Engineering Systems Doctoral Seminar

ESD.83 – Fall 2011

Session 13
Faculty: Chris Magee and Joe Sussman
TA: Rebecca Kaarina Saari
Guest: Professor Richard de Neufville

Massachusetts Institute of Technology
Engineering Systems Division

Session 13: Agenda

- Welcome and Overview of class 13 (5 min.)
- Dialogue with Professor de Neufville (55min)
- Break (10 min.)
- Discussion of other papers and assignment 9- a survey of research on engineering design
  - Introduction to and framing of session (SFST)
  - Discussion of individual papers
  - Attempt to integrate understanding of field from individual papers. *Is an integrated view useful?*
- Theme and topic integration (Magee)
  - Output of engineering design
  - Socio role in integrated view
- Next Steps -preparation for week 14: (5 min.)

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Scale/Scope of Engineering Design

- All technologically-based design (technical knowledge plays a role in *the creation of useful, novel* stuff)
- Knowledge from *all* technical fields (that is science-based) including social sciences
- *All contexts* (large- small, complex-simple, public-private-NGO:, *purposes* for design such as profits, altruism, etc.; all *aspects* of design process including organizational, cognitive etc.; inputs/outputs) are in scope.
- Non-technical design (poetry, music, visual art, dance, *non-technical* organization, etc.) seems to rely on similar cognitive processes but is not in our chosen boundaries.

Function: Why have a session on Engineering Design?

- From a research viewpoint, it is (after human factors), one of the earlier areas of engineering research that involves behavioral sciences.
- From a practice viewpoint, there is no other engineering activity that has nearly as much impact on the world ("Big D").
- A question to address: What might be meant if we use the term "socio-technical engineering design"?
- Simultaneous design of artifacts, processes, standards, organizations and institutions…

Temporal Considerations in Engineering Design

- Design is a *transformation* of existing knowledge to *novel, useful* stuff;
- thus the *accumulation over time* of useful knowledge is an essential consideration in design;
- *Feedback* models for engineering design are important as *iteration* is fundamental to any design process
- The outputs of design cause changes in the way humans live and thus have societal effects *over time*;

Structure of Engineering Design Field

- As usual, there are alternative valid structures one can consider; for examples:
- Fields of engineering design (classical engineering fields and/or nature of design output);
- Scale, time-frame of design project including organizational, attributes of output (ilitities, etc.) and *process variables*
- *Scientific disciplines* and how the process works
- *Social structure* among and between users, designers, clients and other stakeholders

List of papers and categories

Formative essay-

1. Chapter 5 from Simon's *The Sciences of the Artificial*

Cognitive Science and Engineering Design

2. Parasuranam and Sheridan , "A model for Human Interaction.."
3. Chapter 4 from Weisberg's book- *Creativity*
4. Ball, Ormerod and Morely- "Spontaneous Analogizing by novices and experts.."
5. Linsey, Wood and Markman "Modality and Representation in Analogy"

Processes and Organizations for Engineering Design

6. Chapters/essays from *The Mythical Man-Month* by Fred Brooks
7. Frey et al, "The Pugh controlled convergence..: Model.."
8. Chapter 6 from de Weck, Roos and Magee, :"Partially designed, .."
9. Carlile " Transferring, Translating, and Transforming: An Integrative Framework for Managing Knowledge across Boundaries"

Effects of Engineering Design

10. Luo, Olechowski and Magee "Design Strategy…"

Formative Essay

1. Simon: "The Science of Design: Creating the Artificial" (an essay from 1968/9 in his book- *The Sciences of the Artificial*)

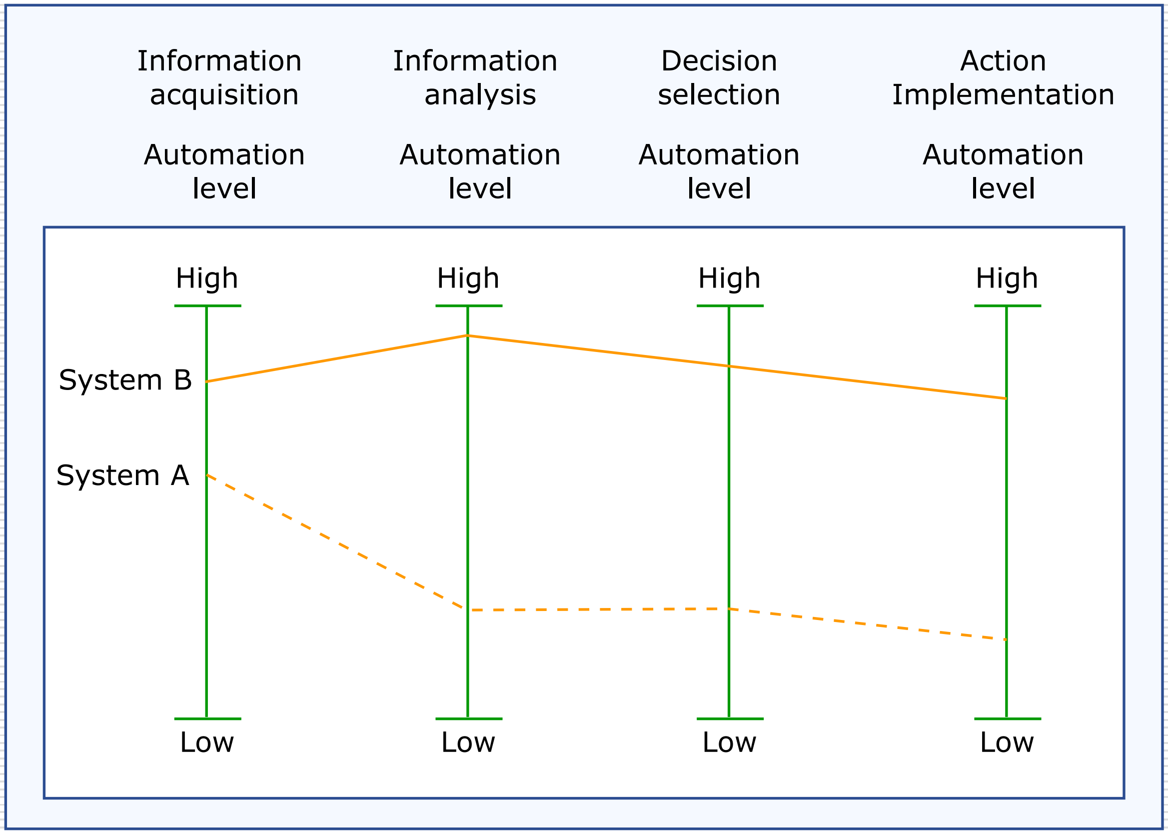
Jameson Toole

Cognitive Science and Engineering Design I

2. Parasuranam, Sheridan and Wickens "A Model for Types and Levels of Human Interaction with Automation", *IEEE Transactions on Systems, Man and Cybernetics- Part A: Systems and Humans*, 2000

Xin Zhang

Systems with different levels of automation



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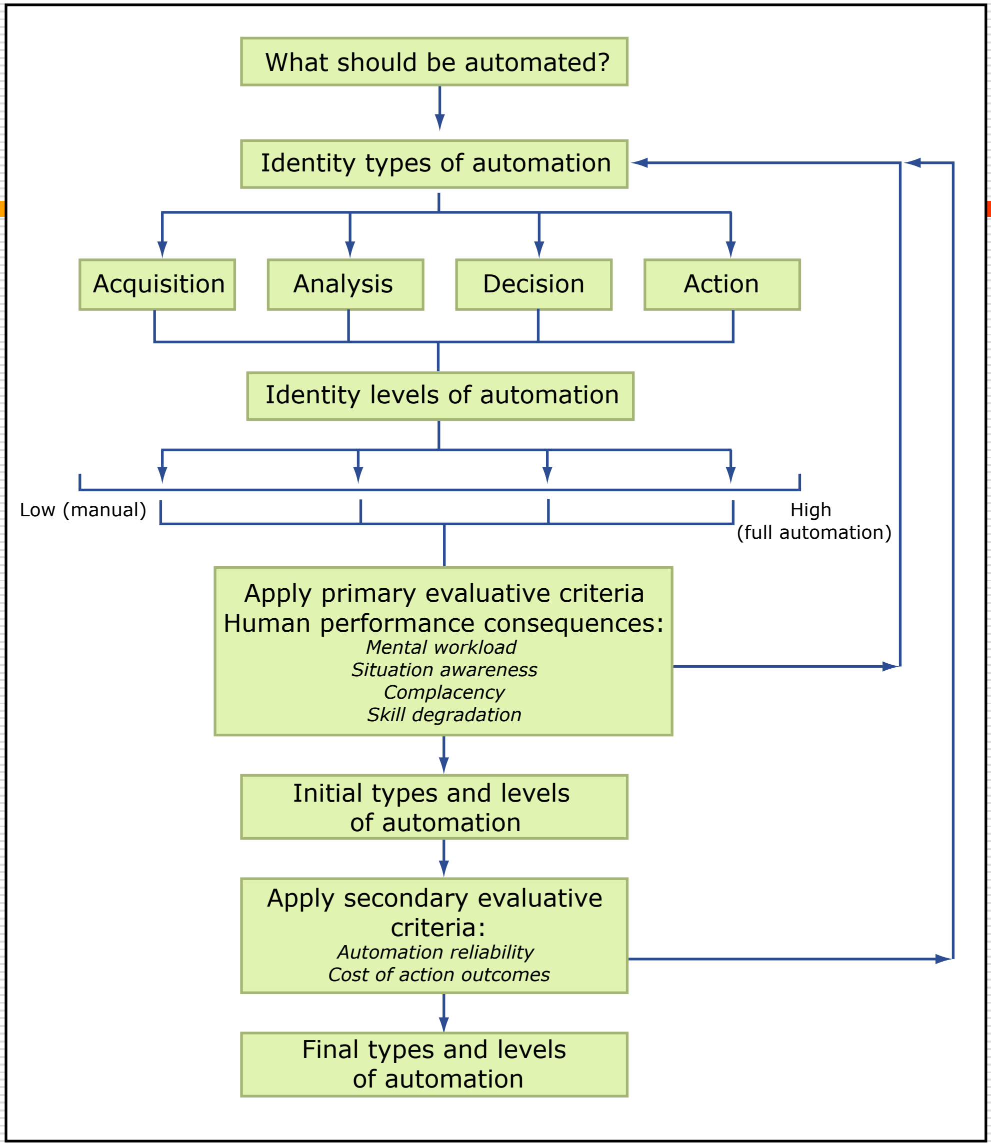
Applying primary and secondary evaluation criteria



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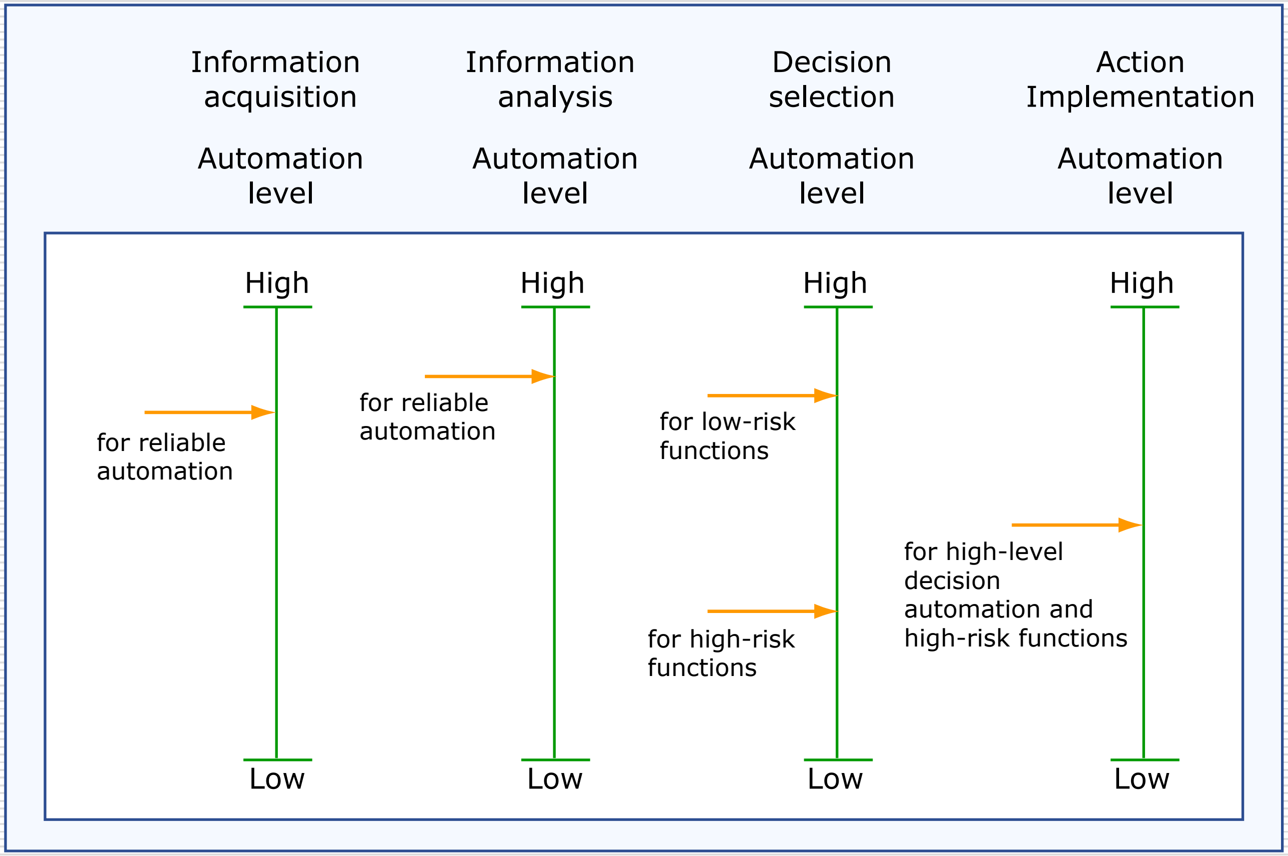
Recommended types and levels for future systems



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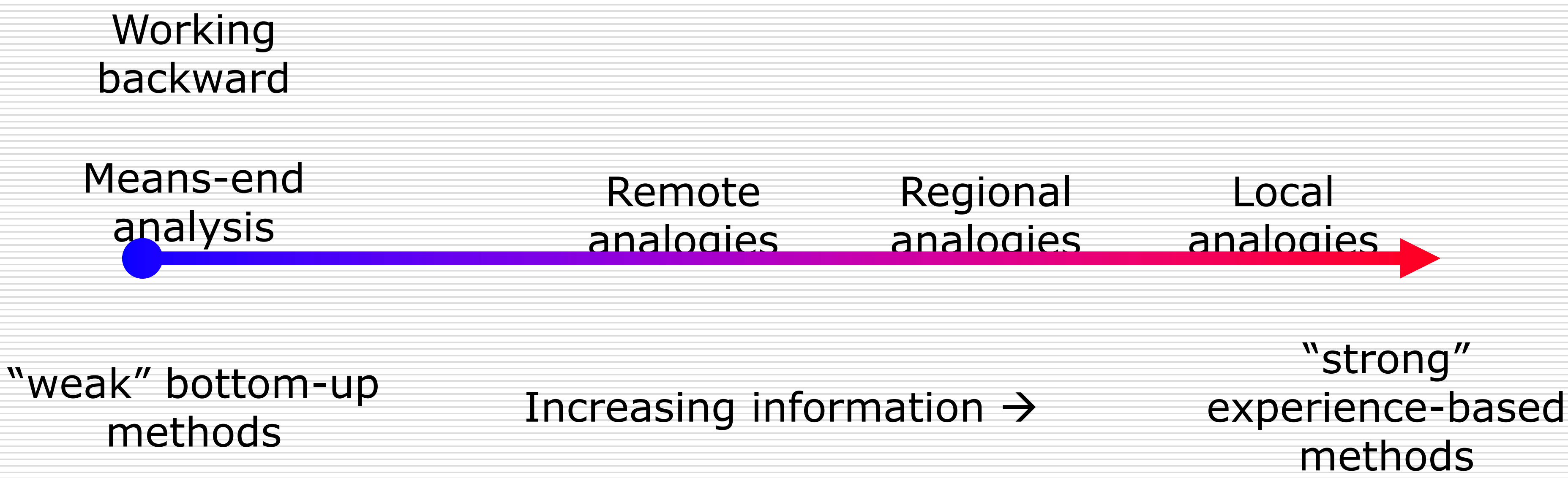
Cognitive Science and Engineering Design II

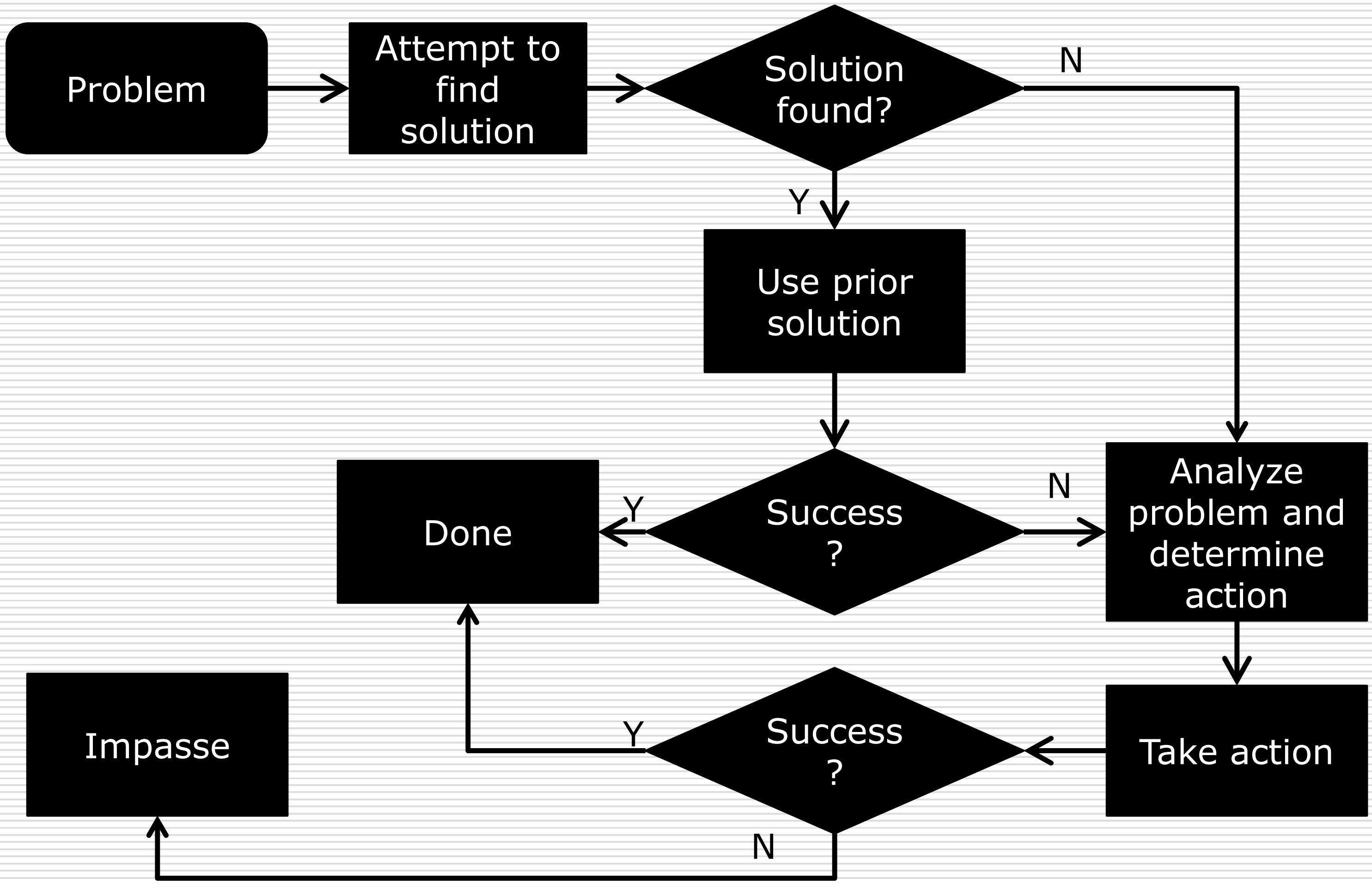
3. R. W. Weisberg, “The Cognitive Perspective Part II: Knowledge and Expertise in Problem Solving” (Chapter from book- *Creativity* 2006)

Jason Ryan

The Continuum of Creative Problem Solving



Weisberg’s problem solving flow chart



Cognitive Science and Engineering Design III

4. Ball, Ormerod and Moreley , "Spontaneous Analogizing in Engineering Design: A Comparative Analysis of Experts and Novices", *Design Studies*, 2004

Josephine Wolff

Cognitive Science and Engineering Design IV

5. Linsey, Wood and Markman, "Modality and Representation in Analogy", *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 2008

David Gerstle

Processes and Organizations for Engineering Design I

6. Brooks, "The Mythical Man-Month and other Essays" Chapters in his book *The Mythical Man-Month* (1974/1999)

Stephen Zoepf

Processes and Organizations for Engineering Design II

7. Frey, Herder, Wijnia, Subrahmanian, Katsikopoulos and Clausing. "The Pugh controlled convergence method: Model Based Evaluation and Implications for Design Theory", *Research in Engineering Design* 2009

Morgan Dwyer

The Pugh Matrix

- Populate Pugh Matrix with Potential Concepts
  - Establish a "datum" concept
  - Establish a set of distinct criteria to evaluate potential concepts
  - For each criteria, evaluate concepts' performance compared to datum
- Iterate
  - Eliminate under-performing concepts
  - Investigate discrepancies
  - Create new concepts by synthesizing knowledge gained through evaluation process

Example of Pugh's Method removed due to copyright restrictions.

The Pugh Matrix provides engineering teams with a structured methodology to organize the design process and to facilitate communication. It also helps teams to identify areas for future study and to create new concepts.

Frey et al’s Contribution

- Quantitative Model of Pugh Controlled Convergence Process (PuCC)
  - PuCC efficiently reduces the size of design spaces
  - PuCC identifies “good” concepts
- Review of Related Academic Literature
  - Hazelrigg (1998) argued that PuCC’s “pair-wise” comparison process is an invalid decision-making process because it does not calculate global utility
  - Czerlinski et al (1999) argue that human cognitive processes respond more effectively to simple decision-making heuristics (like “pair-wise” comparison) as compared to more complicated schemes (like utility functions)

Frey et al’s review of how the Pugh Matrix is used in practice was sufficient to convince me of its utility; the quantitative model was unnecessary and unpersuasive. Perhaps more interesting questions relate to Frey et al’s literature review; for example, how does the Pugh Matrix aid individual cognitive and group social processes?

Processes and Organizations for Engineering Design III

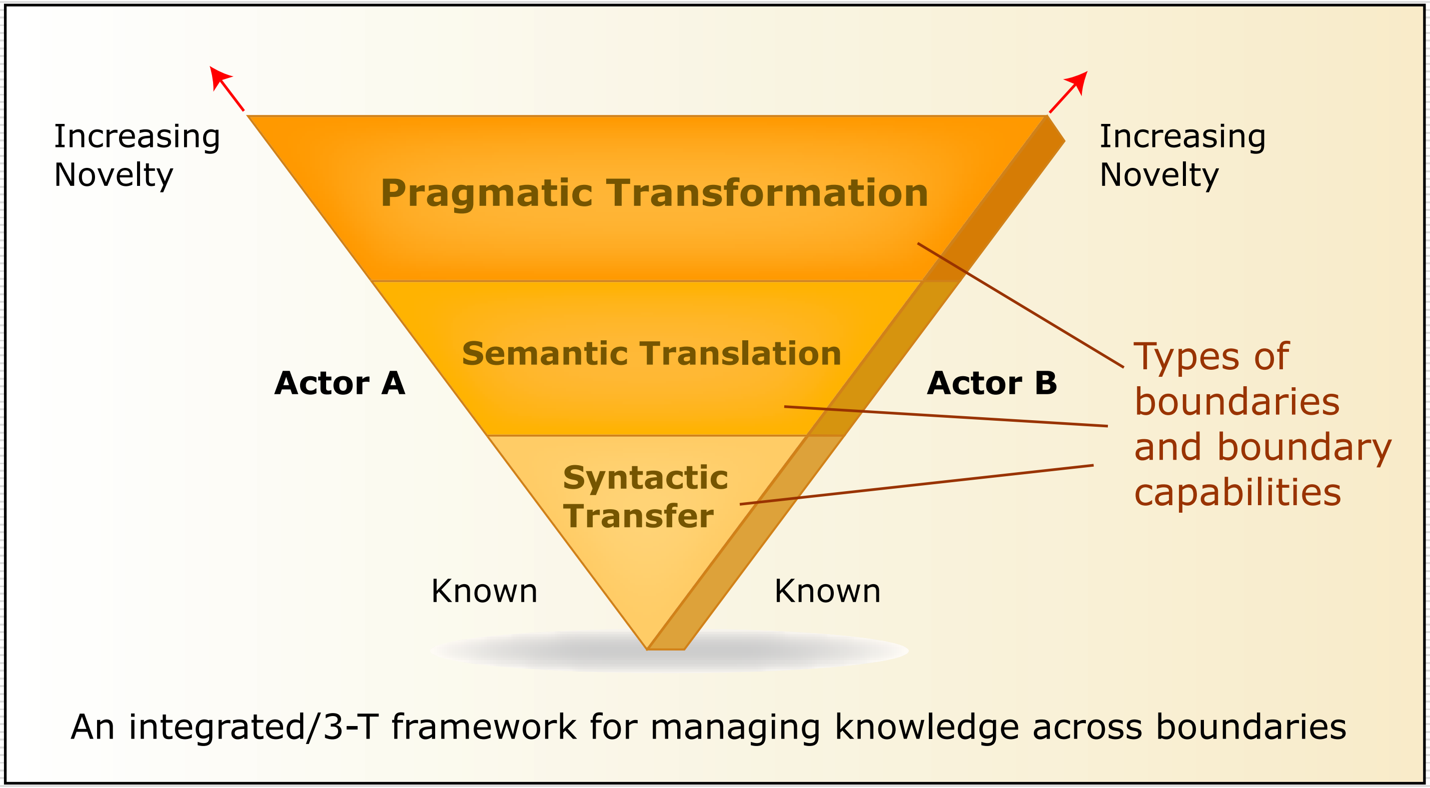
8. de Weck, Roos and Magee, "Partially Designed, Partially Evolved" (a book chapter from 2011 book *Engineering Systems: Meeting Human Needs in a Complex Technological World*)

Steven Fino

Processes and Organizations for Engineering Design IV

9. Carlile, "Transferring, Translating and Transforming: An Integrative Framework for Managing Knowledge across Boundaries", *Organizational Science*, 2004

Jonathon Krones



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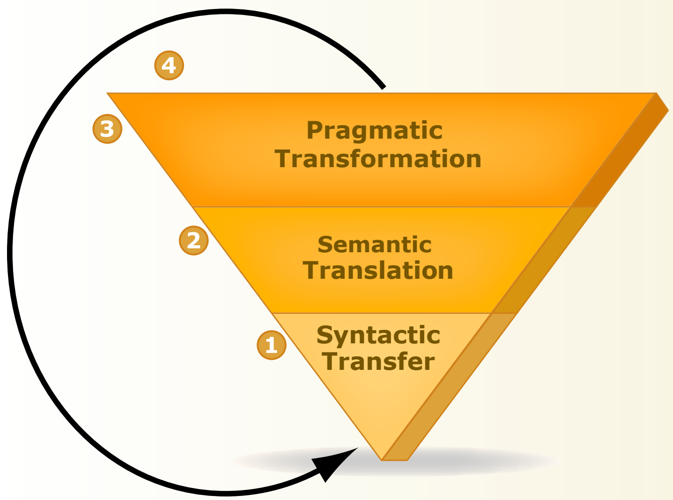

4. Supports an **iterative** approach where actors get better at developing an adequate common knowledge for sharing and assessing each other's knowledge.
3. A pragmatic capacity establishes common interests for making trade-offs and **transforming** domain-specific knowledge.
2. A semantic capacity develops common meanings for identifying novel differences and dependencies and **translating** domain-specific knowledge.
1. A syntactic capacity requires the development of a common lexicon for **transferring** domain-specific knowledge.

3-T framework and the four characteristics of a "Pragmatic" boundary capability.

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Carlile, PR (2004). "Transferring, Translating, and Transforming: An Integrative Framework for Managing Knowledge across Boundaries," *Organization Science*, ***15***(5): 555–568.

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Effects of Engineering Design

10. Luo, Olechowski and Magee, "Technologically-based Design as a Strategy for Sustainable Economic Growth" (paper submitted in October, 2011)

Bill Young

Technologically-based Design

Main argument: “Tech-based design has important strategic value for long-term sustainable economic growth.”

- Key ideas:
  - Differentiate between innovation, invention, and design
  - Not all design created equal (tech-based design leverages deep expertise
  - Deep expertise best determinant of successful design (can be accumulated)
  - In depth study of Singapore reveals they are leveraging many (but not all) aspects of tech-based design as part of a successful national strategy for economic growth

Critique

- Line between art and engineering increasingly blurring (IDEO, MIT Media lab, data analytics companies, etc.)
- Accumulation of deep expertise possible in any field (e.g. work of Roger Martin, Hillary Austen)

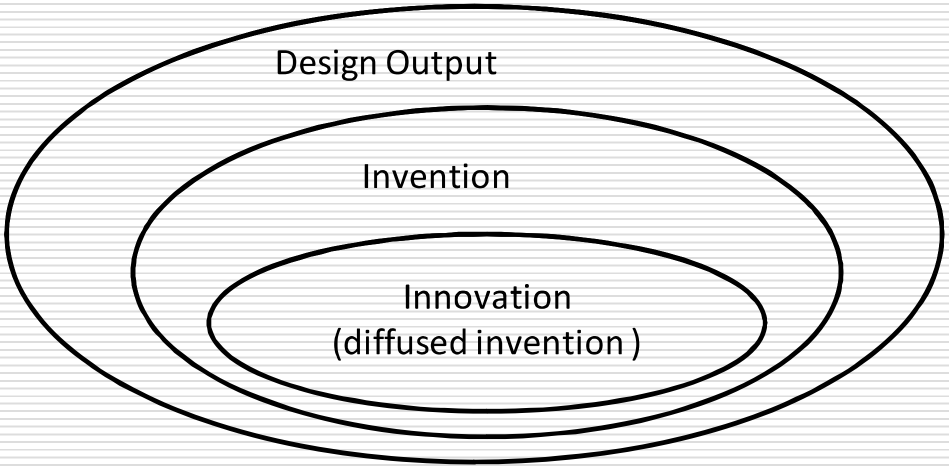

Fig.1. Relationship between Design Output, Invention, and Innovation

Figure from "Technologically-Based Design as a Strategy for Sustainable Ec
By J. Luo, A. Olechowski, C. Magee

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Output of Engineering Design

- If you wanted to *quantitatively* study the effect of engineering design over time, what could you do?
- Use a metric of "goodness" that results from new designs and plot it over time.
- The best-known example?

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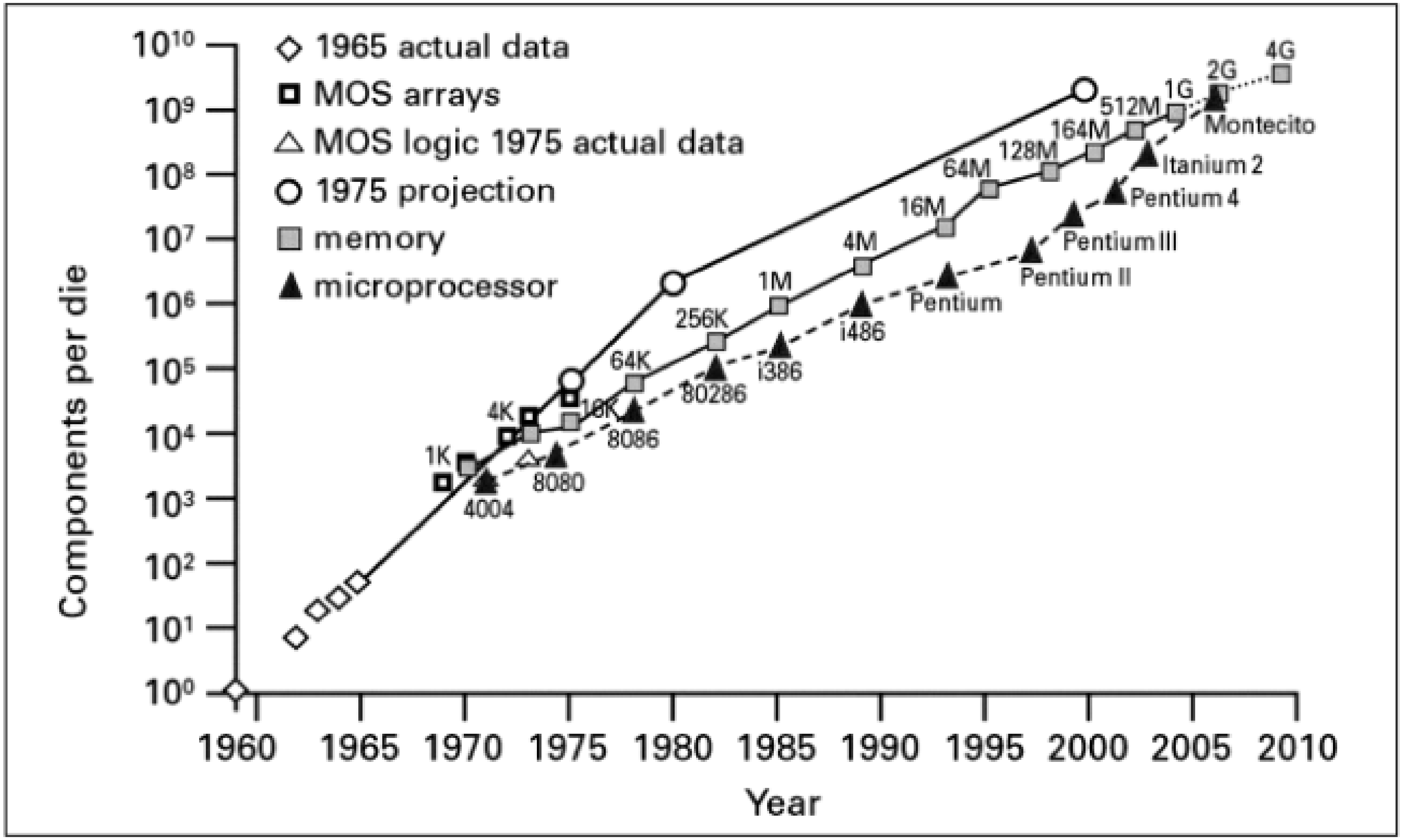

FIGURE 9. Integrated circuit complexity, actual data compared with 1975 projection. Source: Intel.

From Moore, G. E. "Moore's Law at 40"

Output of Engineering Design

- Moore's Law is a special example even if does cover ~ 10 orders of magnitude and ~ 5 decades.
- What might be done to more generally study the effects or outputs of engineering design over time?
- Study functional performance and many other cases of tradeoff metrics like transistors per die.

Terminology - Functional Performance

- Function- **what** a system, device etc. **does**

Functional technological classification with operands and operations

Operand			
	Matter (M)	Energy (E)	Information (I)
Operation			
Transform	Blast furnace	***Engines, electric motors***	**Analytic engine, calculator**
Transport	Truck	***Electrical grid***	**Cables, radio, telephone and Internet**
Store	Warehouse	***Batteries, flywheels, capacitors***	**Magnetic tape and disk, book**
Exchange	eBay trading system	Energy markets	World wide web, Wikipedia
Control	Health care system	Atomic energy commission	Internet engineering task force

- Performance- **How well the function is achieved** and measured by a FPM (Functional Performance Metric) : **Tradeoff metric**

Table 2
Operation and functional performance metrics for measuring the progress in energy technology

Operation	FPM name	FPM units
Storage	Stored specific energy	Watt-hours per liter
	Energy storage density	Watt-hours per kg
	Stored energy per unit cost	Watt-hours per U.S. dollars (2005)
Transportation	Powered distance	Watts × km
	Powered distance per unit cost	Watts × km per U.S. dollars (2005)
Transformation	Specific power	Watts per liter
	Power density	Watts per kg
	Power per unit cost	Watts per U.S. dollars (2005)

Functional Performance Metrics

Generic technical function	Functional performance metric	Years	References
Energy storage	• Watt-hours per liter • Watt-hours per kg • Watt-hours per $	• 1884-2005 • 1884-2004 • 1950-2005	Koh and Magee, 2008
Energy transport	• Watts times per 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 per $	• 1890-2004 • 1890-2004	Moravec, 1999 Koh and Magee,

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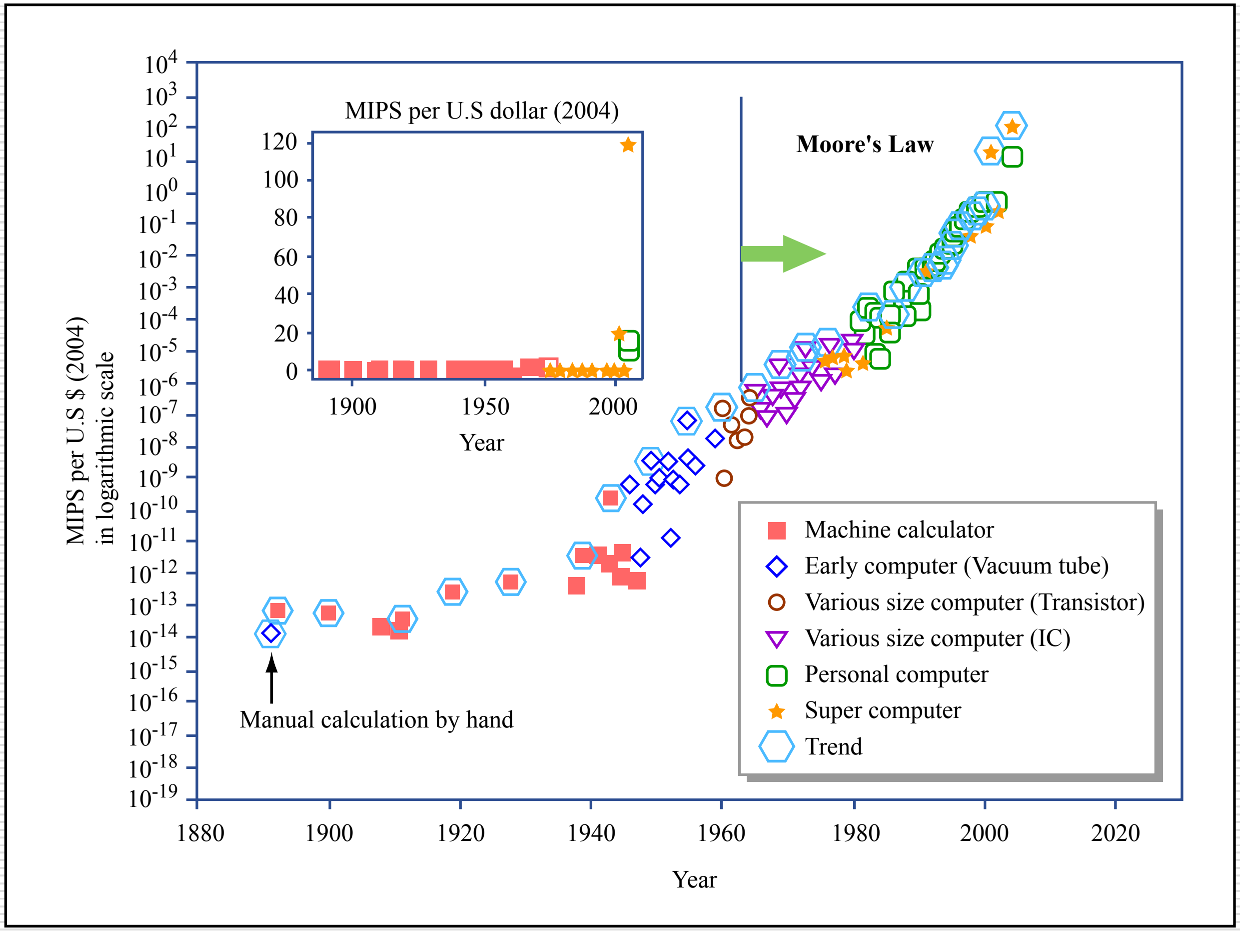
Temporality

- Time dependence of capability
- Only the “best” or highest capability is considered for each time period
- This is independent of the basic Technical Artifact, System or Approach (TASA) and is the highest for the particular function or tradeoff metric



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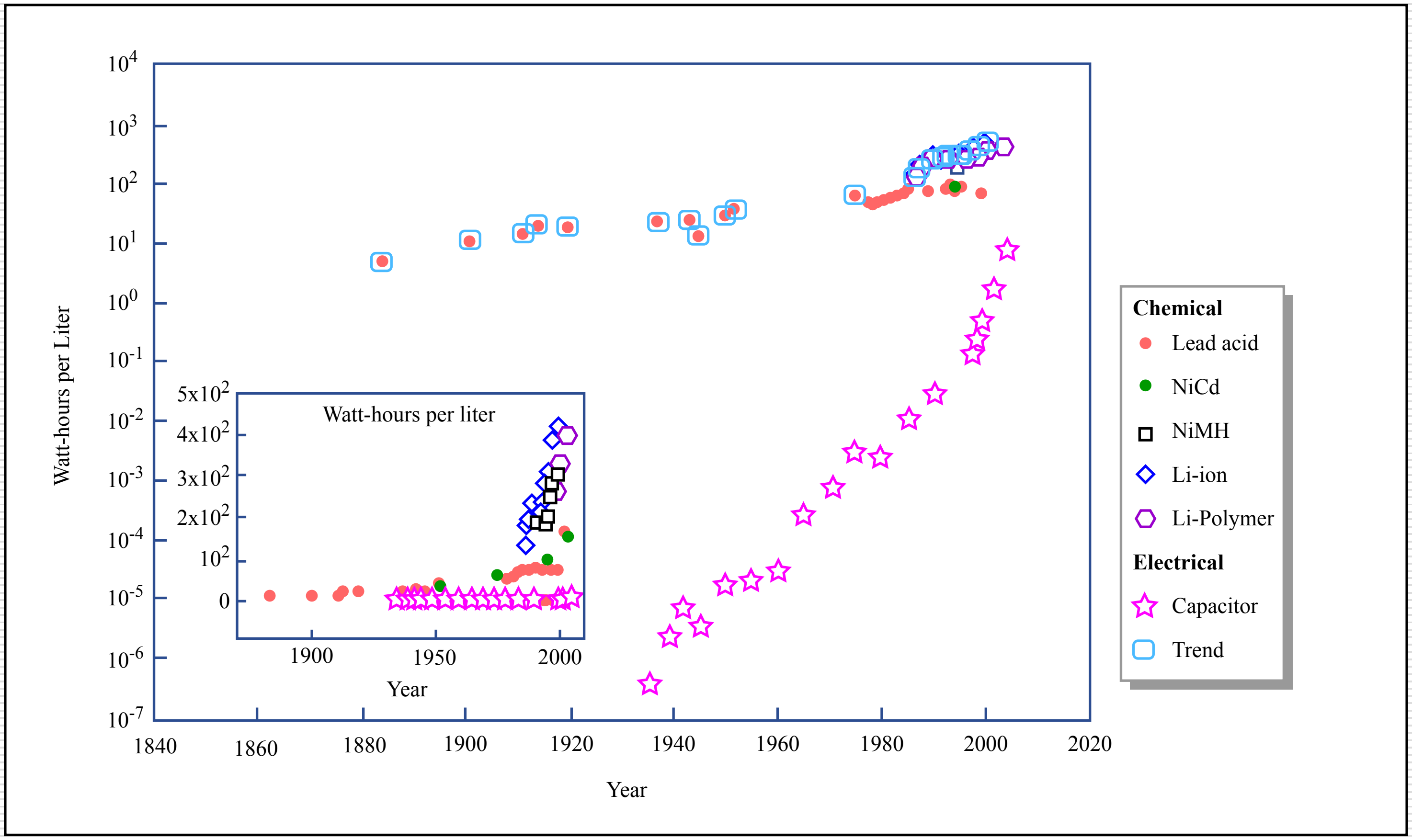

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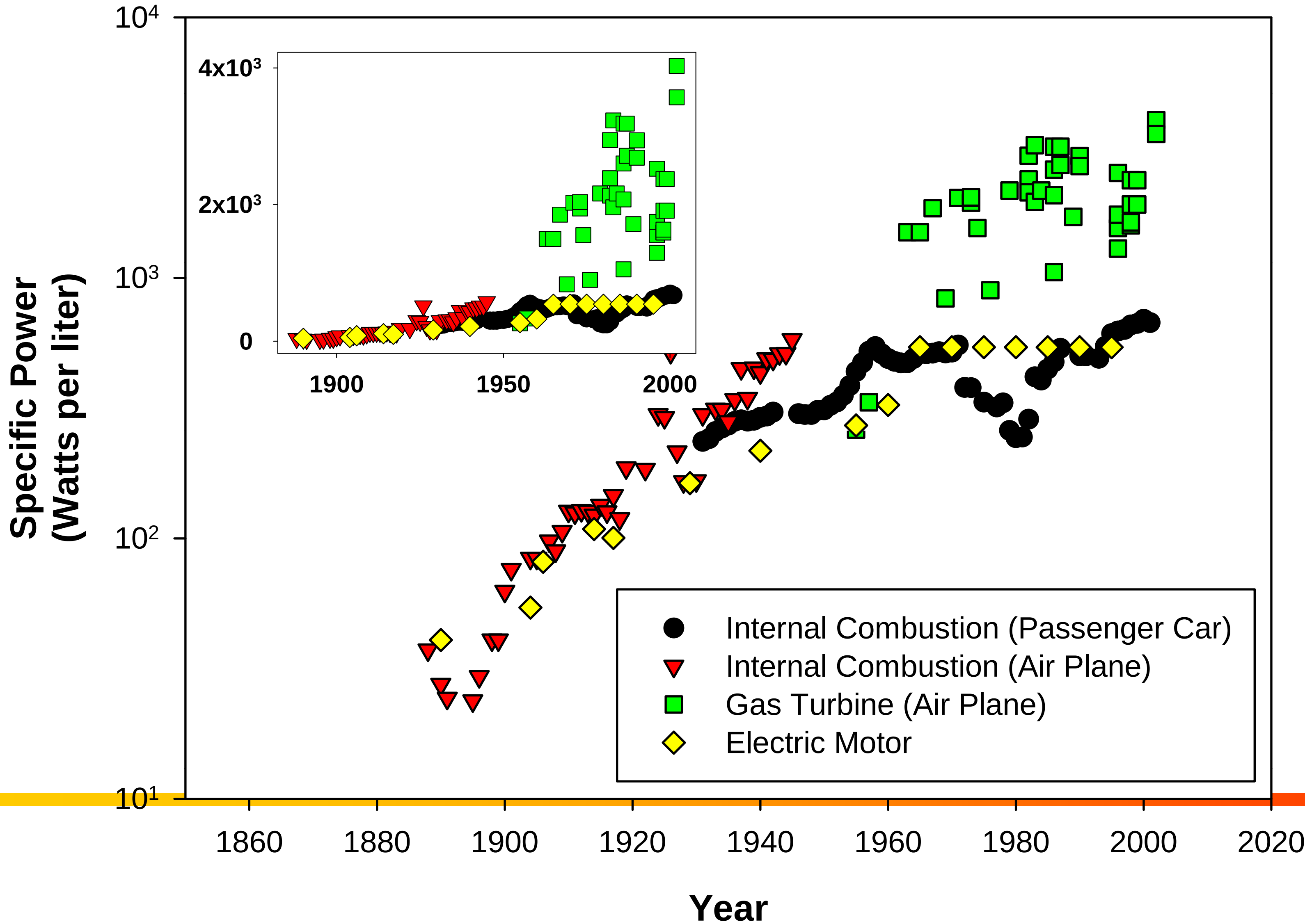
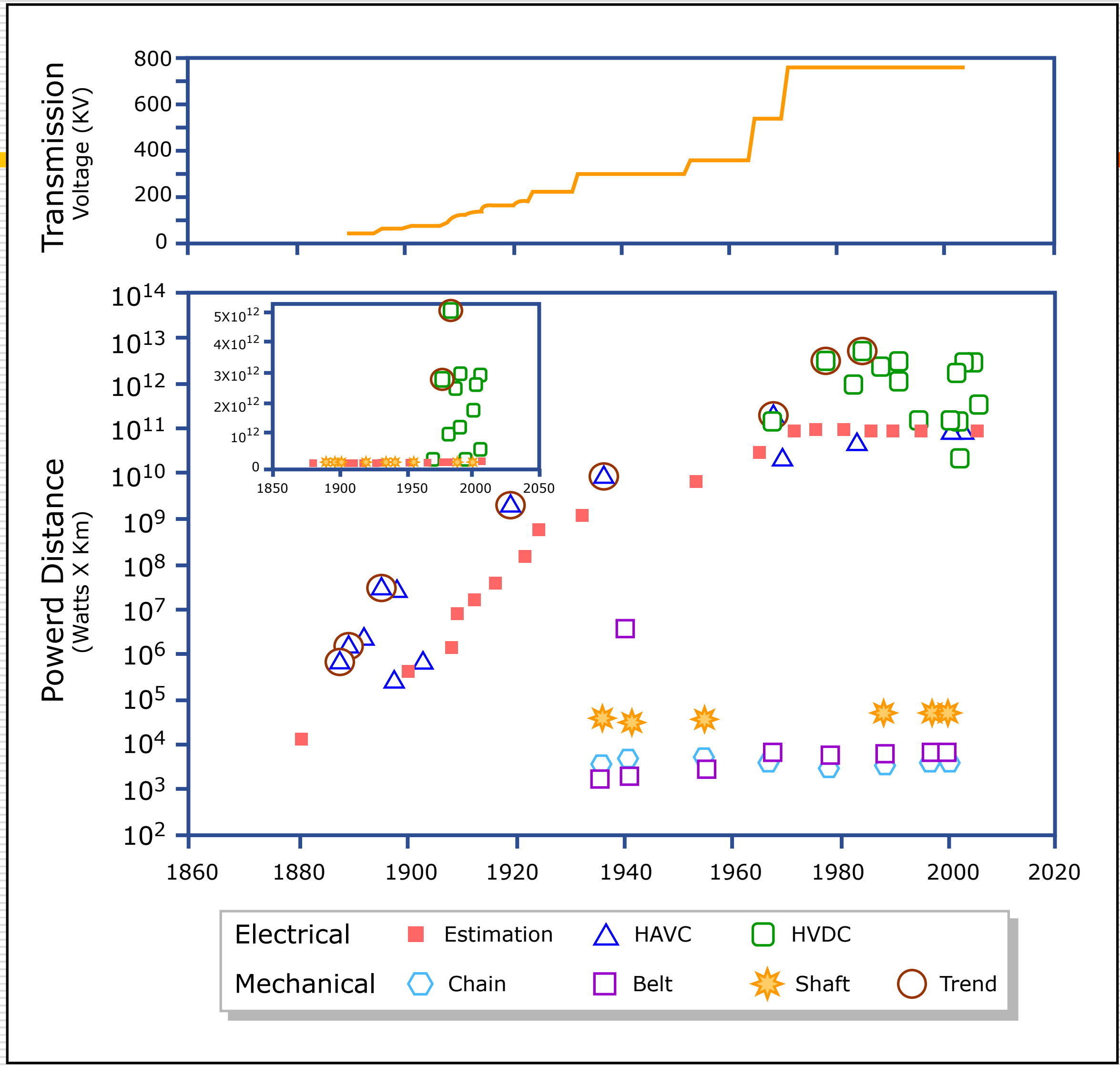


Specific Power
(Watts per liter)
Year
Internal Combustion (Passenger Car)
Internal Combustion (Air Plane)
Gas Turbine (Air Plane)
Electric Motor



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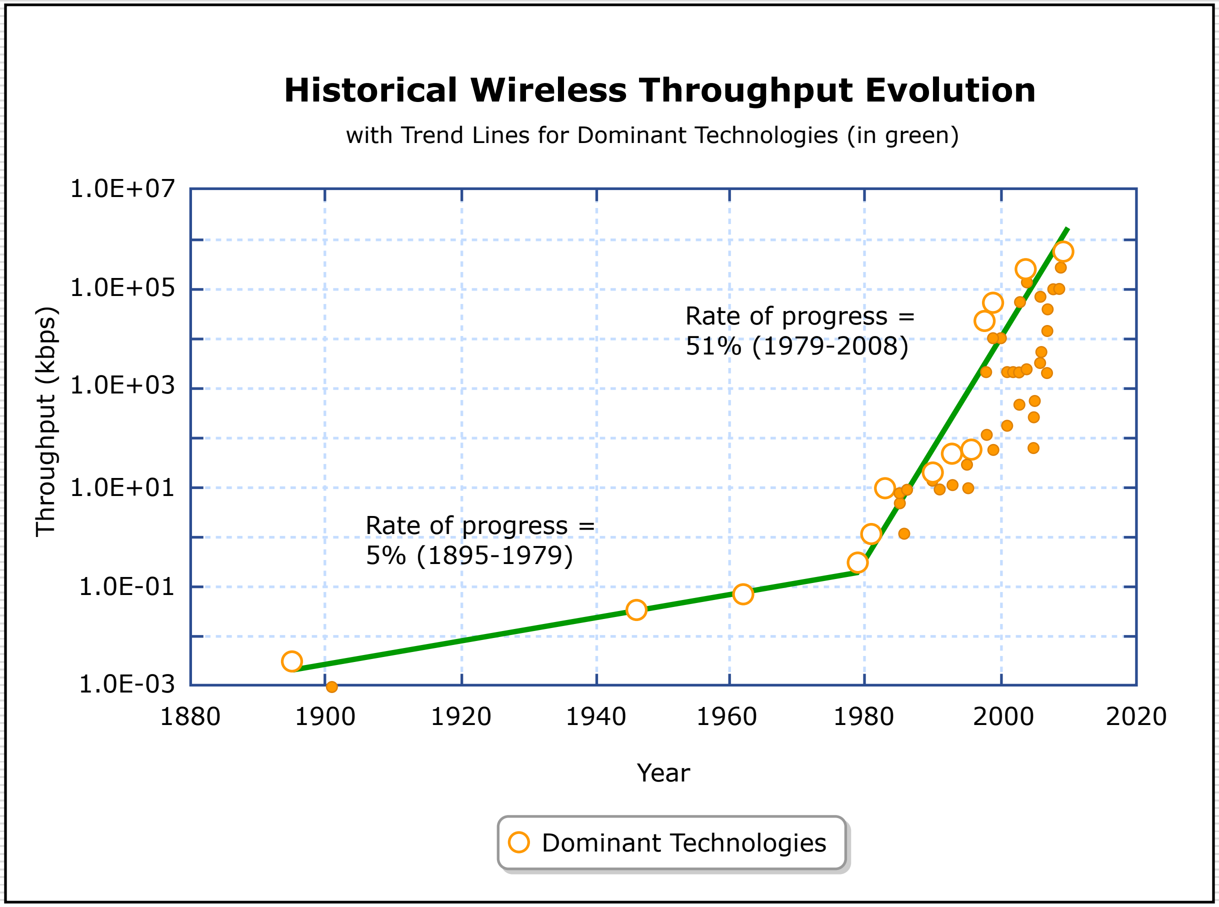

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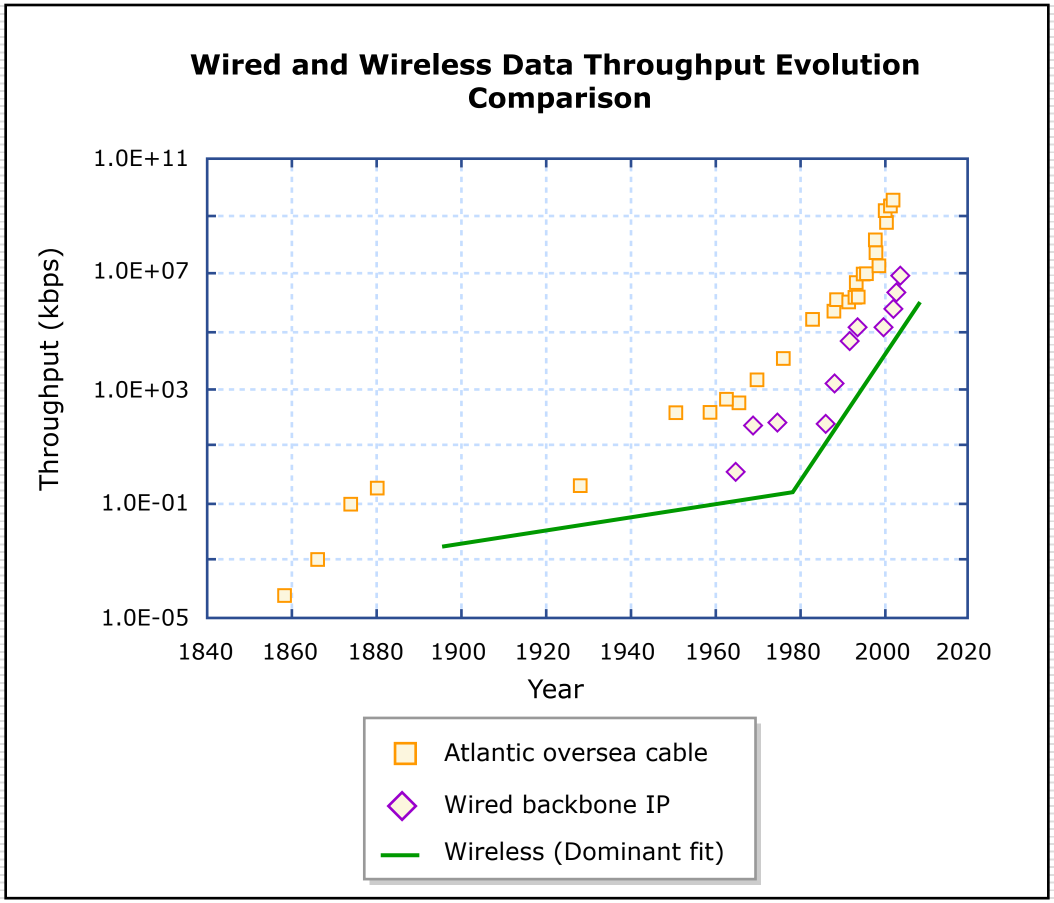

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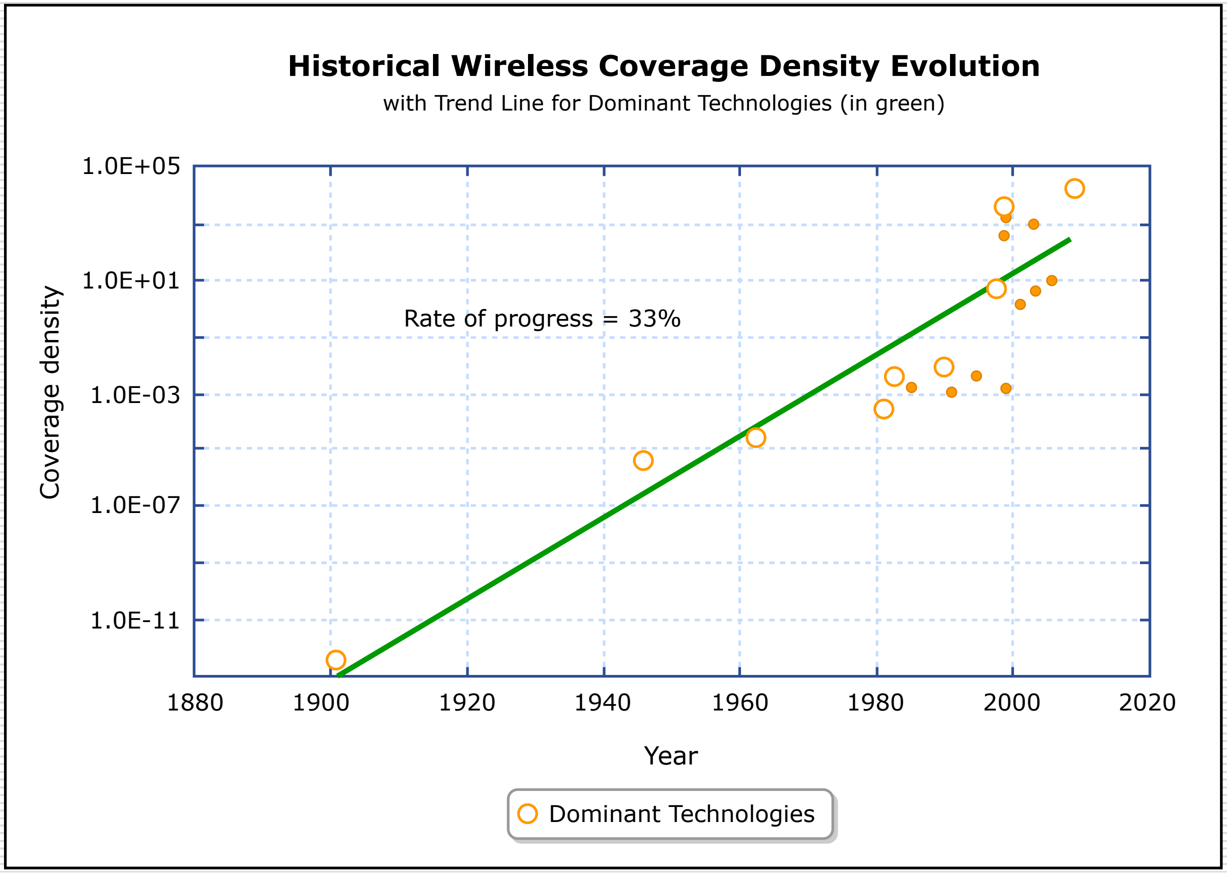

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Technical Capability Metrics Time Dependence

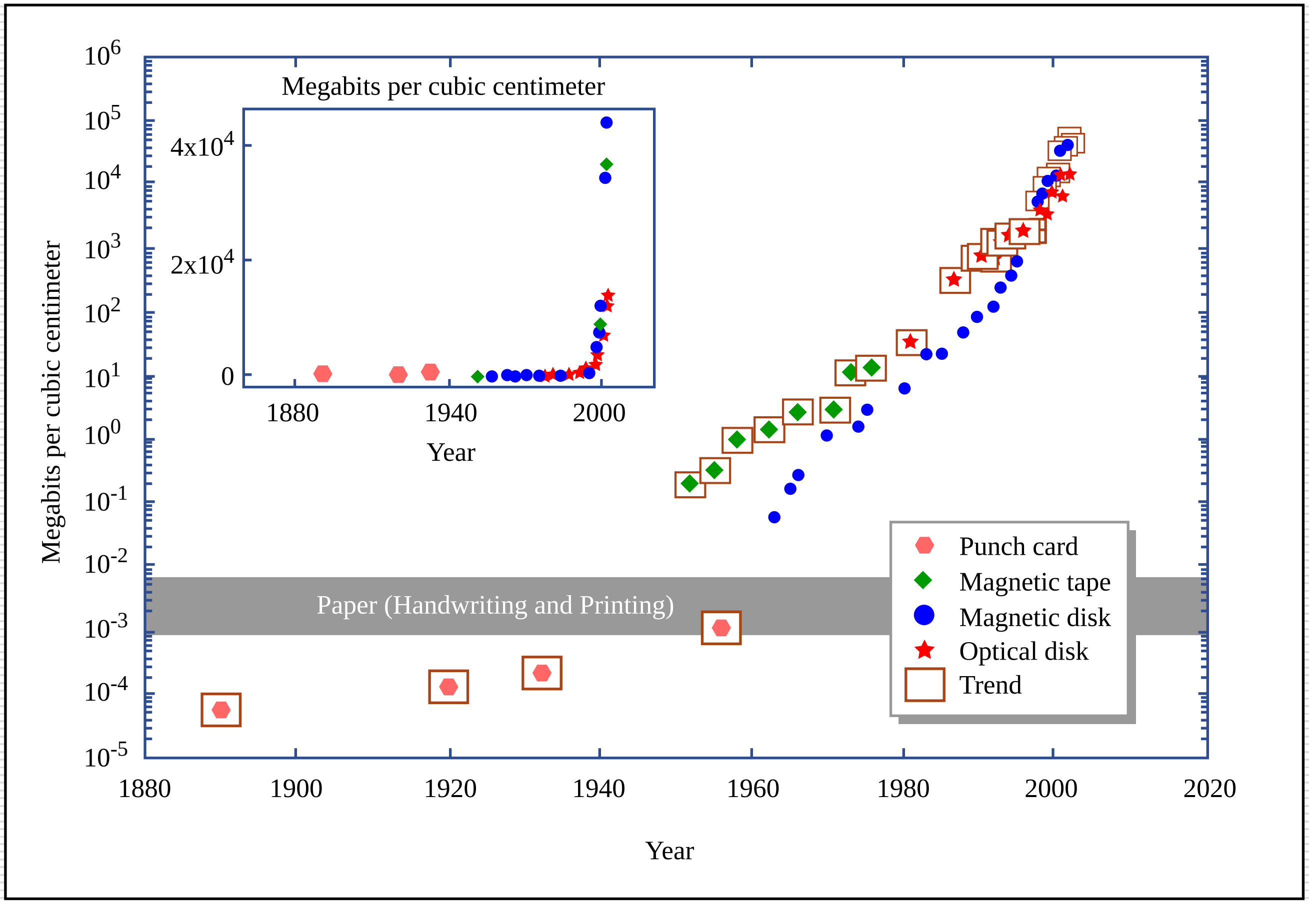
- Exponentials with time over long periods (rate of improvement ranges from 2% per year (or less) to more than 40% per year. Rates of improvement are relatively constant
- For 14 FPMs and for 31 tradeoff metrics, only 3 cases of limits are seen. None of these fit the logistic or S curve often seen for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

Presentation Outline

- Introduction
- Caveat
- Schematic overview of creative design (= invention) process
- Measurement of technological capability
- Temporality Results for T. C.
- **Some Design Implications**
- Systems analyses and choices about what to design

Selected Design Implications

- Know what the rates of change are (or a reasonable estimate) for the devices you are designing and of the subsystem elements you are using-know what the best are likely to be in the near future.
- Shop for and/or use subsystems with knowledge of their effectiveness in hand..
- Project when inventions are useful!



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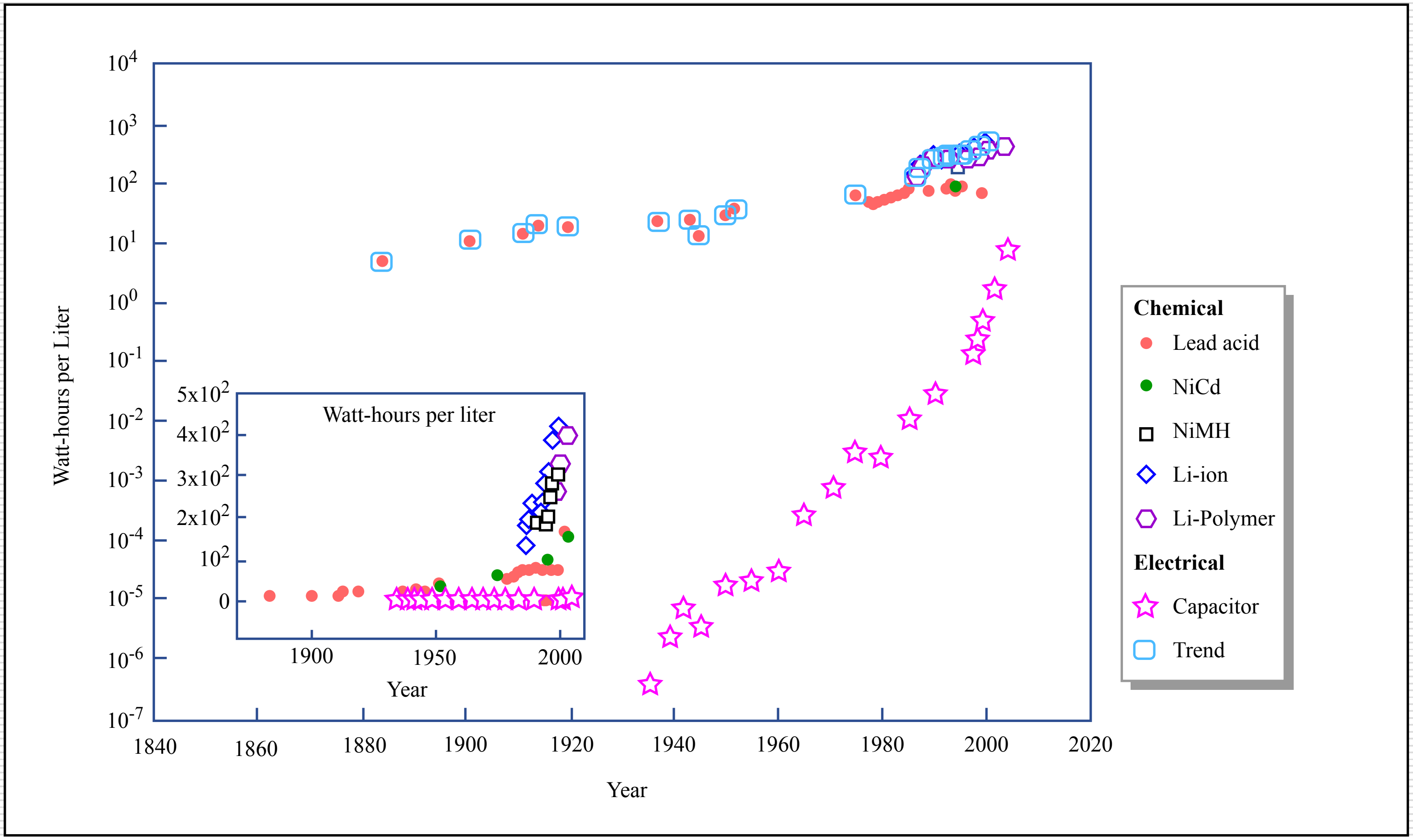

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Selected Design Implications

- Know what the best are likely to be in the near future.
- Shop for and/or use subsystems with knowledge of their effectiveness in hand..
- Project when inventions are useful!
- **The major implication is that the design process that leads to these improvements is cumulative;**
- **What are the societal implications?**

Societal Implications of Continuous Exponential Increase in Technological Capability Without Limit

- In general, they are enormous and are driving human and societal change in an accelerating fashion for > 200 Yrs.
- In specific cases, it is hard to anticipate the nature of the change –thus even timing is not determined by examination of either capability or diffusion of technology

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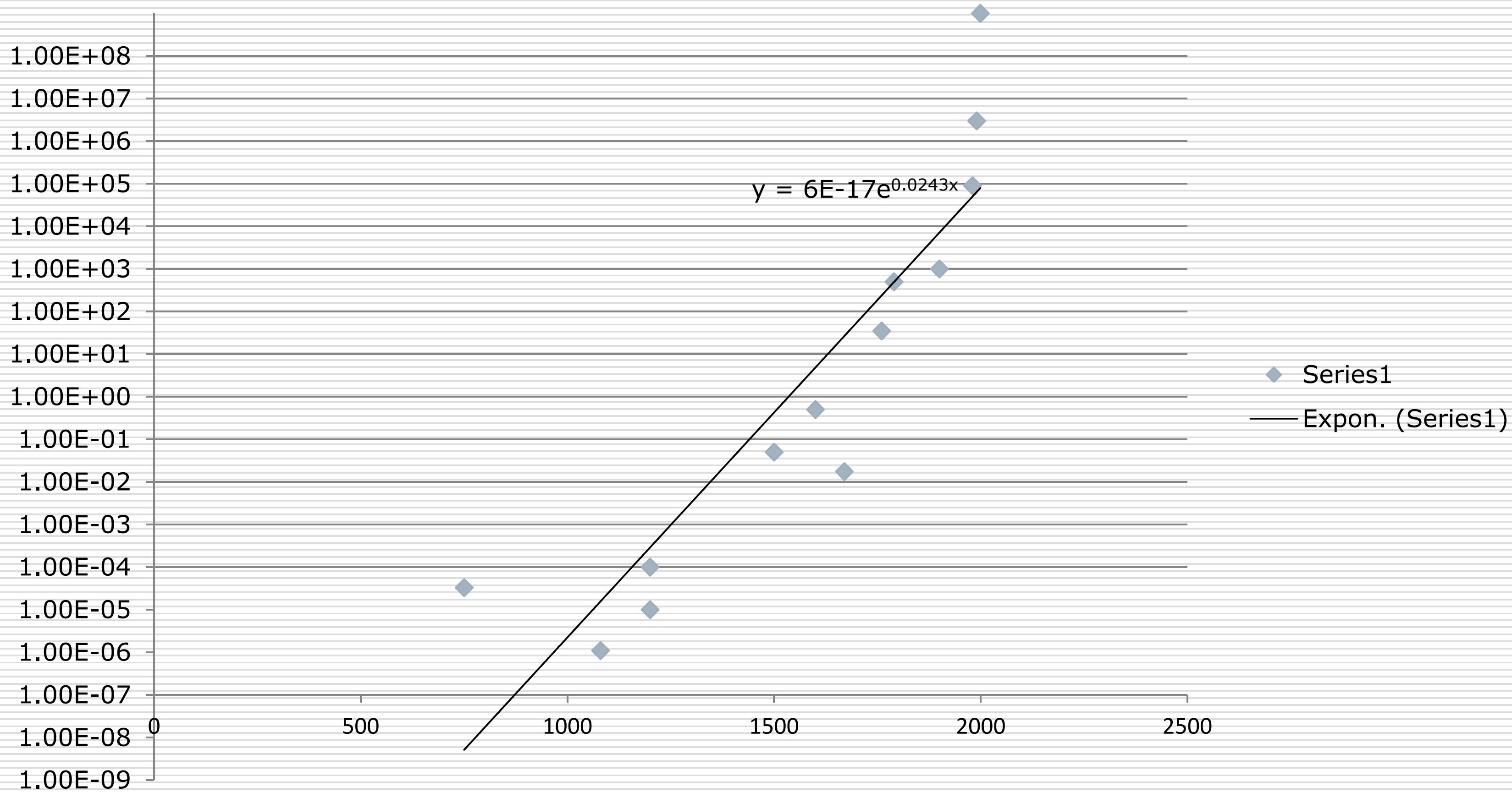
Clock Accuracy divided by Volume



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Societal Implications of Continuous Exponential Increase in Technological Capability Without Limit

- In general, driving of societal change in an accelerating fashion for > 200 Yrs.
- In specific cases, it is hard to anticipate the nature of the change
- Energy Systems Changes, predictable?: cost-effective storage and solar PVs fully economically viable by 2030; however, the social/geo-political result is not at all clear
- Population…large societal change beyond N

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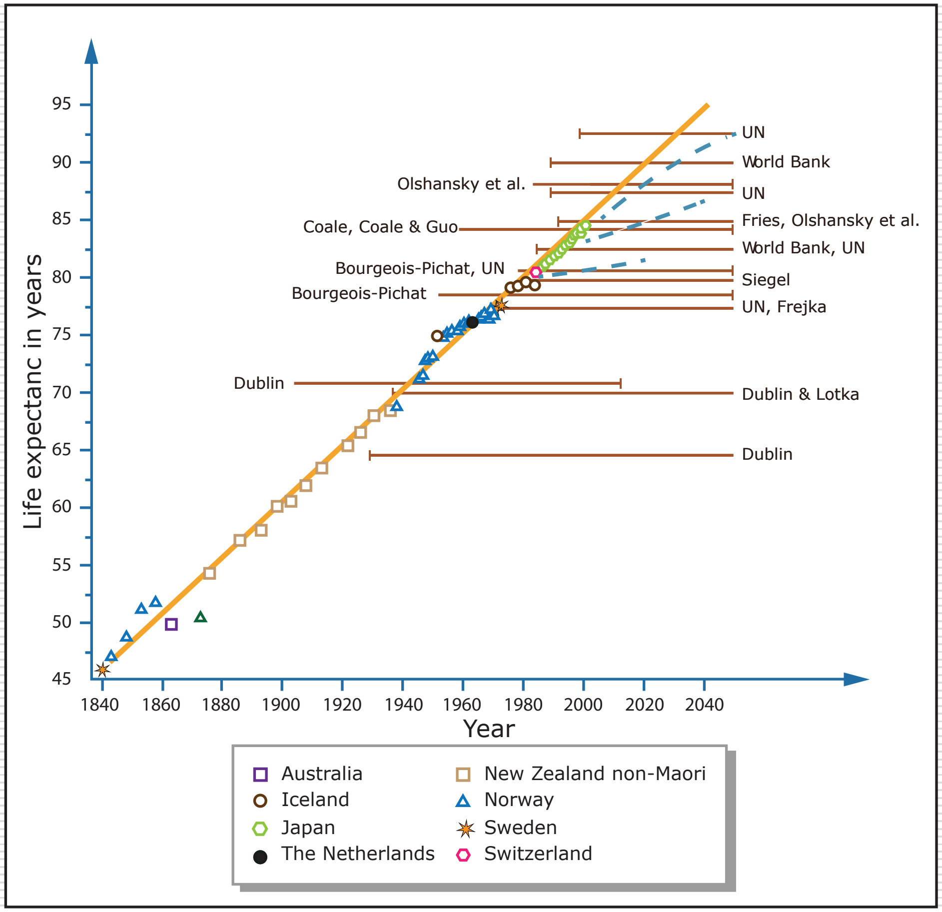
Broken Limits



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Technical Capability Progress Rates

Technology	FPM units	Years	Rate of progress
Genome sequencing	Basepairs/$	35	45%
MRI resolution	Details/mm/sec	25	42%
MRI res./cost	Details/mm/sec /$	25	41%
Computation	MIPS	105	37%
Wireless coverage density	Bitspersecond/ m^2	105	33%
Computation	MIPS/$	90	31%
Info Storage	Mb/cc/$	90	26%
CT Resolution	Details/mm/sec	30	22%
Capacitance Energy Storage	Watthours/liter	40	21%
Info Storage	Mb/cc	90	20%
Wired info transport	Mbs/$	150	19%
Wired info transport	Mbs	150	19%
Capacitance Energy Storage	Watthours/$	40	18%
Wireless info transp	Kbps	105	18%
Wireless spectral efficiency	Bps/Hz	105	15%
Capacitance energy storage	Watthours/kg	40	15%
Electrical energy transport	wattKm	115	13%

Technology	FPM units	Years	Rate of progress
PV Solar energy transformation	Watts/$	50	12%
Flywheel energy storage	Watts/kg	25	11%
Fossil fuel to mechanical power	Watts/$	105	6%
Fossil Fuel to mechanical power	Watts/cc	105	6%
Energy transport-electrical	Wattsxkm/$	80	4%
Fossil fuel to mechanical power	Watts/kg	100	4%
Battery energy storage	Watts/cc	115	4%
Battery energy storage	Watts/$	60	3%
Battery energy storage	Watts/kg	115	3%
Energy transform, electrical to mech	Watts/cc	105	3%
Energy transform electrical to mech	Watts/kg	105	3%
Energy transform-solar to food	Cal./acre	~200	1.5%
Telescope resolution	Effective diameter	350	0.7%
Pharmaceutical effectiveness	Lifeyears/$	75	-2%
Education effectiveness	Amount learned/$	150	-2%

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