Towards quantification of the Role of Materials Innovation in overall Technological Development

Christopher L. Magee

May 6 2010

ESD 342

Massachusetts Institute of Technology
Engineering Systems Division

Chemical Heritage Foundation

- The Chemical Heritage Foundation (CHF) fosters an understanding of chemistry's impact on society. An independent nonprofit organization, we strive to inspire a passion for chemistry, highlight chemistry's role in meeting current social challenges, and preserve the story of chemistry across centuries.

Robert W. Gore Materials Innovation Project

The Robert W. Gore Materials Innovation Project aims to illuminate the diverse contributions of materials innovation within the broader process of technological development in the contemporary age. It documents, analyzes, and makes known the immense benefits of materials innovation through its white paper series, Studies in Materials Innovation. The Gore Innovation Project is made possible by the generous financial contribution of Robert W. Gore, chairman of W. L. Gore & Associates.

- **Patterning the World: The Rise of Chemically Amplified Photoresists**
  by David C. Brock
- **Innovation and Regulation on the Open Seas: The Development of Sea-Nine Marine Antifouling Paint**
  by Jody A. Roberts
- **Sun & Earth and the “Green Economy”: A Case Study in Small-Business Innovation**
  by Kristoffer Whitney

Topics to discuss today

- **Why quantify**
- Alternative possible approaches for quantifying
- Technical Capability dynamics
  - Metric types
  - Typical time dependence
- **Materials in overall technological development**
  - Lifecycle and industry types
  - **Hierarchy of innovation contributions**
- **Quantitative estimates of materials contributions**

Why Quantify

- The annual rate of progress in a field (4% for batteries, 35% for information transport) tends to be stable. The amount of stretch one must take on to keep up as well as the nature of change in the industry depend on these rates of change.
- It would be instructive for planning about R & D and useful to the Gore project and nice to know if we could (for example) say:
  - "Materials Innovation has contributed xy % of the total technological progress in information processing (computation) and zw% in information storage".

Technical Capability Dynamics

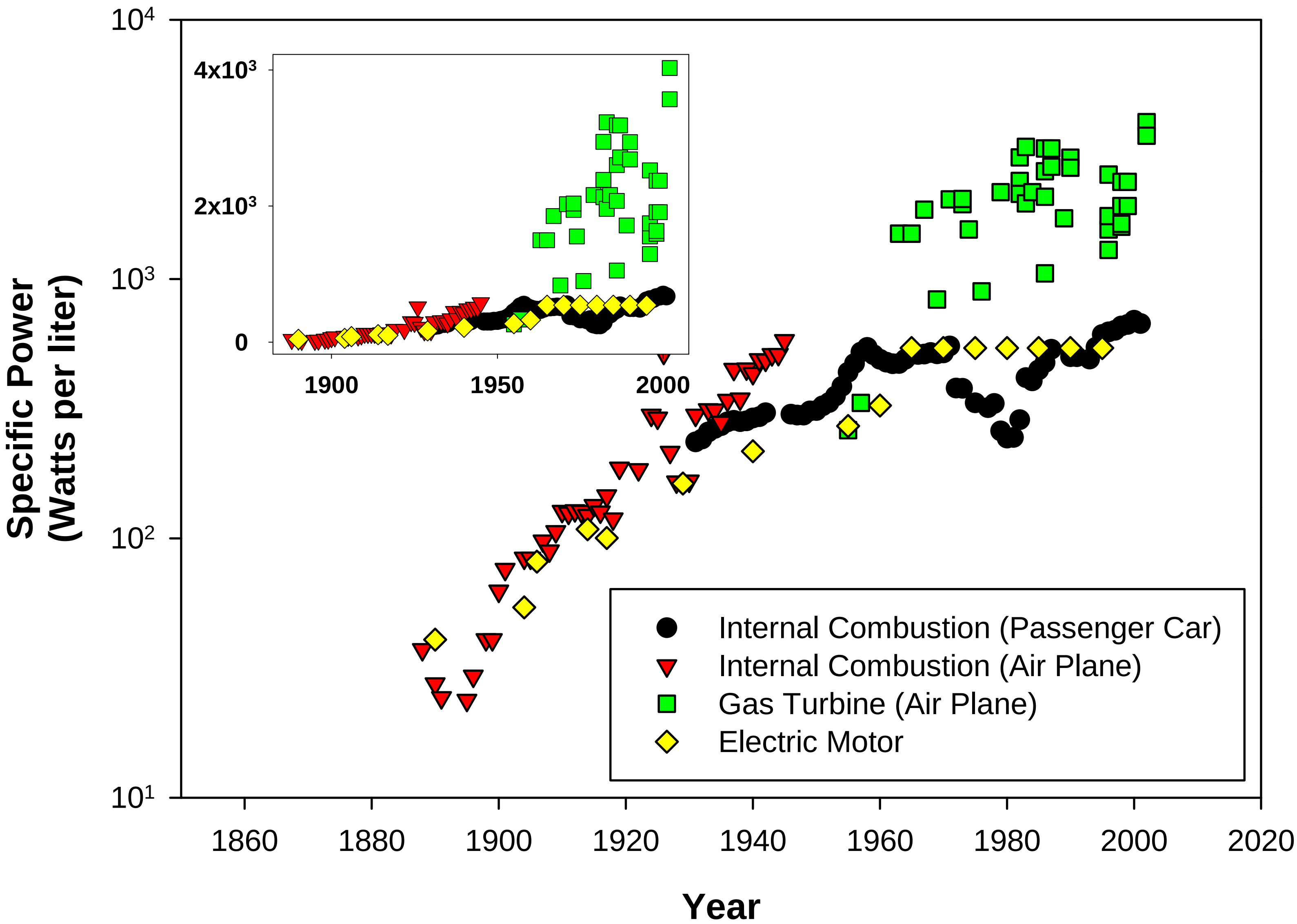
- *A technical capability metric is a performance measure of a key intended technical function of the Technological approach, system or artifact (TASA).*
- Three types are distinguished
  - Figures of merit (general)
  - Tradeoff metrics (productivity)
  - Functional Performance Metrics (FPMs)- tradeoff metrics that apply to generic functional areas (apply to various TASA)
- **FPMs (especially) and tradeoff metrics better represent overall technological progress than do figures of merit**

Functional Performance Metrics

Generic technical function	Functional performance metric	Years	references
Energy storage	• Watt-hours per liter • Watt-hours per kg • Watt-hrs per $	• 1884-005 • 1884-2004 • 1950-2005	Koh and Magee, 2008
Energy transport	• Watts times km. • Watts x km. per $	• 1889-2005 • 1889-2005	Koh and Magee, 2008
Energy transformation	• Watts per KG • Watts per liter • Watts per $	• 1881-2002 • 1881-2002 • 1896-2002	Koh and Magee, 2008
Information storage	• Bits per cc • Bits per $	• 1880-2004 • 1920-2004	Koh and Magee, 2006
Information transport	• Mbs • Mbs per $	• 1850-2004 • 1850-2004	Koh and Magee, 2006
Information transformation	• MIPS • MIPS/$	• 1890-2004 • 1890-2004	Moravec, 1999 Koh and Magee,

Technical Metrics Time Dependence

- Exponentials with time over long periods (rate of improvement ranges from 2% per year (or less) to more than 40% per year. Rates of improvement are relatively constant


Specific Power
(Watts per liter)
10^4
10^3
10^2
10^1
4x10³
2x10³
0
1900
1950
2000
Internal Combustion (Passenger Car)
Internal Combustion (Air Plane)
Gas Turbine (Air Plane)
Electric Motor
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year

Technical Metrics time dependence 2

- Exponentials with time over long periods (rate of improvement ranges from 2% per year (or less) to more than 40% per year. Rates of improvement are relatively constant
- For 14 FPMs and for 31 tradeoff metrics, only 3 cases of limits are seen. None of these fit the logistic or S curve often seen for market share.
- Figures of merit probably do show limits more often (and for efficiency can even be S curves)
- Although the progress occurs as a result of volatile human processes (invention, marketing, innovation etc.), the results are surprisingly “regular”. (Ceruzzi essay – 2005)

Topics to discuss today

- **Why quantify** (and why not)
- Alternative possible approaches for quantifying
- **Technical Capability dynamics**
  - **Metric types**
  - **Typical time dependence**
- Materials in overall technological development
  - Lifecycle and industry types
  - **Hierarchy of innovation contributions**
- **Quantitative estimates**

Hierarchy of technical change in information transport functional category

Category of Change	Examples
Materials/Process Improvement	Coatings on glass fibers
Materials/Process Substitution	Glass fibers vs metallic conductors
Component Redesign	Routers, twisted wire
System Redesign	Cellular concept for wireless
Phenomenon Change	Wireless vs wired transmission
System Operation	TCP/IP

Quantification of Materials Innovation Contribution

- Lower levels of hierarchy are materials/process dominated.
- *Overall* technological change can be assessed (in generic functions) by FPM progress
- Find *tradeoff metrics* that capture progress at *lower (material/process) levels* of the hierarchy
- Compare metrics progress at the different levels to assess contribution to overall technological progress made by materials innovations.
- Example- information transformation (computation)

Hierarchy of technical change in information transformation functional category

Category of Change	Examples
Materials/Process Improvement	Purity of Silicon
Materials/Process Substitution	Single crystal vs. polycrystalline Silicon
Component Redesign	Semiconductor device design
System Redesign	Fully modular processors
Phenomenon Change	Vacuum tubes to transistors
System Operation	Software on IC

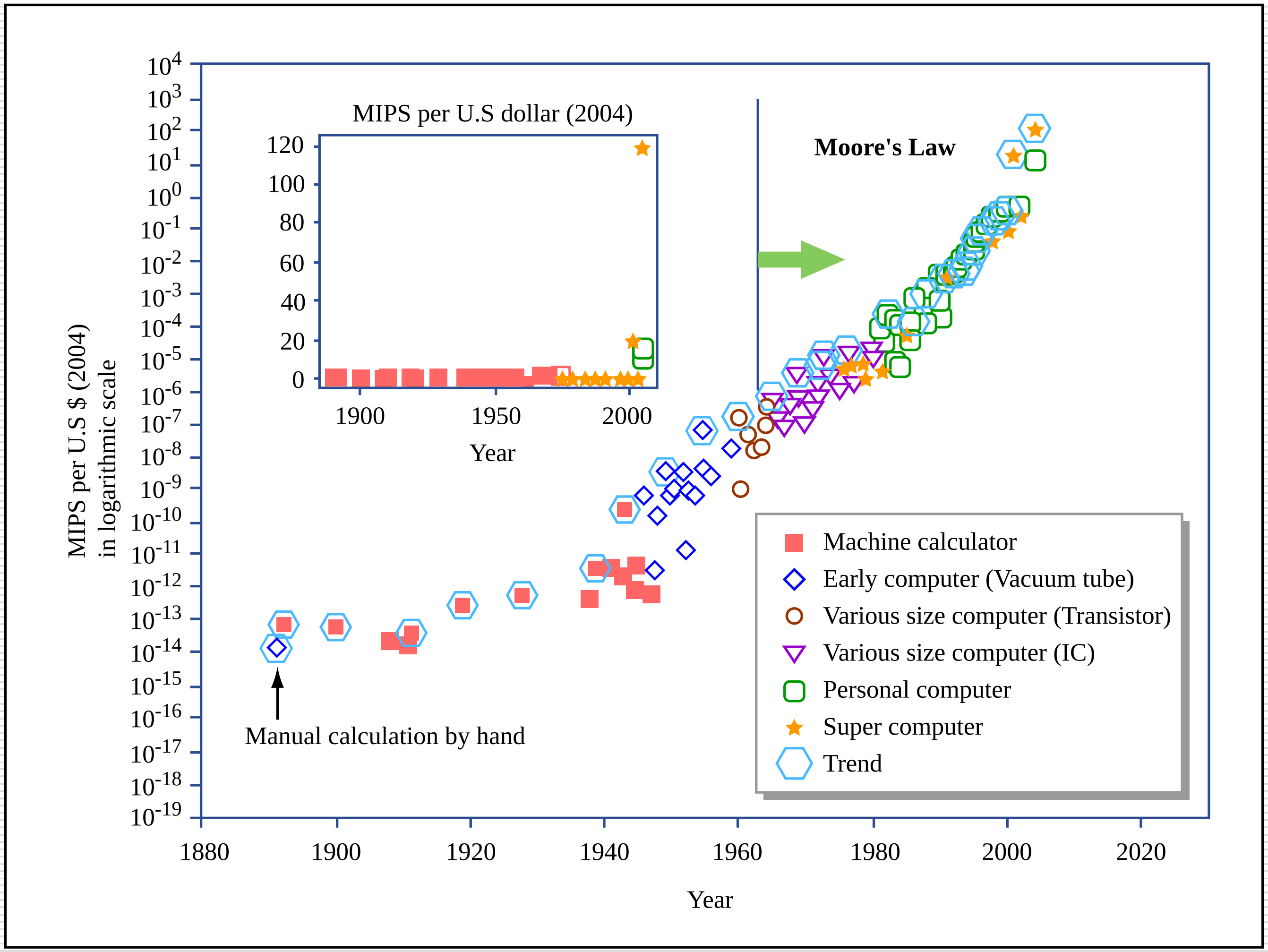


Image by MIT OpenCourseWare.

Comparative Progress

Metric	Progress from 1965 – 2005	Annual progress rate
Moore's Law-transistors per die	$3x10^7$	~42%
Computation, MIPS/$	10^9	~50%

Integrated circuits (Moore's law) innovations are responsible for 42/50 (~84%) of total Computation Progress

MIT ESD
Massachusetts Institute of Technology
Engineering Systems Division

Materials and Process Innovation in Moore's Law

- About 84 % of total information processing progress since 1965 is apparently due to IC improvements consistent with Moore's law. How much of Moore's Law Progress is due to materials/processes innovations?
- Fortunately, there have been many studies of the underlying changes and one study was done in particular depth by Walsh et al (2005)

Critical competencies in semi-conductors

- Semiconductor device design
- Inorganic chemistry
- Batch processing
- Silane chemistry
- Crystalline materials
- Wafering
- Controlled environment processing
- Scale intensive
- Continuous Silicon processing
- Wafer Bonding

Materials and Process Innovation in Moore's Law

- About 84 % of total information processing progress since 1965 is apparently due to Moore's law. How much of Moore's Law Progress is due to materials/processes innovations?
- From Walsh et al study of competencies critical to compete in IC, the only "non-material" competency was "Device Design".
- Moore in a 2006 paper directly addresses the contribution due to device design (which saturated by the early 1970s).

MIT ESD
Massachusetts Institute of Technology
Engineering Systems Division

Overall contribution of Materials and Process Innovations to Computation

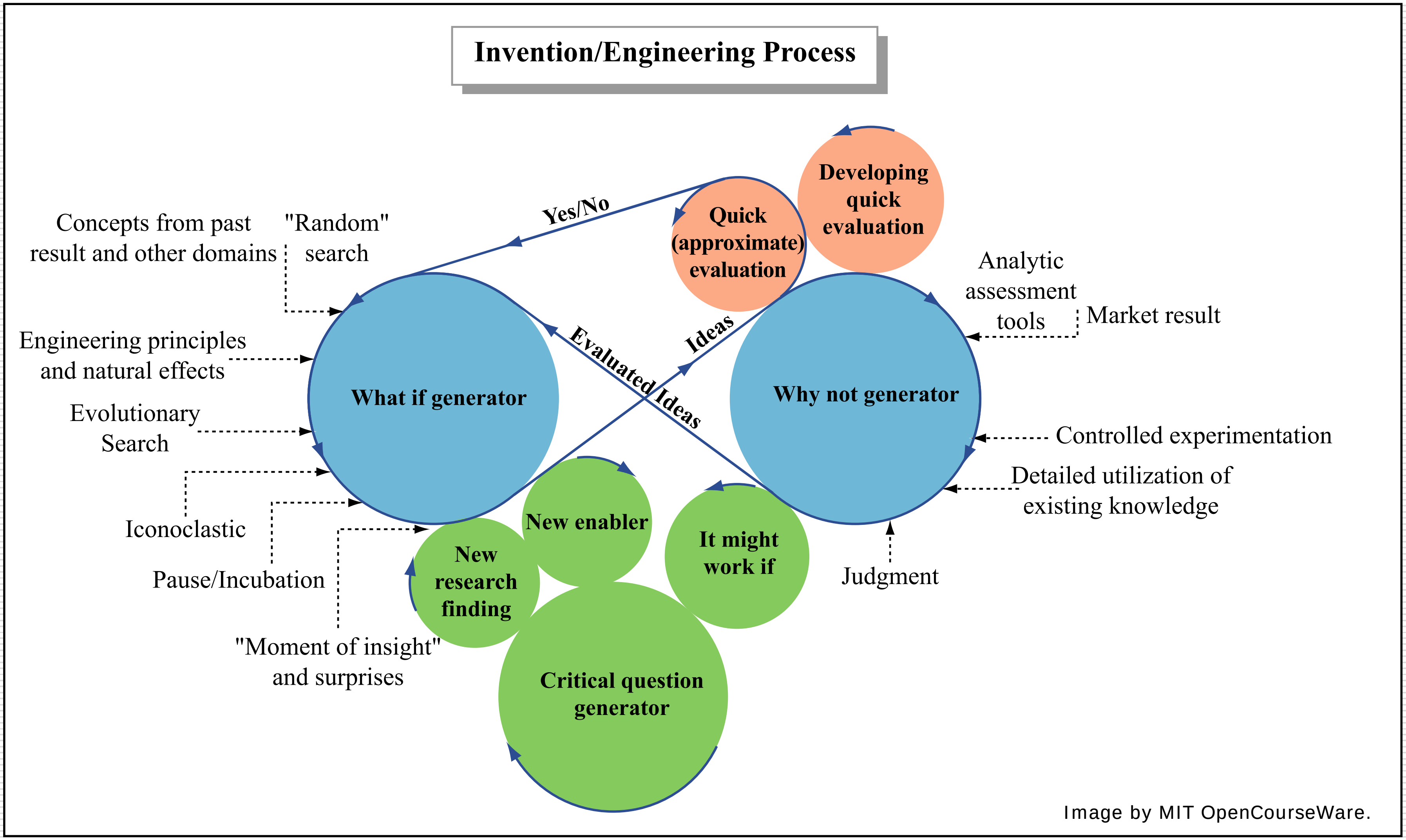
- From Moore's analysis, device design contributed ~ 4 doublings to overall Moore's Law (before 1973). This means that a further 8% per year of the Moore's Law Progress in not due to materials/process innovations.
- Thus, overall slightly more than 2/3 (34%/50%) of the progress in computation was due to materials and process innovations.

Summary

- About 2/3 of progress in computation over the past 40 years is due to materials and process innovations.
- Significant contributions (perhaps even larger fractions in some cases like energy storage) from materials innovations are probable in other functional areas of progress but lack of lower level metric studies render estimates very speculative

Negotiation Fronts or requirements for engineering/invention

- Natural law (Mother Nature's laws apply everywhere)
- Society (perceived as valuable by others who act upon their perception)
- Imagination/creativity-independent invention
- Existing knowledge/capability (**technology, science** (*inventions "ahead of their time"*)
  - Babbage
  - da Vinci
  - IPOD
  - numerous others



Accumulating Knowledge

Search techniques
Preparation or
prototyping skill

Results from assessing
Evaluation techniques
Limits and tradeoffs

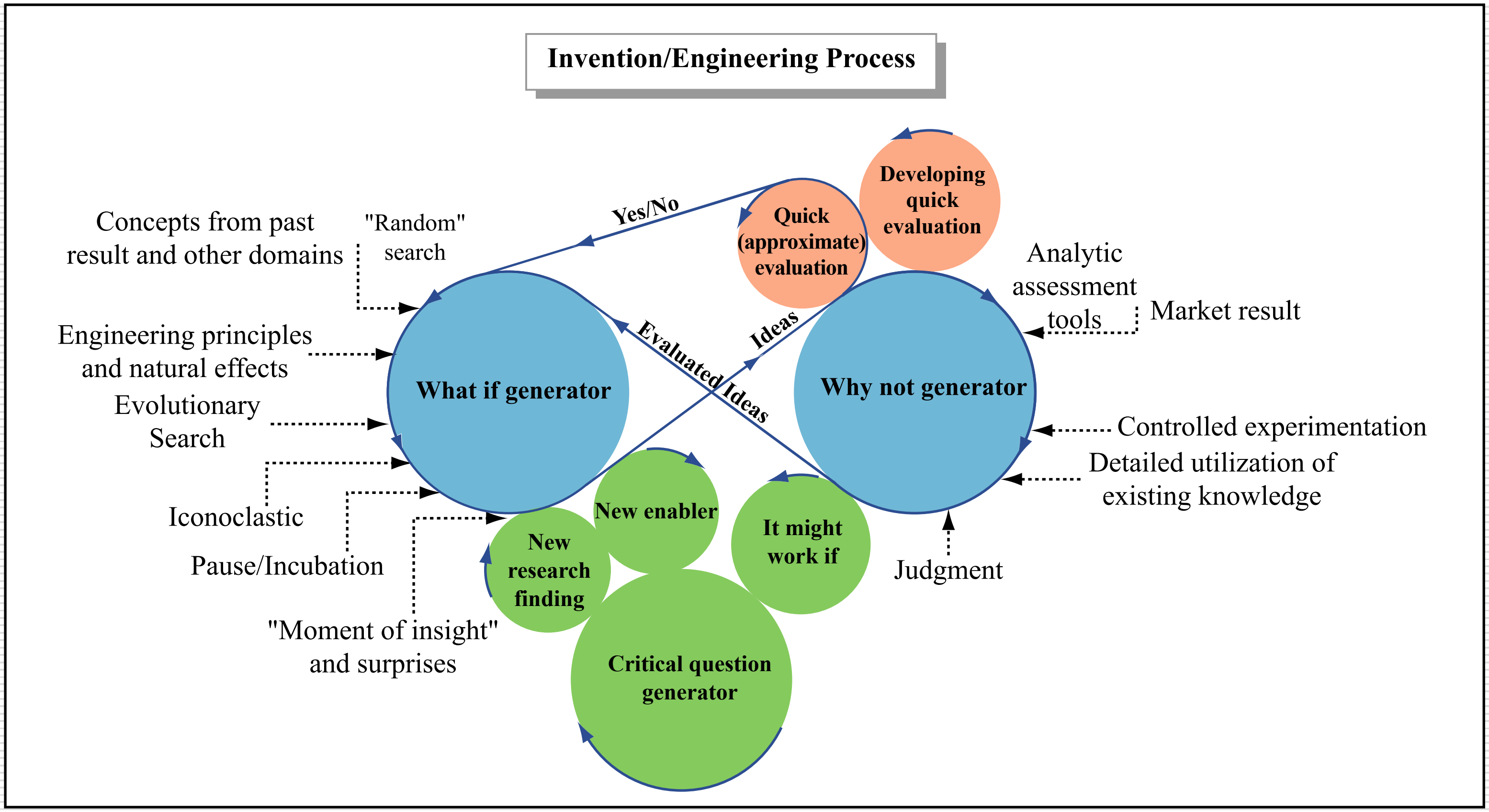


Image by MIT OpenCourseWare.

Accumulating Knowledge

- Search techniques
- Preparation or prototyping skill

- **New science**
- Critical questions
- **New enabling approaches**

- **New combinations**
- **New capabilities**
- **New design principles**
- **Previously impossible actions**

- **Results from assessing**
- **New evaluation techniques**
- Limits and tradeoffs

Influences on Rates of progress III

- "maturity" – empirically eliminated
- *R&D spending*- likely to exceed limits where increases are useful and thus does not have significant explanatory power.
- Market structure for industry or sector
- Capability of people
- Demand for output
- Weakness of supporting science
- Fundamental aspects of the evolving technology
  - *Structure* from a scaling law perspective
  - *Structure* from a decomposability perspective

Scaling effects

- For fundamental reasons, a cost-constrained tradeoff metric can improve as size increases. Human (and earthly) **limits** dictate that 10^{12} improvement over time is not feasible. Imagine a wind turbine or solar concentrator that is 10 (or 1,000 or 10^8) km high.
- If the cost-constrained FPM increases as scale decreases, **limits** are potentially more distant (*Feynman- "There's Plenty of Room at the Bottom")*
- Caveats
  - Scaling is a multi-factor problem
  - **Limits** for specific embodiments are easily seen to be scaling law dependent but **not rates of progress**

Decomposability of Technological Approaches

- A fundamental characteristic with the potential to explain much of the known variation in rates (energy vs. information and even possibly among energy technologies)
- The *evaluation (or selection) process is much faster* for a highly decomposable technological approach (HDTA) as the need for integrated testing is overcome.
- The *generation process* for HDTA can be independently pursued for different components and levels and is thus more prolific which supports *faster* evolution
- Whitney has pointed out that for fundamental reasons systems processing power are less decomposable than systems processing information

A Somewhat Simple Alternative Explanation

- The hypothesis is that the **current capability** (FPM) reflects existing knowledge and also that the **rate of improvement** achieved is similarly related to the existing knowledge, Thus, the increase in capability in a given time period is proportional to the existing capability at the start of that time period.

$$dFPM / dt = \alpha \times FPM$$

$$FPM = FPM_0 \exp[\alpha(t - t_0)]$$

- Not so simple because the progress must depend on the amount of effort to improve (resources and quality devoted to improvement) as well as the practical and scientific knowledge available; the **effort** should also reflect the value of improvement and is therefore also proportional to FPM; thus

$$\alpha = \beta \times \eta$$

- The institutional (social) system co-evolves and affects the technological capability improvement rate
- Not so simple because of fundamental limits to capability
- Fact: The fundamental limits have been generally **grossly underestimated**

Broken Limits