic characteristic of technology

4. Romer–Technological Knowledge:

- (see pp-189-191) “Rival good”- property: use by one person or firm precludes use by another
- “Non-rival good”- property: use by one person or firm in no way limits use by another – so technology is naturally non-rival, it can be readily shared or adopted by others
- “excludable” – if the owner of a good can prevent others from using it – ex., legal (patents) or commercial trade secret
- Technology – is partially excludable
- So: non-rival feature of technology-based growth is “unbounded growth” and “incomplete appropriability”– meaning it can only be partly excluded
- So: technology is unlike many other economic goods
- Note: given the power of technology (from human capital in research) for growth, our investment in human capital/research is too low
- Technological innovation needs market incentives as key to growth by technological agents doing research

5. Romer – Role of Human Capital:

- Increase in the total stock of <u>human capital engaged in research</u>, & increase in the amount of <u>research</u>, are directly proportional to the increase in <u>economic growth</u>
- Total level of human capital and fraction of that capital devoted to research is now highest in human history
- <u>Lack of human capital (engaged in research) = economic stagnation</u>
- So: little growth in prehistoric times (except increase in labor)
- Civilization, therefore economic growth, could not begin until human capital was spared from production and allocated to research
- Gov't policy: subsidies for capital compares poorly to subsidy for human capital (engaged in research)
- Gov't's best policy should encourage allocation of human capital to research; next best: subsidize production of human capital (education)
- **PROSPECTOR THEORY**

6. Prospector Theory

- Romer argues that talent ("engaged in research") is the pacing mechanism for innovation-based growth
- Develops "Prospector Theory" (not in this article)
- Reviews the chemical engineering sector in the 3nd half of the 19th century
  - Germany and Britain dominate the sector
    - Because they created institutions to train large numbers of chemical engineers
- It's like the California Gold Rush in 1849---
  - The nation/region that creates a strong talent pool in a sector – ie, the largest number of well-trained prospectors – will find the most gold (ie,dominate technical advance)

7. Romer on Growth, Trade, and Research Relationships (pp. 212-215):

- Growth is co-related with the degree of integration into world markets
- Having a large number of consumers or large population is not key – not a substitute for trade with other nations
- Trade forces economic integration with a large pool of human capital
- Economy with large stock of human capital (engaged in research) fosters economic growth
- Accounts for unprecedented growth of 20th century economies
- Less developed economies can benefit from access to human capital via trade and the integration it brings (story of growth in Asian economies)
- Closed economies stagnate

8. Endogenous Growth Theory

- For Romer, unlike Solow, growth theory incorporates innovation as an *ENDOGENOUS not exogenous* factor
- Romer views technology innovation as inside and part of an economic system, not outside it
- Romer's concepts of technological knowledge and human capital engaged in research create tools to begin to measure innovation's eco. role
- Romer takes the major next step past Solow
- Classical Economics could not explain why "the rich get richer" - the wealth of nations - it was an equilibrium system
- Growth theory is a dynamic system - explains growth based on innovation capacity - and some nations have big innovation capacity lead

Paul Krugman on the Neoclassical Economic Challenge in the 2008 Financial Crisis:

- *"As I see it, the economics profession went astray because economists, as a group, mistook beauty, clad in impressive-looking mathematics, for truth. (…) But while sabbaticals at the Hoover Institution and job opportunities on Wall Street are nothing to sneeze at, the central cause of the profession's failure was the desire for an all-encompassing, intellectually elegant approach that also gave economists a chance to show off their mathematical prowess."* -Paul Krugman, Princeton (and Nobel economics awardee)

Dale W. Jorgenson, Prof. of Economics, Harvard (in "US Economic Growth in the Information Age" (Issues in Sci & Tech, Fall 2001))

- **Basic Point: 90's – story of technology breakthrough driving economic growth**
  - Resurgence of US economy in '93-'00 outran all expectations
  - Rapid decline in IT prices provides key to the surge in 90's US economic growth
  - This development is rooted in the semiconductor technology sector

2. Jorgenson: "Better, Faster Cheaper" mantra of new economy

- History: Bell Labs '47 (Bardeen, Brattain, Shockley) develops transistor – from semiconductor materials: electrical switch for encoding information in digital form
- Integrated Circuit:
  - 1958 -Jack Kilby, of Texas Instruments, and Robert Noyce, Fairchild Semiconductor – develop IC's/semiconductors
  - IC: millions of transistors to store data in binary form – so at first IC is for data storage – Memory Chips (DRAMS)
  - Gordon Moore (Fairchild Semiconductor) – Moore's Law – each new IC: every 2 years doubles the no. of transistors per chip & cost of transistors per chip cut in half
  - This is a huge deflationary factor in economy
  - 1968 – Noyce, Moore and Andy Grove found Intel
  - Begin making Microprocessors or Logic Chips or Microchips
    - First logic chip – 2300 transistors
    - Pentium 4 of years ago has 42 million transistors

3. Jorgenson-Computing price/growth

- Communications Equipment
  - Cost also down driven by cheaper semiconductors
  - Transmission technologies – ie, fiber optics, microwave broadcasting, communications satellites, DWDM (dense wavelength division multiplexing – multiple signals over fiber optic cable simultaneously) -- progress at rates faster than Semiconductors – key to “free” internet
- Result: Growth Resurgence
  - Accelerating growth in output and productivity in 90’s
  - Driven by decline in Semiconductor prices
  - Leads to price declines in computers, communication equipment
    - Computers: 90-95: -15%/year price decline; 95-00: -32%/year
    - Software: 90-95: -1.6%; 95-00: -2.4%

- Yields: capital growth in high productivity goods
- Big growth in 90’s in this area, much higher than any other capital goods -- And:

  \- widespread: pervasive in economy - in homes, business, gov’t

4. Jorgenson-Accounting for Growth

- Massive increases in computing power in US:
  - Raises productivity in IT-producing industries &
  - Contributes to productivity in whole economy
- Productivity Measures:
  - IT sector productivity increased steadily from ’48-’99; sharp acceleration in ’95-’00 in response to Semiconductor price drops
- Purchase of productivity enhancing equipment:
  - boosts growth in US ONE FULL POINT
  - IT alone accounts for half of this
- IT, 4.26% of GDP, yields surge of US productivity in ’95-’00
- **Summary: IT growth drives capital investment in IT capital goods, which drives productivity gains, which drives US growth**
- Background:
  - ‘45-’73: US productivity growth 2% range
  - ’73-’93: US productivity below growth 1+% range
  - ’95-’00: US productivity growth 3.5%, and economic growth 4.2%

5: Jorgenson: What’s Next??

- <u>Acceleration of growth depends on accelerating productivity</u>
- What happens now that Moore’s Law has slowed?
  - Semiconductor industry shifted to 3-year product cycle after ’03
- “Performance of IT industries has become crucial to future growth prospects. We must give close attention to uncertainties that surround the future development of IT.”
- And: What will IT role be of Korea, Malaysia, Singapore, Taiwan, China, India?
  - Economic law of comparative advantage is now knowledge-based instead of resource-based
  - Knowledge moves faster and is less excludable than physical resources

Part 2 of Class 1: Patterns of investment in Science and Technology

- Private investment requires short time-frames – Merrill Lynch
- Federal direct investment in R&D; industry in development
- Federal investment in human capital (education)
- Next class: Nelson on "national innovation systems"
- Later Class: Connecting research to development – the "Valley of Death"

Merrill Lynch – The Next Small Thing

– Steven Milunovich, John M.A. Roy, An Introduction to Nanotechnology – 9/4/01 Merrill Lynch Report (http://www.slideshare.net/tseitlin/intro-to-nanotechnology-merrill-lynch)

- **BASIC POINT: how do investors look at potential technology breakthroughs? Do they believe they drive growth?**
- GROWTH PATTERN:
- Merrill Report cites its economist Norman Poire
- Poire: growth innovations drive the economy and stock market
- Takes 28 years for wide acceptance of a new technology
- Takes 56 years for rapid growth to evolve
- Takes 112 years for technology maturity – after that, growth in the technology area parallels growth of population rates

2. Merrill Report – "Vision /Enabler/ Researcher Mass" Pattern:

- For example, Nanotechnology = fabrication at the molecular scale (ie, at 100 nanometers, where nanometer = 10 hydrogen atoms)
- First: **<u>Vision</u>** – Richard Feynman – "Plenty of Room at the Bottom" – 1959 envisioned the potential of nanotechnology
- Second: **<u>Enabler</u>** – for example, the scanning tunneling microscope (IBM) allowed measurement and basic manipulation of nanoscale systems (20 years ago)
- Third: **<u>Research Mass</u>** – 1st: Eric Drexler's 1981 journal article; by 2000, 1800 journal articles (similar to total number of internet articles in early 90's)

3. Merrill Report: Investment Timetable Must be Short Term

- “Although the futuristic market is fascinating, it is not inevitable” - p.2
- “Nanotechnology is close to commercial markets” – p.2
- Article reviews key short term markets – p.5
  - 0-2 years - short term
  - 0-5 years – mid term
  - 5+ years – long term
- These categories give a good perspective on how far out investors will look
- “The keys to nanotechnology are manufacturing and communication. If you can’t build it in volume, then there is not much you can do with it.” – p.5

4. Merrill Report: Near-Term Nano Investment Focus:

- **Opportunity One: Instrumentation** – p.1 – "In any new technology the first winners are the tool makers"
  - Note the interdisciplinary nature of efforts in nano instrumentation effort: "chemistry and mechanical engineering"; teams of "chemists, physicists, biologists, material scientists to accelerate research and commercial spinoffs"
- **Opportunity Two: Semiconductors**
  - "Within the next ten years, molecular electronics is expected to become available as a replacement for silicon-based computing – HP's Stan Williams – p.4
  - ***Merrill: no investor interest because the time-frame is too long-term***
  - Ultra small nano-based hard drives available at IBM (Peter Vettiger) in 2-3 yrs, or memory chips in 3-5 yrs
  - Intel's Gary Marcyk combined "complementary" aspects of silicon and nanotechnology microprocessors in mid–term, making a better investment option than nanotech microprocessors at HP

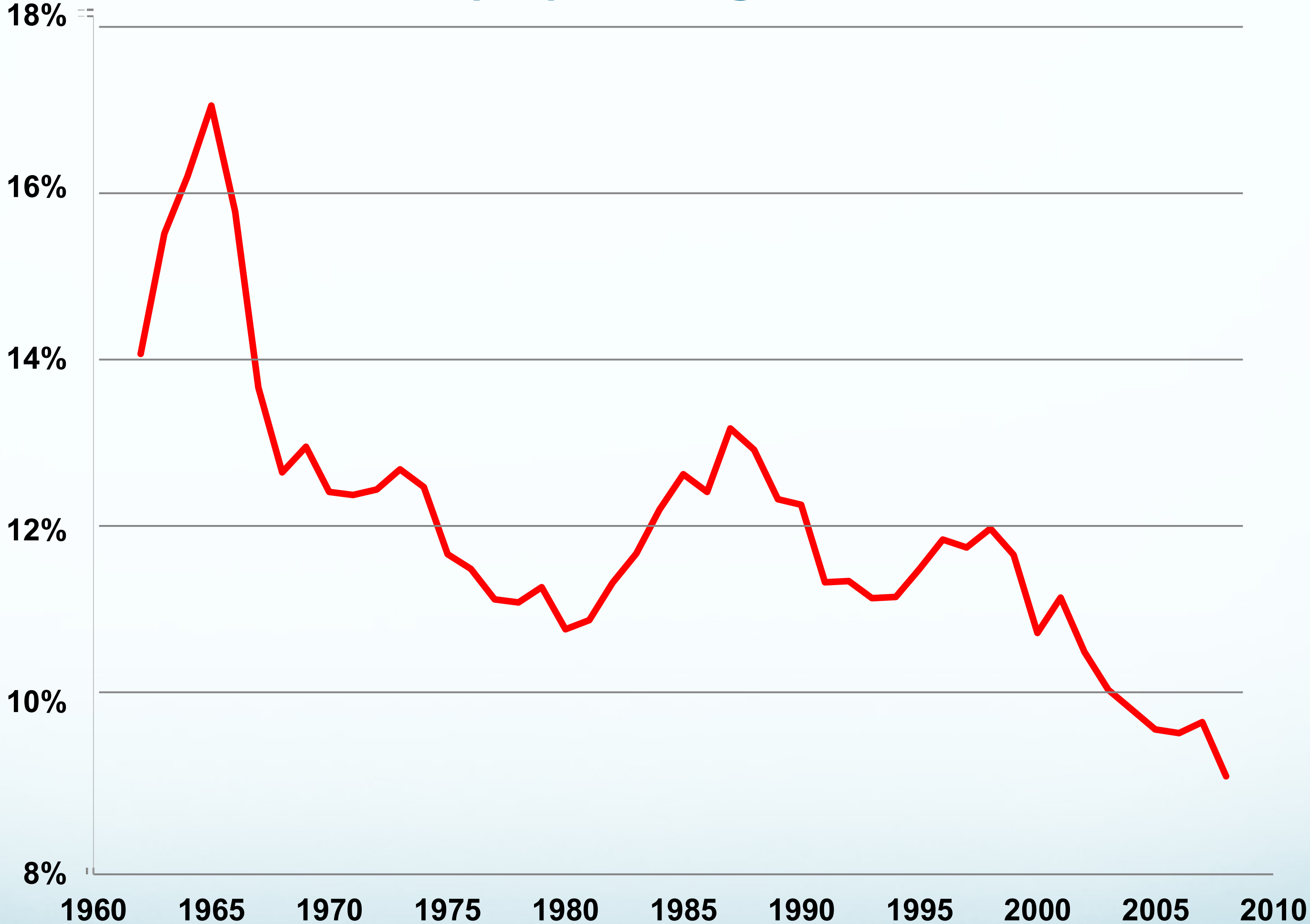
SO: WHO WILL DO THE LONG TERM RESEARCH AND DEVELOPMENT? – IS THIS A GOV'T ROLE PROVIDING "PUBLIC GOOD"?

DIRECT (EXPLICIT) INNOVATION FACTOR #1: R&D INVESTMENT [Solow]

- **<u>BASIC POINT</u>:**
- **IF SOLOW IS RIGHT,**
  - IE, TECHNOLOGICAL AND RELATED INNOVATION IS RESPONSIBLE FOR 2/3' S OF US ECONOMIC GROWTH
- **THEN R&D INVESTMENT IS A CRITICAL PILLAR FOR OUR ECONOMY.**
- LET' S REVIEW R&D INVESTMENT PATERNS:

I. FEDERAL RESEARCH FUNDING:

Total federal R&D outlays as a percentage of total discretionary spending: FY 1962–2008



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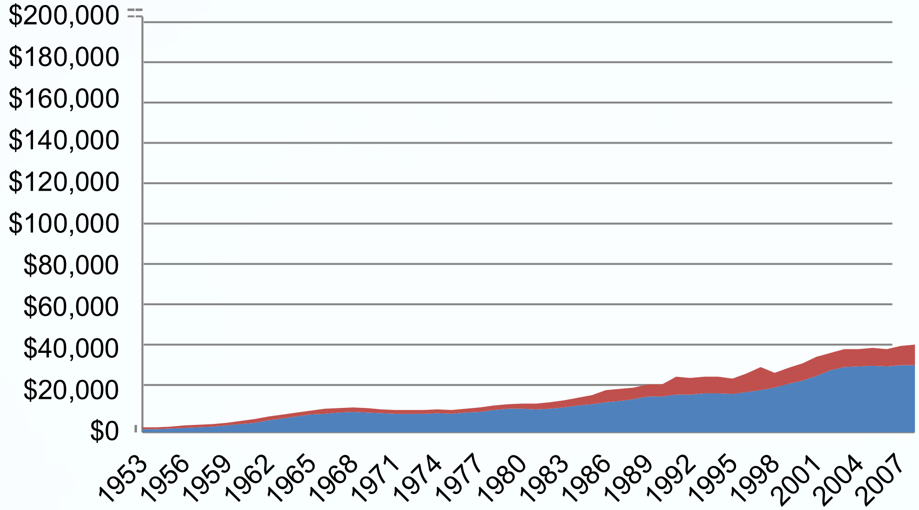
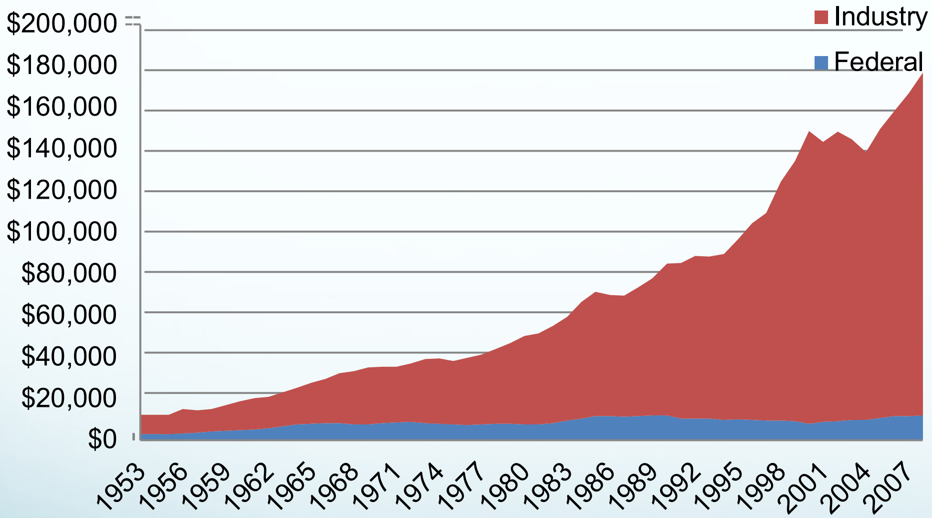
Breakout of Research Funding by Gov't and Industry:



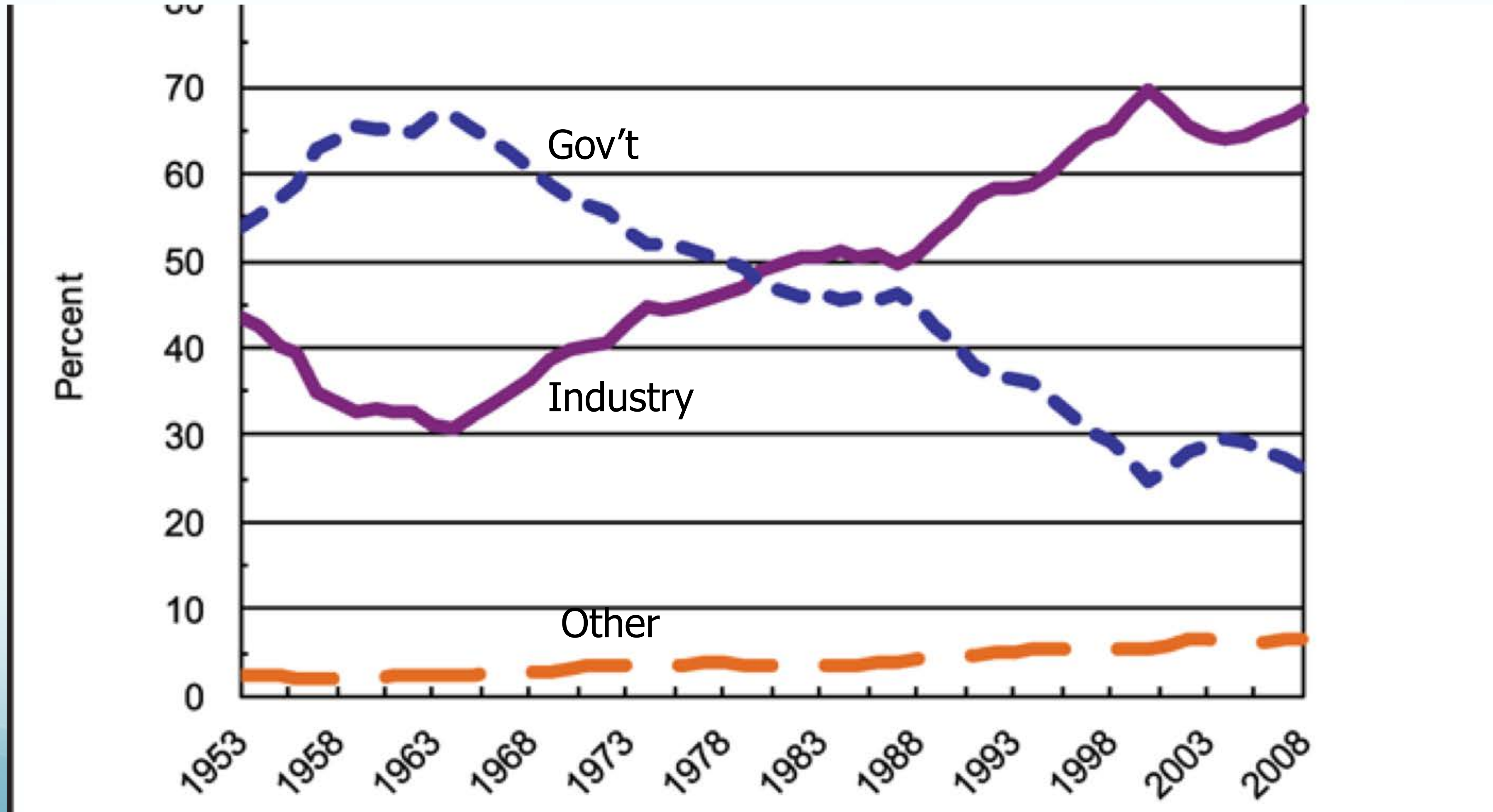
←Investment in Basic Research



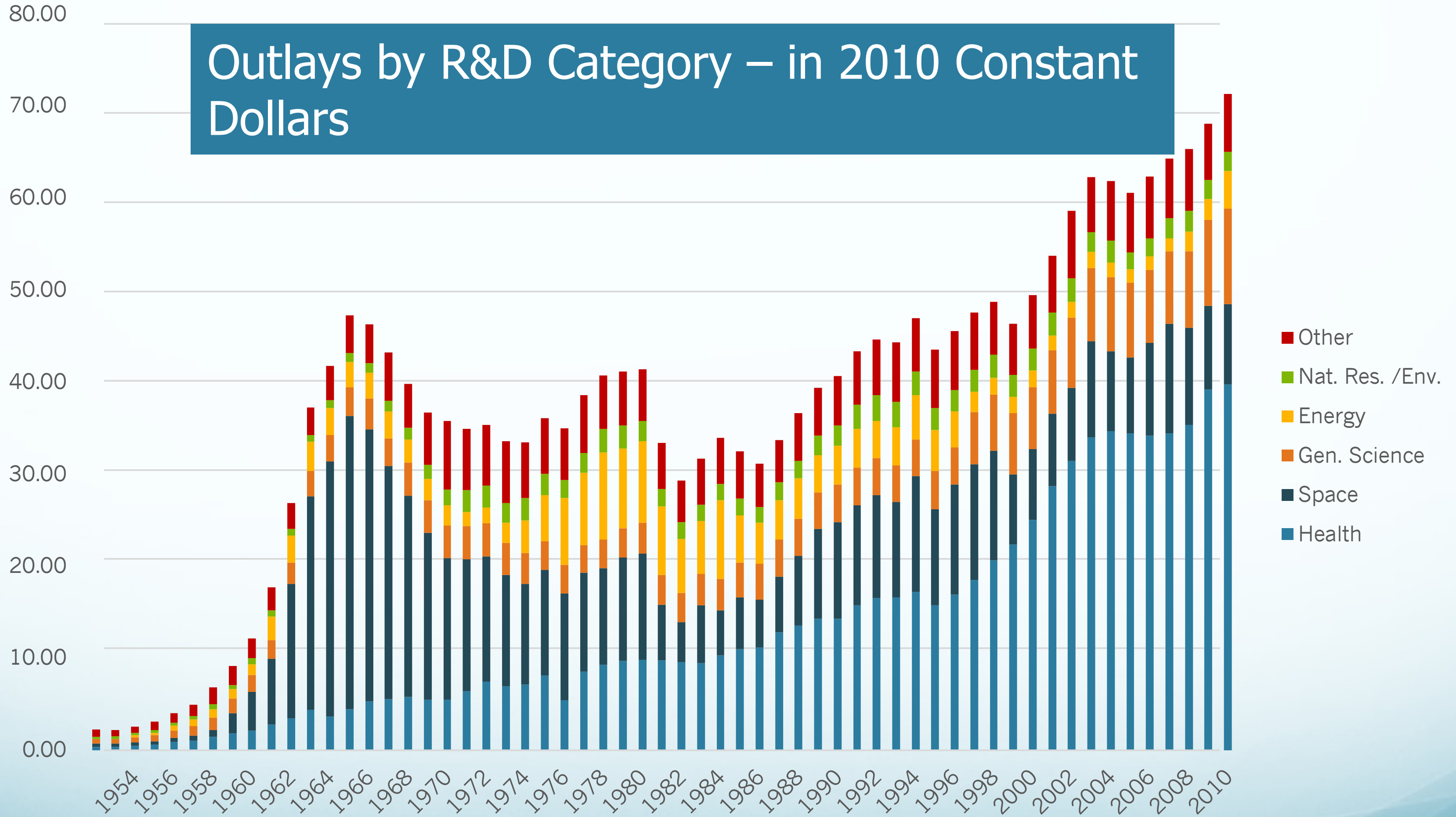
←Investment in Development

- Orange: Industry
- Blue: Gov't

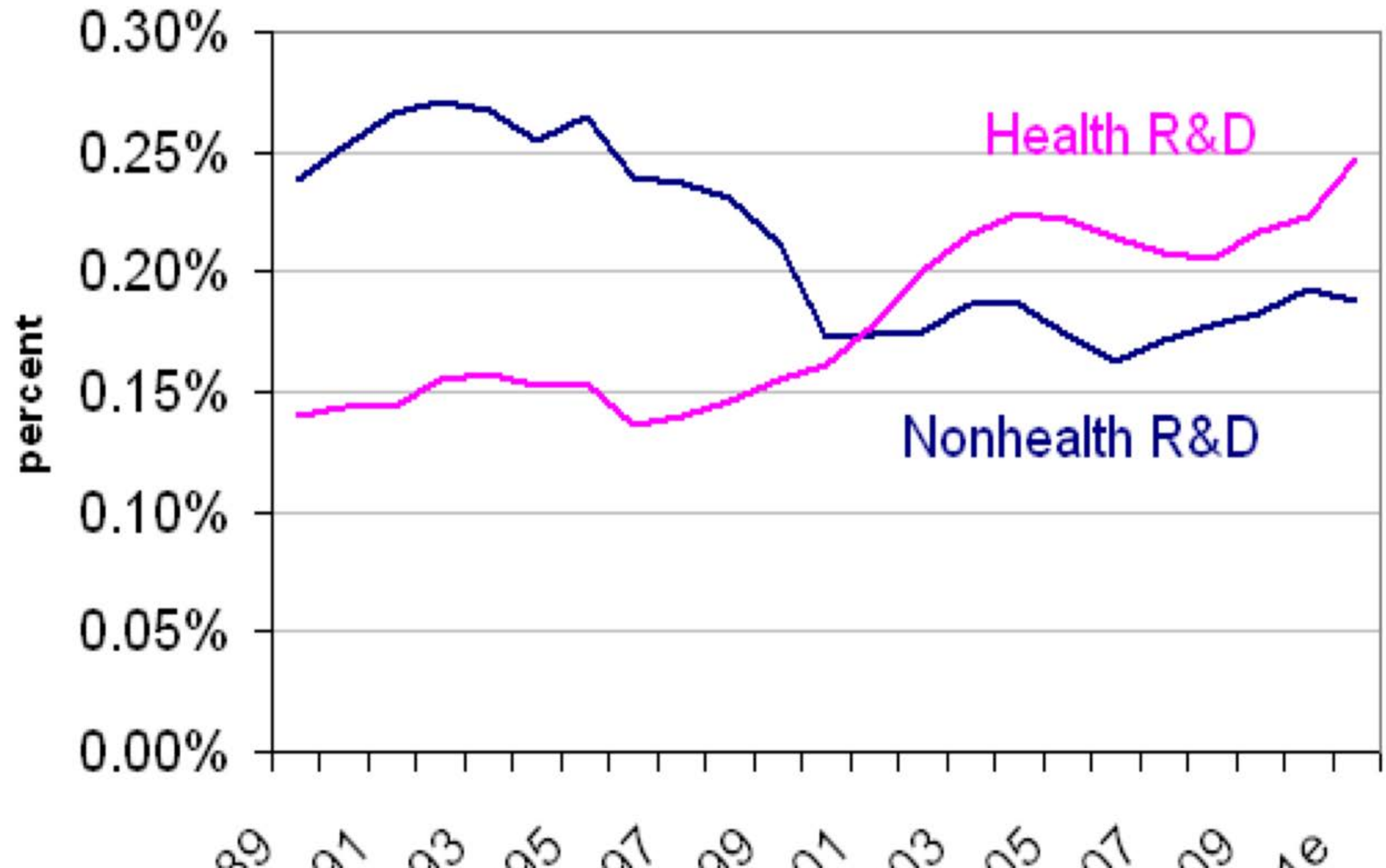
Share of US R&D Support by Industry/Gov't 1953-2008



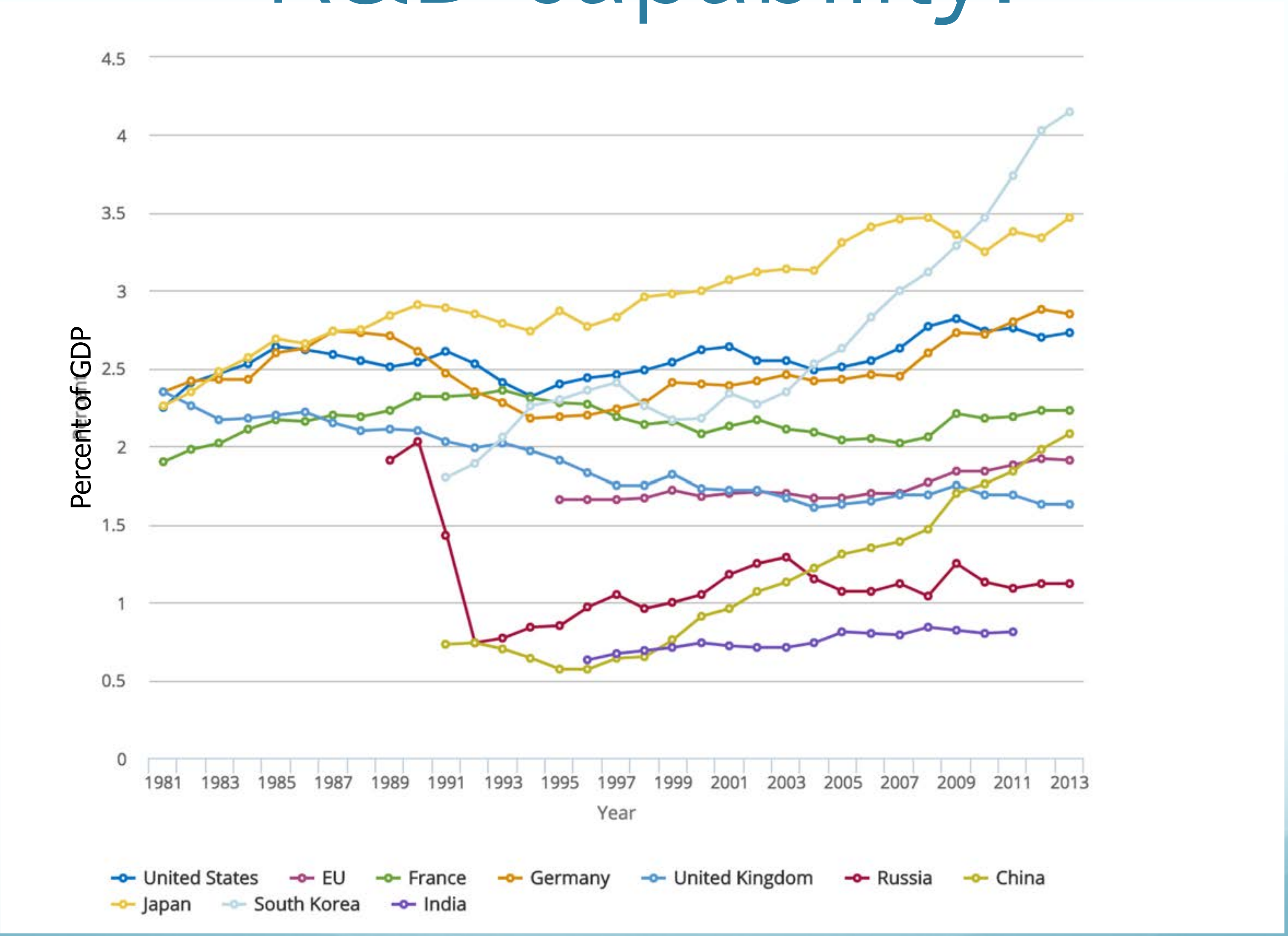
Trends in Non-Defense R&D by Function,1953-2011



Federal Non-Def. R&D Trends (as share of GDP)



Other nations build their R&D capability:



Source: NSF. This image is in the public domain.

SUMMARY-FEDERAL R&D FUNDING

FEDERAL R&D ROLE DECLINING:

Federal share of R&D as % of GDP in decline

- Life science (NIH) –doubled ’98-’03, near $30b
- Physical science research declined as % of GDP

R&D FUNDING CAPACITY THREATENED:

Increasing pressure on Federal budget

- Explosive short term debt – major deficits through decade, which will be exacerbated as boomers retire
- Soc. Sec./Medicare Trustees estimate $72 trillion new present value of federal unfunded entitlement liabilities – total US wealth $45 T
- Taxation capacity may be politically broken
- Congressional budget, appropriations processes breaking down

DIRECT (EXPLICIT) INNOVATION FACTOR #2: TALENT [Romer] -

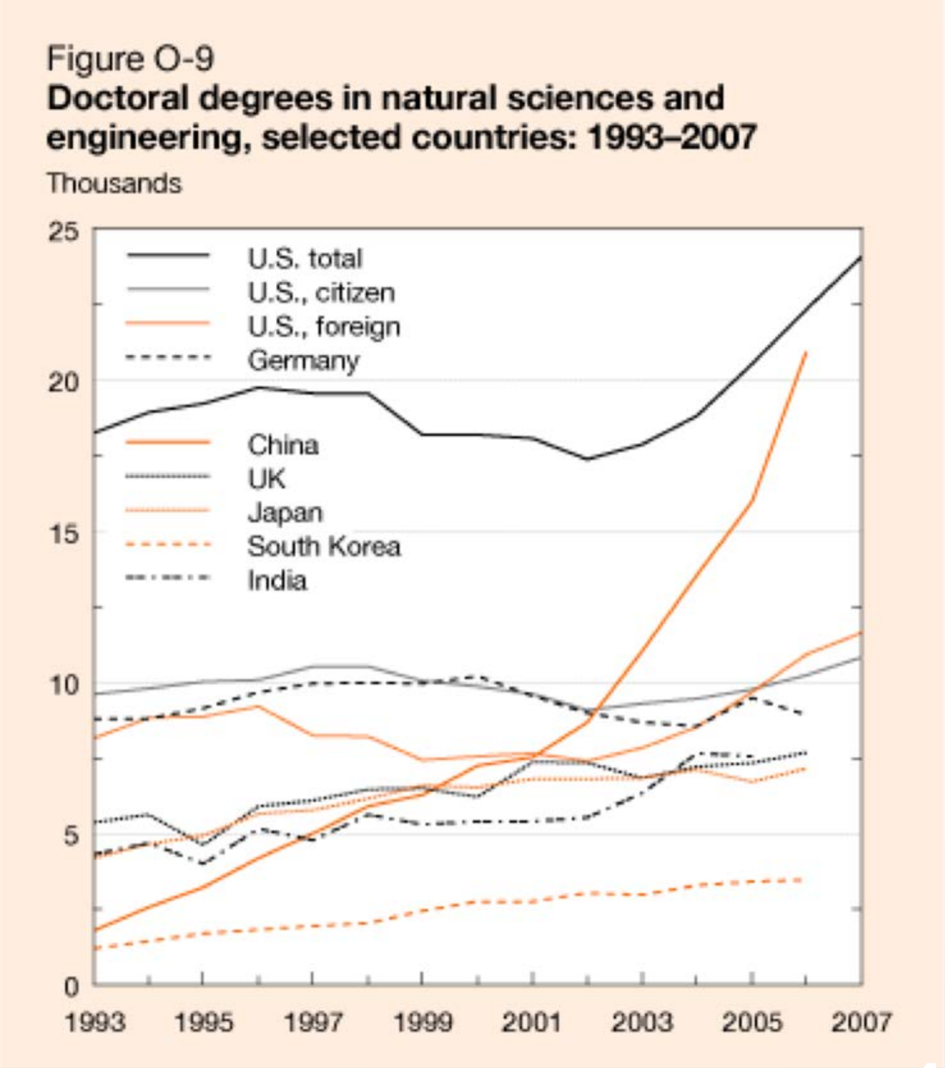
- **BASIC POINT: IF ROMER IS RIGHT,**
  - HUMAN CAPITAL (TALENT) ENGAGED IN RESEARCH, IS CRITICAL INPUT FOR THE TECHNOLOGICAL ADVANCE WHICH DRIVES ECONOMIC GROWTH
- **THEN TALENT DEVELOPMENT IS A SECOND KEY ECONOMIC PILLAR**
- LET' S LOOK AT US TALENT PATTERNS:

TALENT:

- Romer: Prospector theory - # of "prospectors" impacts number of finds
- **You don't fit your talent base to your economy; your talent base sizes your economy – the relationship is dynamic**
- Total # overall US degrees increased between '90 and '00
- But: science/engineering degrees declined same period

NS&E Doctorates by Selected Countries, 1993-2007

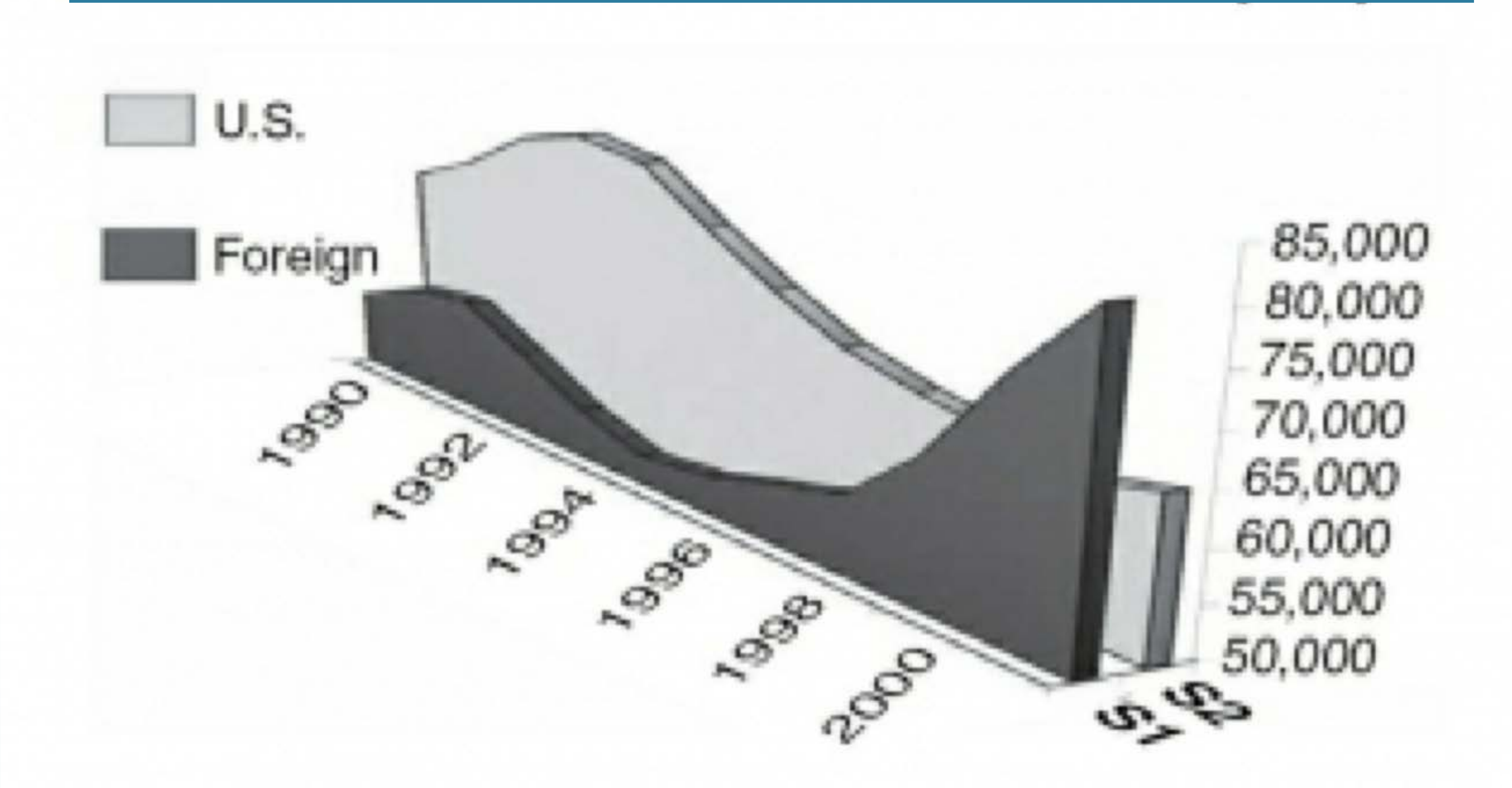
- NSF/NSB, SEI 2010
- Most of the post-2002 increase in U.S. NS&E doctorates reflects degrees awarded to temporary and permanent visa holders, who in 2007 earned about 11,600 of 22,500 NS&E doctorates in the U.S.
- Foreign nationals have earned more than half of U.S. NS&E doctorates since 2006, 31 percent of whom are from East Asia, mostly from China.



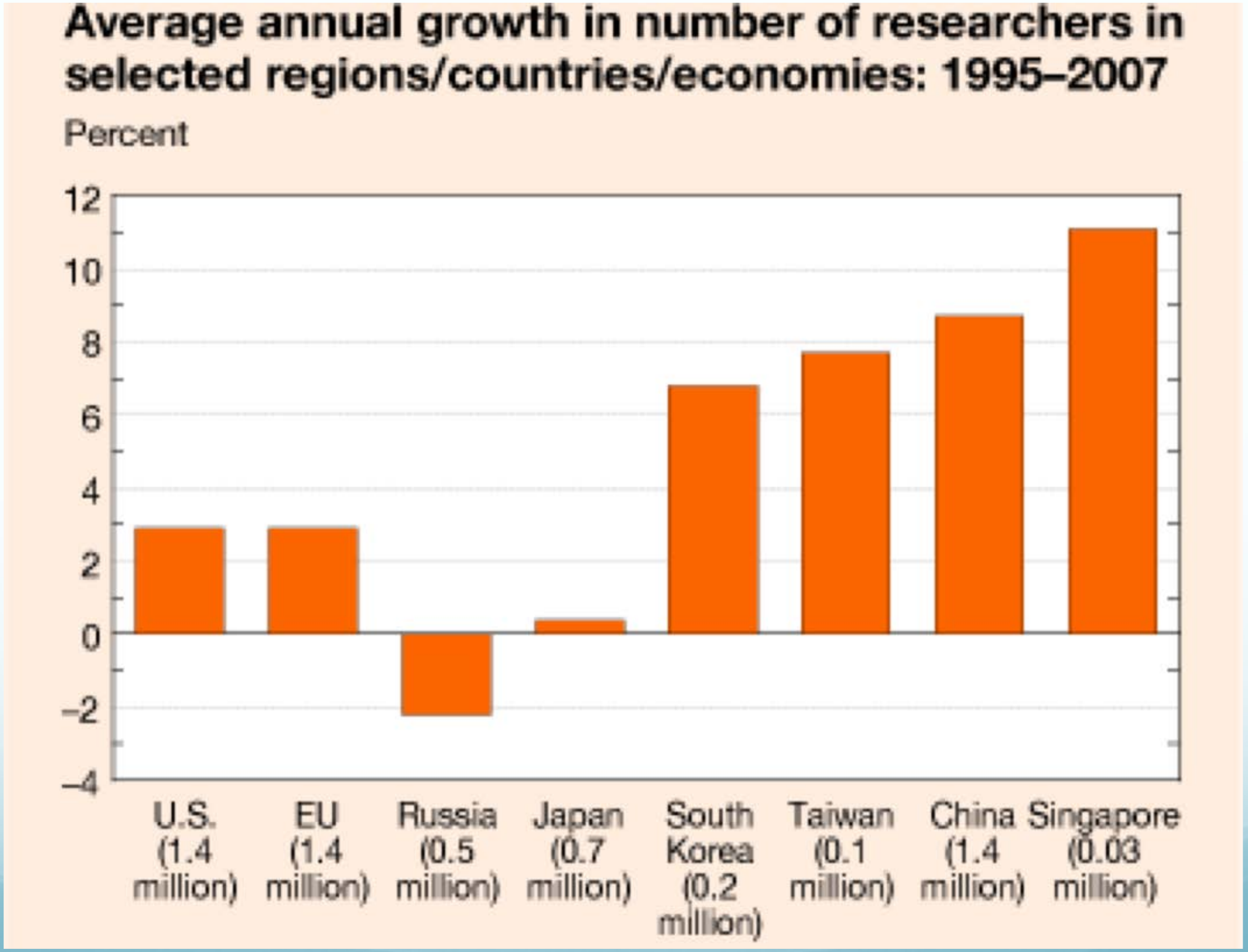
Source: NSF. This image is in the public domain.

US Innovation Depends on Presence of Foreign Born S&E – Will They Stay?

Foreign-born students awarded majority of US science graduate and PhD degrees – 2002 data

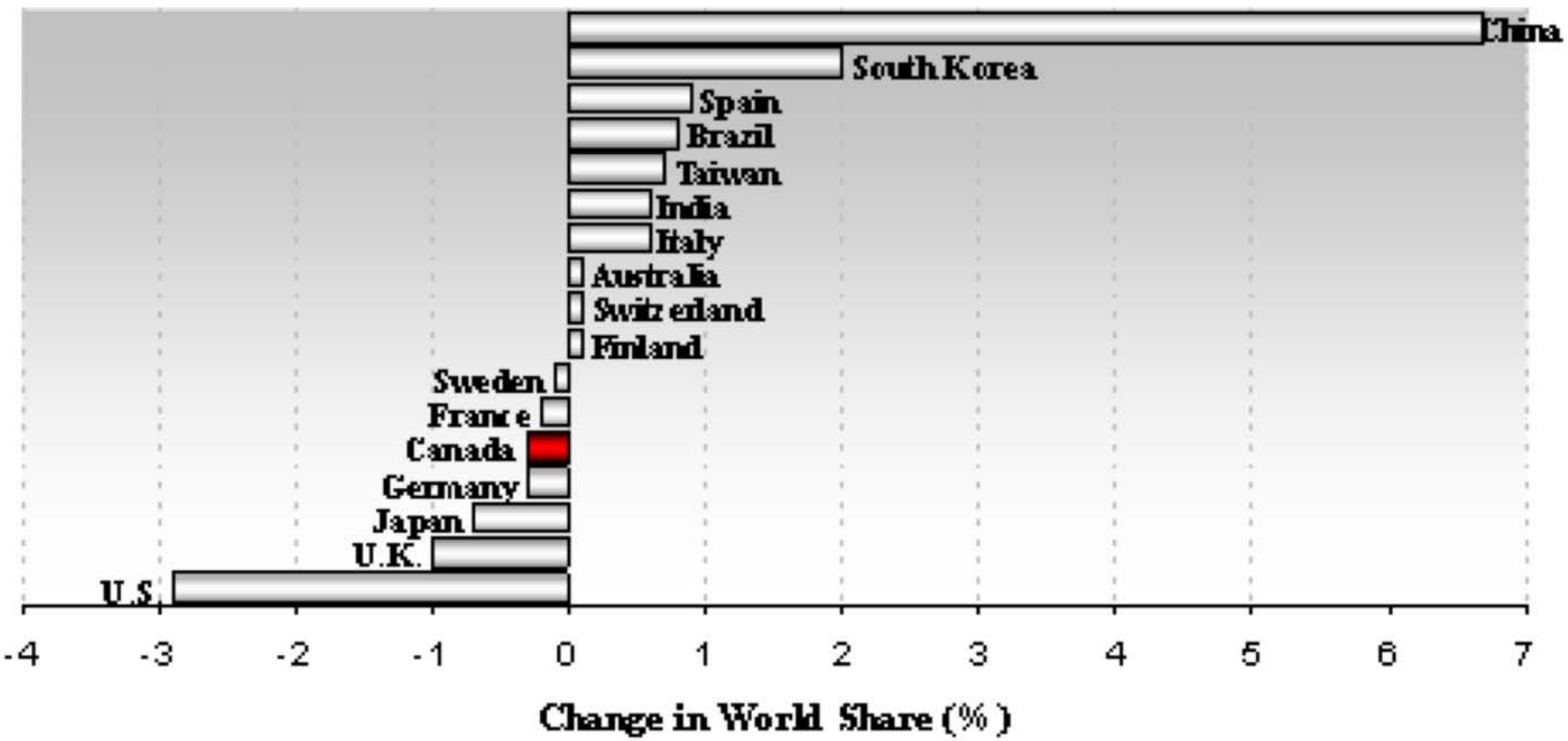


Average Annual Growth Rate in Nos. of Researchers by Country/Economy 1995-2007



Source: NSF. This image is in the public domain.

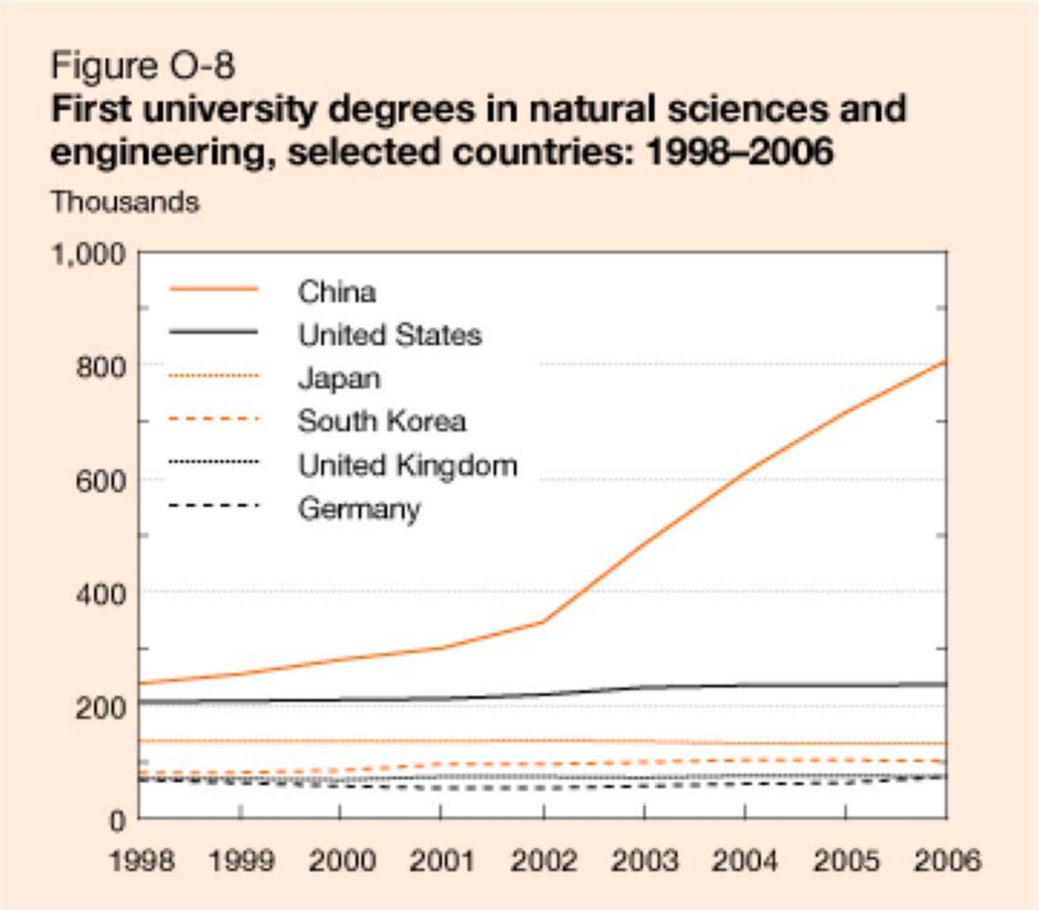
Change in World Share of NSE Publications, 2005 vs. 1996



Source: Observatoire des sciences et des technologies

Image from A Review of Canadian Publications and Impact in the Natural Sciences and Engineering, 1996 to 2005. Courtesy of the Research Council of Canada. This is a copy of an official work that is published by the Government of Canada and that the reproduction has not been produced in affiliation with, or with the endorsement of, the Government of Canada.

Significant increases in first university degrees in natural sciences and engineering in China against the rest of the world (NSB/NSF Indicators 2010):



Source: NSF. This image is in the public domain.

MENU OF **<u>DIRECT</u>** U.S. INNOVATION SYSTEM FACTORS:

- DIRECT– GOV’T –
  - Univ. R&D
  - Gov’t Labs
  - Education, Training
  - Support for Industry R&D (primarily via Defense, agency missions)
    - Primarily research, but support through all stages if agency mission
- DIRECT – PRIVATE SECTOR
  - Industry R&D
    - Primarily Development
    - Goes through engineering, prototyping and production
  - Training

WRAP-UP:

- **Solow** – key to growth: "technology and related innovation" (shorthand: R&D)
- **Romer** – behind technology: "human capital engaged in research" – prospectors (shorthand: Talent)
- **Jorgenson** – key to 90's growth: SC's, multiply productivity throughout economy
- **Merrill** – investors understand value of technology breakthroughs, but only support short term development

WRAP-UP, CON'T:

- **Direct Innovation Factors** -
  - R&D and
  - Talent