Progress towards a “more useful theory” of Engineering Innovation

Workshop on modeling Technological Innovation
Santa Fe Institute

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August 13, 2008

Outline

- Definitions and scope
- Engineering/invention/creativity/innovation
- Technical capability progress
  - What can we learn from examining why Gordon Moore was so "lucky"?
  - Is the existing explanation of the "luck" reasonable?
- Key issues to be addressed for furthering our progress towards a more useful theory of innovation
- Concluding Remarks

Theory Scope

- Theory for engineering/technological innovation
  - many phenomena, social/economic causes, technical constraints
  - predict innovations, combinations and systems
  - predict their penetration over time, how well they work over time, future growth, value, impact**s** on society
  - model invention and innovation process.
- Aspects with "adequate" theory status
  - Processes
  - Diffusion
- "More useful theory" perspective of current presentation:
  - a "reasonably valid" model that explains/predicts why various technological approaches have *technical capabilities* that *increase at very different rates.*

Scope of this Presentation

- Emphasizes ***functional performance*** or technical capability ***but not diffusion*** of technological approaches or artifacts
- This is not usual for good reasons-
  - *Our emphasis is on technology diffusion, i.e., the widespread adoption of technologies over time, in space, and between different social strata…Only through diffusion do technologies exert any noticeable impact on output and productivity growth, on economic and social transformations, and on the environment. Without diffusion, a new technology may be a triumph of human ingenuity, but it will not be an agent of global change.* Grubler 1998
- However,
  - has undeniable importance of diffusion –economically-
  - led to non-productive neglect?
  - or at least confusion in formalism?

Scope of this Presentation II

- Emphasizes ***functional performance*** or technical capability ***but not diffusion*** of technological approaches or artifacts
- Focuses on measurable technical capability dynamics using **engineering** metrics over time
  - Figures of merit
  - Tradeoff metrics
  - Generic tradeoff metrics (FPMs)
- Tradeoff metrics (including FPMs) not containing natural resource constraints
  - Simplify empirical patterns
  - Best reflect product and service opportunities and economic/social impact (Watts/KG, bps/$)

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- Output/Input**

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)

Scope of this Presentation III

- Emphasizes ***functional performance*** or technical capability ***but not diffusion*** of technological approaches or artifacts
- Focuses on measurable technical progress and thus on engineering metrics for technical capability over time
- FPMs include **all technical** improvements whether having large or fairly small social/economic impact*;*
- Includes engineering/invention ***at all levels of a technology improvement hierarchy***

Scope of this Presentation IV- ***High level of abstraction relative to engineering innovation***

- Emphasizes ***functional performance*** or technical capability ***but not diffusion***
- Focuses on measurable technical progress and thus on metrics for technical capability over time
- The preferred metrics include **all technical** improvements*;*
- Includes engineering/invention ***at all levels of a technology improvement hierarchy***
- ***To lead to useful theory, such an approach must be consistent with details at lower levels of abstraction***

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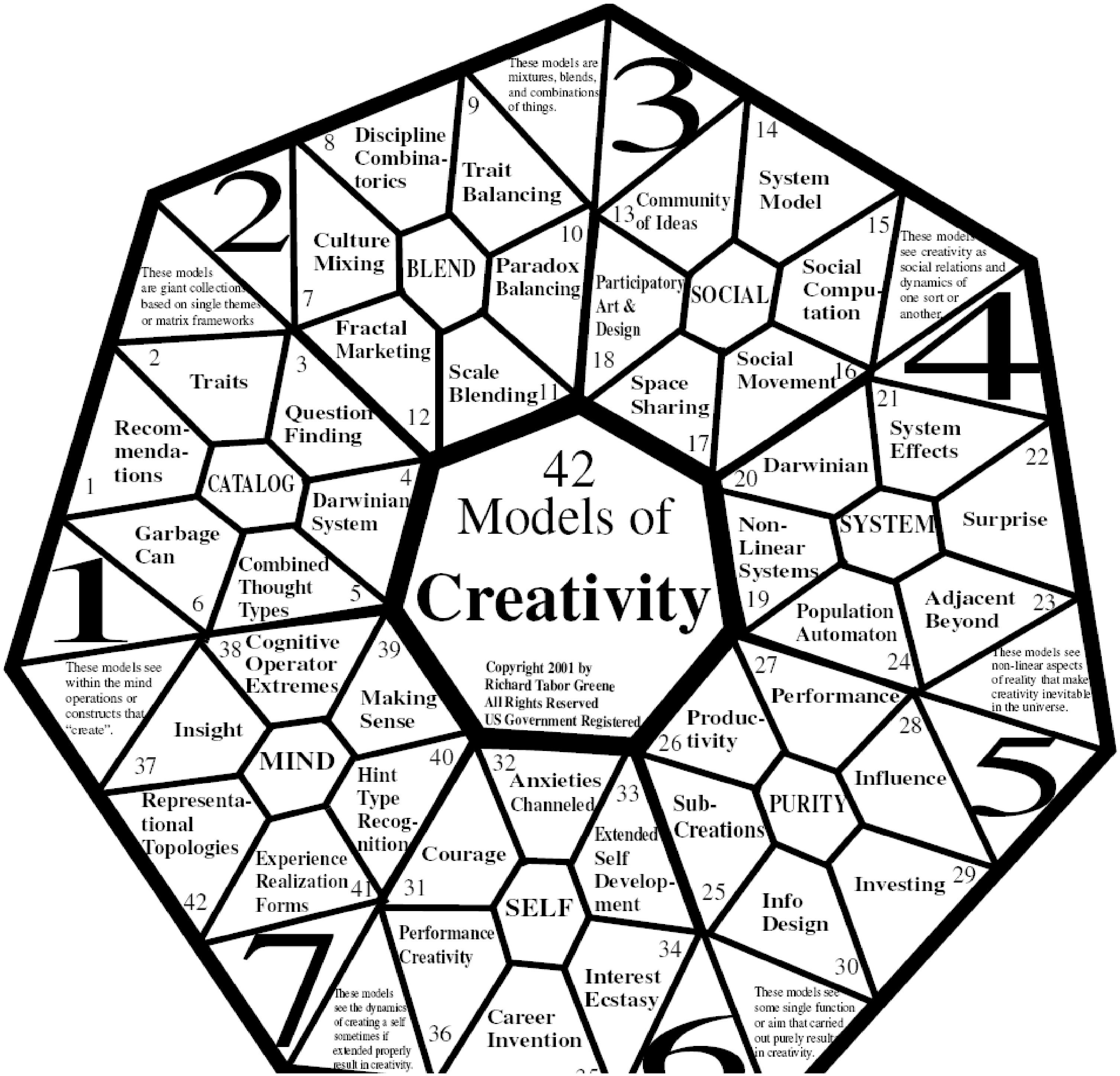
Engineering/invention/creativity/innovation **EICI**

- Important work has been done in a wide variety of disciplines/fields
  - Engineering (design) educators, psychologists- cognitive scientists, historians of technology, economists, organizational theorists, creativity and expertise specialists, etc.
- Observation has largely been case based but some experimentation in constrained situations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Models of
Creativity
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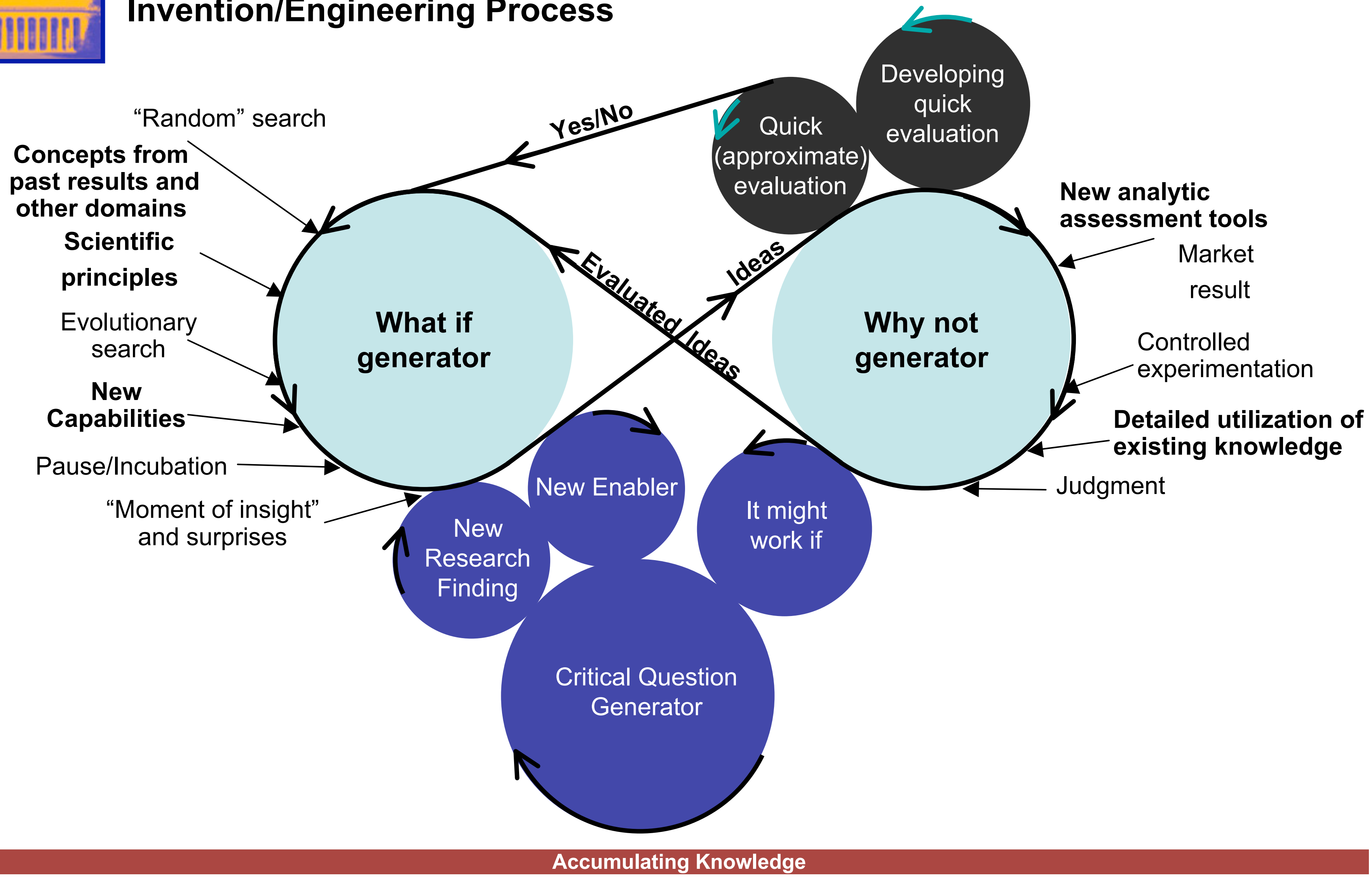
1
These models see within the mind operations or constructs that "create".
2
These models are giant collections based on single themes or matrix frameworks
3
These models are mixtures, blends, and combinations of things.
4
These models see creativity as social relations and dynamics of one sort or another.
5
These models see non-linear aspects of reality that make creativity inevitable in the universe.
6
These models see some single function or aim that carried out purely results in creativity.
7
These models see the dynamics of creating a self sometimes if extended properly result in creativity.
CATALOG
BLEND
SOCIAL
SYSTEM
PURITY
SELF
MIND
1 Recom-menda-tions
2 Traits
3 Question Finding
4 Darwinian System
5 Combined Thought Types
6 Garbage Can
7 Culture Mixing
8 Discipline Combina-torics
9 Trait Balancing
10 Paradox Balancing
11 Scale Blending
12 Fractal Marketing
13 Community of Ideas
14 System Model
15 Social Compu-tation
16 Social Movement
17 Space Sharing
18 Participatory Art & Design
19 Non-Linear Systems
20 Darwinian
21 System Effects
22 Surprise
23 Adjacent Beyond
24 Population Automaton
25 Sub-Creations
26 Produc-tivity
27 Performance
28 Influence
29 Investing
30 Info Design
33 Extended Self Develop-ment
34 Interest Ecstasy
36 Career Invention
31 Courage
32 Anxieties Channeled
Performance Creativity
37 Insight
38 Cognitive Operator Extremes
39 Making Sense
40 Hint Type Recog-nition
41 Experience Realization Forms
42 Representa-tional Topologies

Invention/Engineering Process



- Search techniques
- Preparation or prototyping skill

- **New science**
- Critical questions
- Enabling approaches

- **New combinations**
- **New capabilities**
- **New design principles**

- **Results from assessing**
- Evaluation techniques
- Limits and tradeoffs

History of invention plus cognitive science

- "Invention always occurs in the combined social, economic, institutional and cultural contexts and must be understood in terms of these contexts. Inventors must 'negotiate' their work on two fronts. On the one hand, with nature, they must ground their work in an understanding of what materials, natural processes and so on afford. On the other hand with society, they must arrive at inventions that have a practical and valued place."

» Perkins 2004

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

EICI fundamentals summary

- Feedback to the search (generation) process from evaluation (selection) is an essential part of the process
- EICI co-evolves with *science* (both benefit and contribute) which *is particularly important in the cumulative process*.
- EICI is a social process with communication within and among groups an essential element
- All aspects of knowledge *accumulate* and are *widely* used in *later* EICI activities
- ***Time*** is the essential independent variable
- Separation of specific innovations at various levels of a hierarchy and even objective assessment of importance of particular "inventions" is problematic
- Transgressive thought (rule-breaking and importation of knowledge from other fields) is a key ingredient in EICI
- Successful invention processes are idiosyncratic
- ***Prediction*** may not be a realistic goal

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Merton's Self-fulfilling Prophecy

- *The self-fulfilling prophecy is, in the beginning, a **false** definition of the situation evoking a new behavior which makes the original false conception come **true**.*
- SEMATECH, roadmaps, Moore's role, etc. are convincing to many that a self-fulfilling prophecy is the major explanation of Moore's "luck".
- This attributes the innovation stream to a "purely" social technology –make a prediction and get people to align with it.
- The prediction (extrapolation) was for a certain form of time dependence (exponential) and a specific rate of progress(1&1/2 year doubling) for a specific technical capability metric

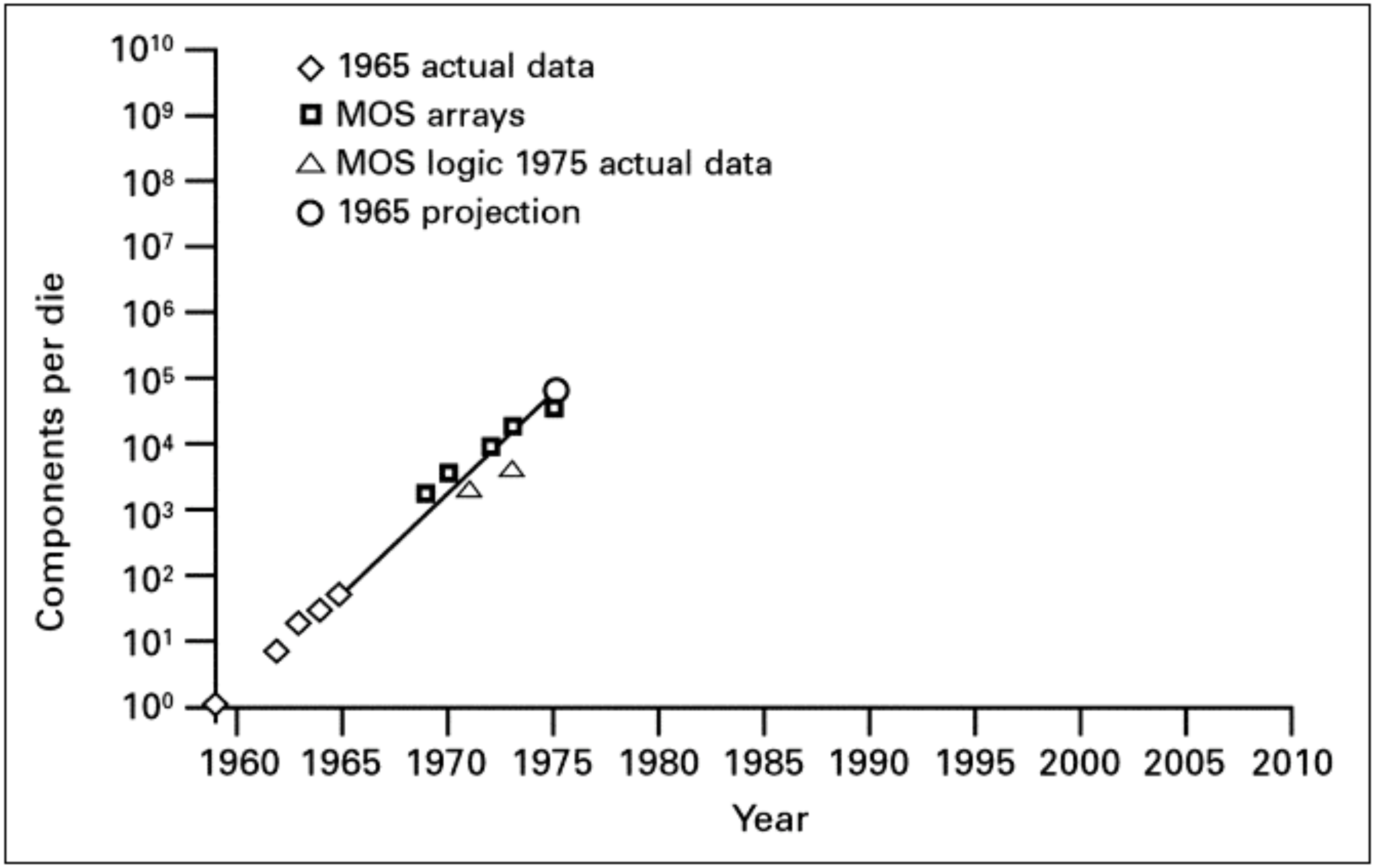


Figure 6. Integrated circuit complexity (1959–1975). Source: Intel.

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

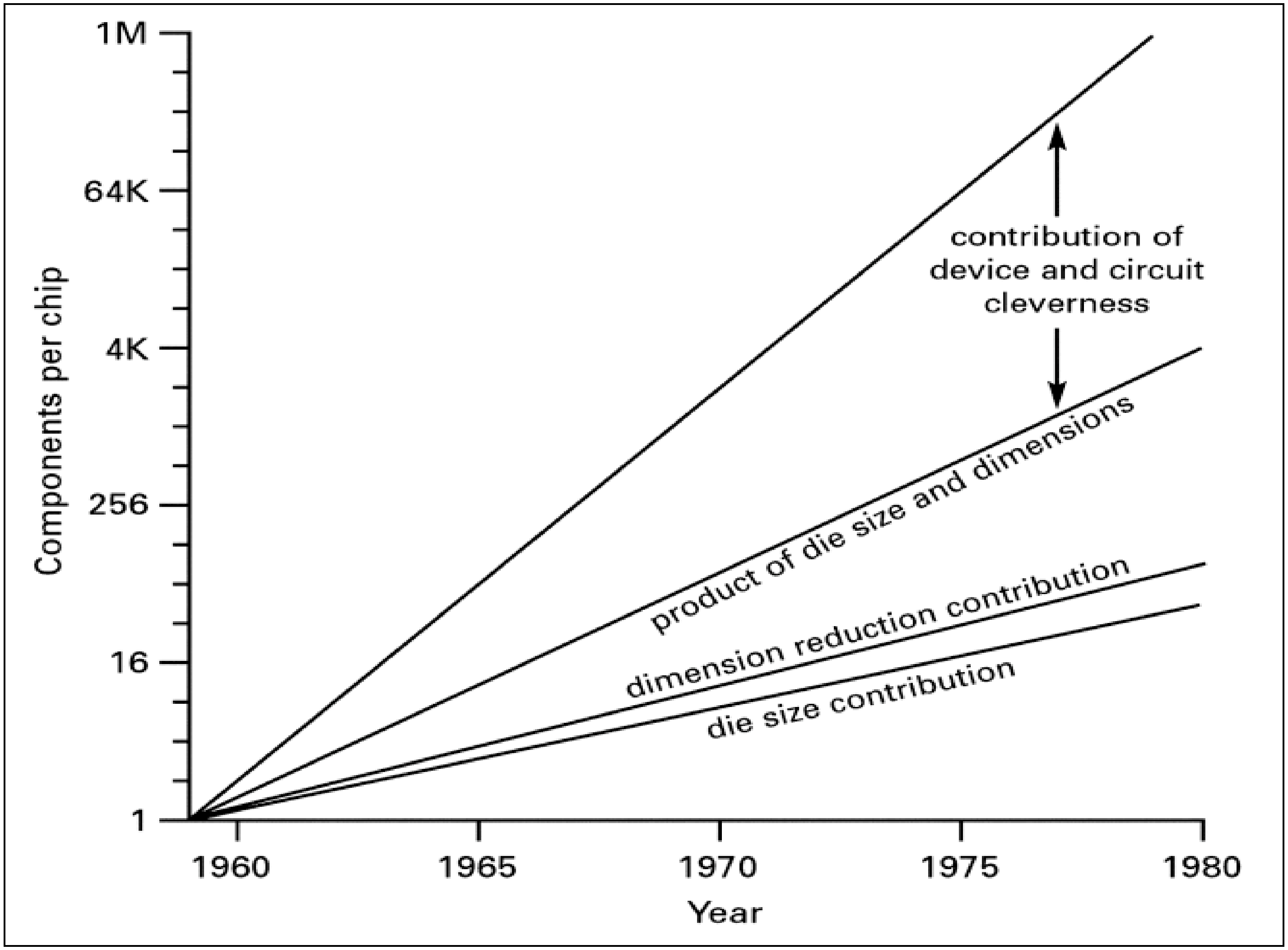


FIGURE 7. Resolution of complexity increase into contributing factors. Source: Intel.

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

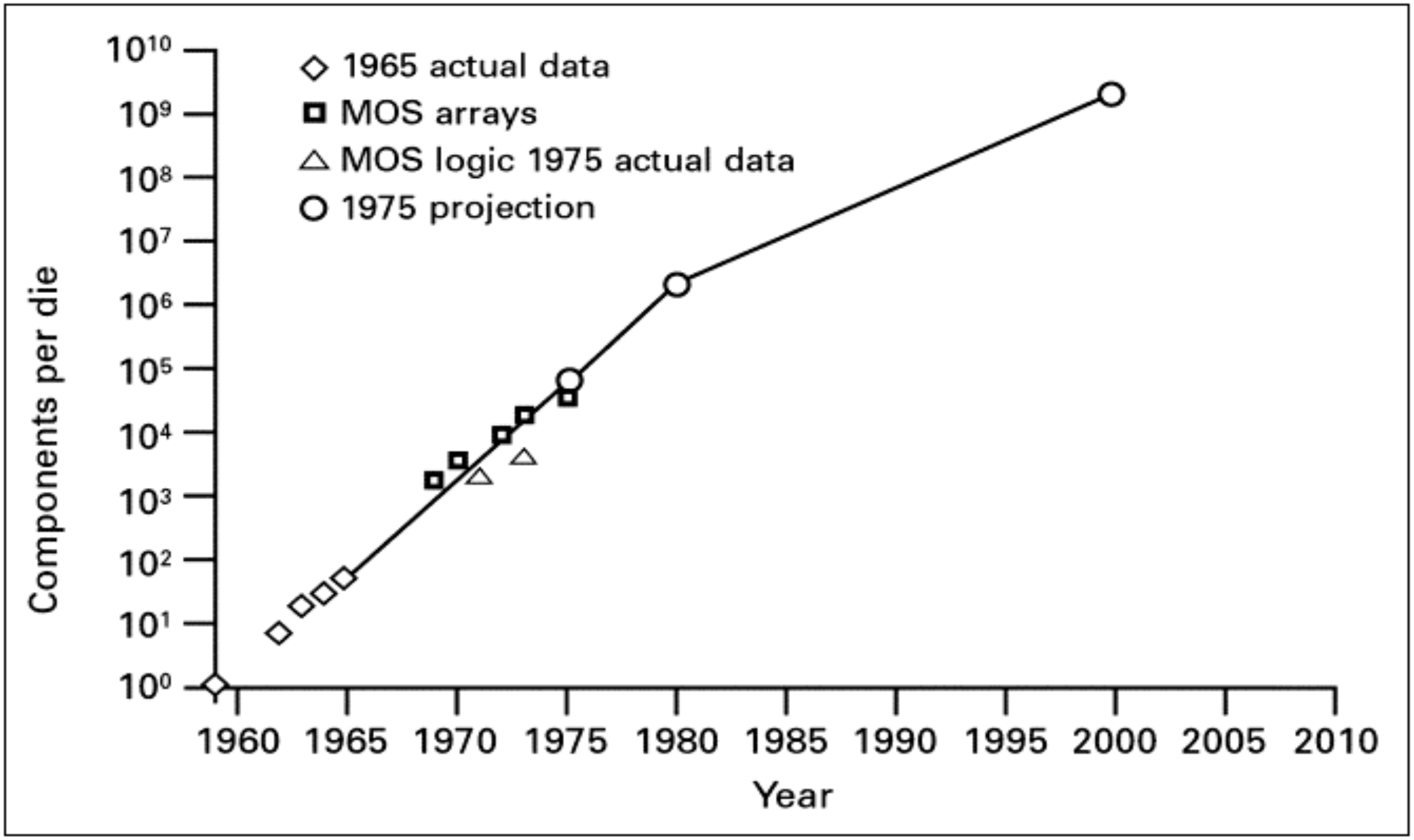


FIGURE 8. Integrated circuit complexity, 1975 projection. Source: Intel.

From Moore, G. E. “Moore’s Law at 40”

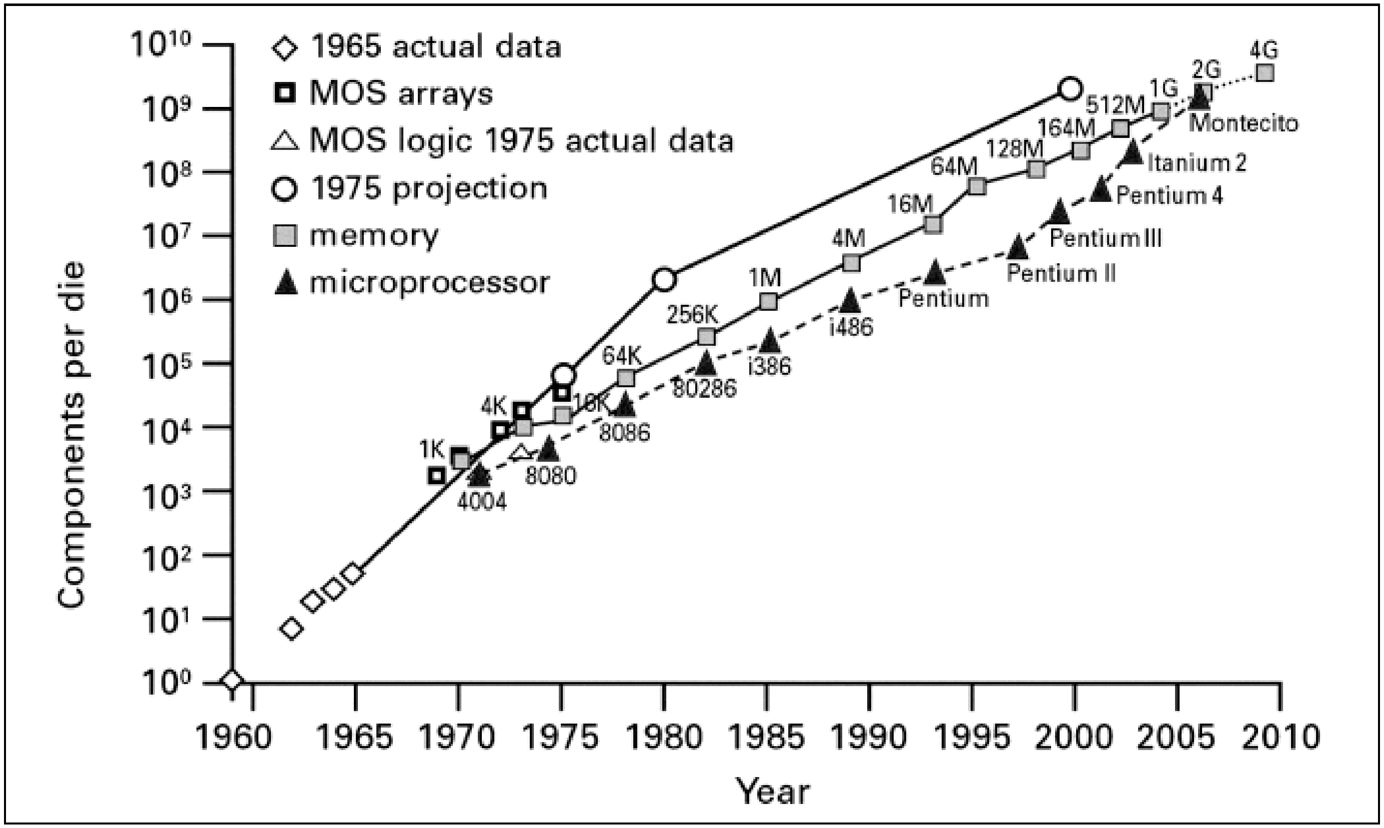
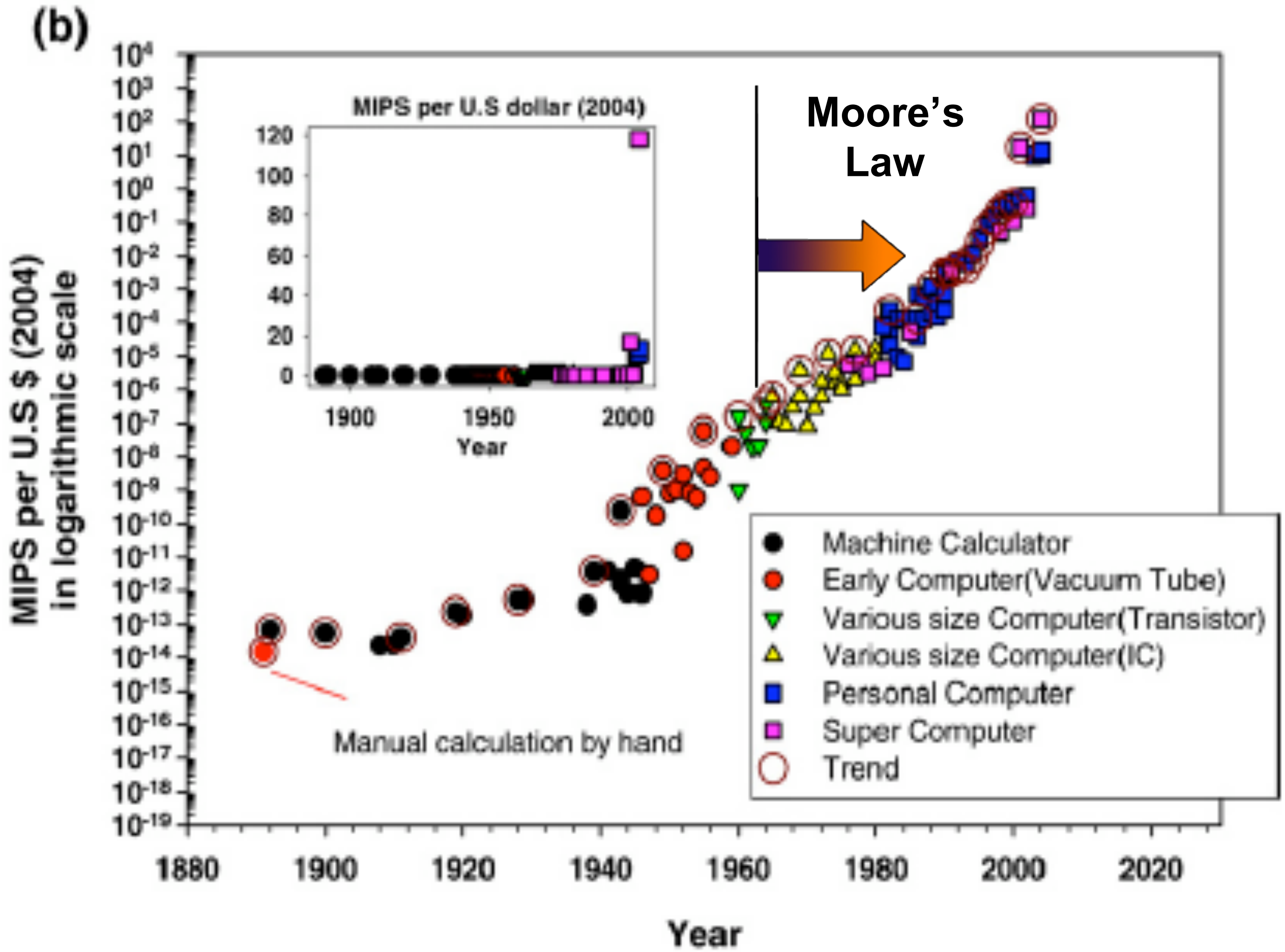


FIGURE 9. Integrated circuit complexity, actual data compared with 1975 projection. Source: Intel.

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

If not a self-fulfilling prophecy, then what could be the sources of Moore's "Luck"?

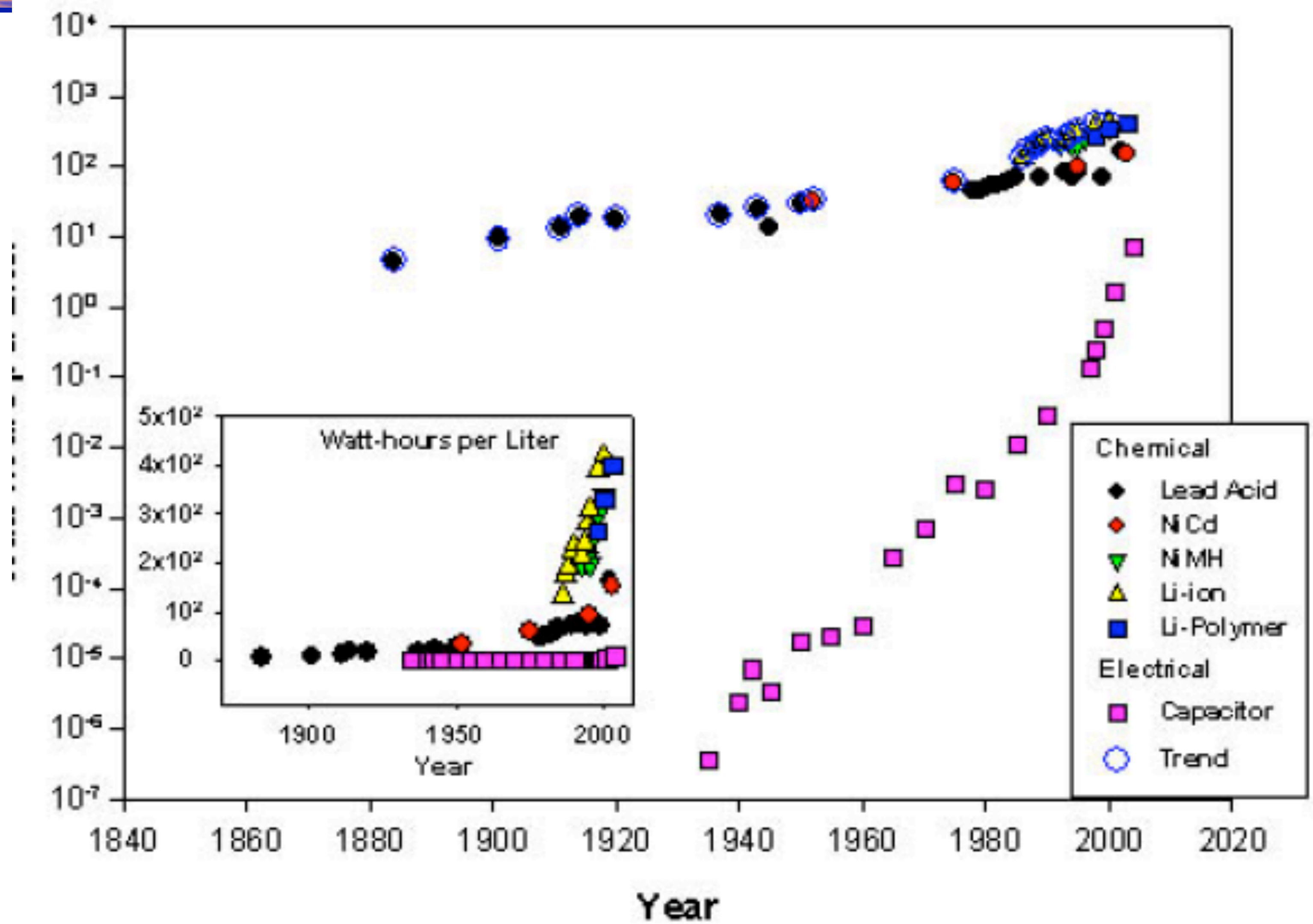
- He was implicitly predicting a trend that had already been followed for a number of years.


(b)
MIPS per U.S $ (2004) in logarithmic scale
Year
MIPS per U.S dollar (2004)
Moore's Law
Manual calculation by hand
Machine Calculator
Early Computer(Vacuum Tube)
Various size Computer(Transistor)
Various size Computer(IC)
Personal Computer
Super Computer
Trend

If not a self-fulfilling prophecy, then what could be the sources of Moore's "Luck"?

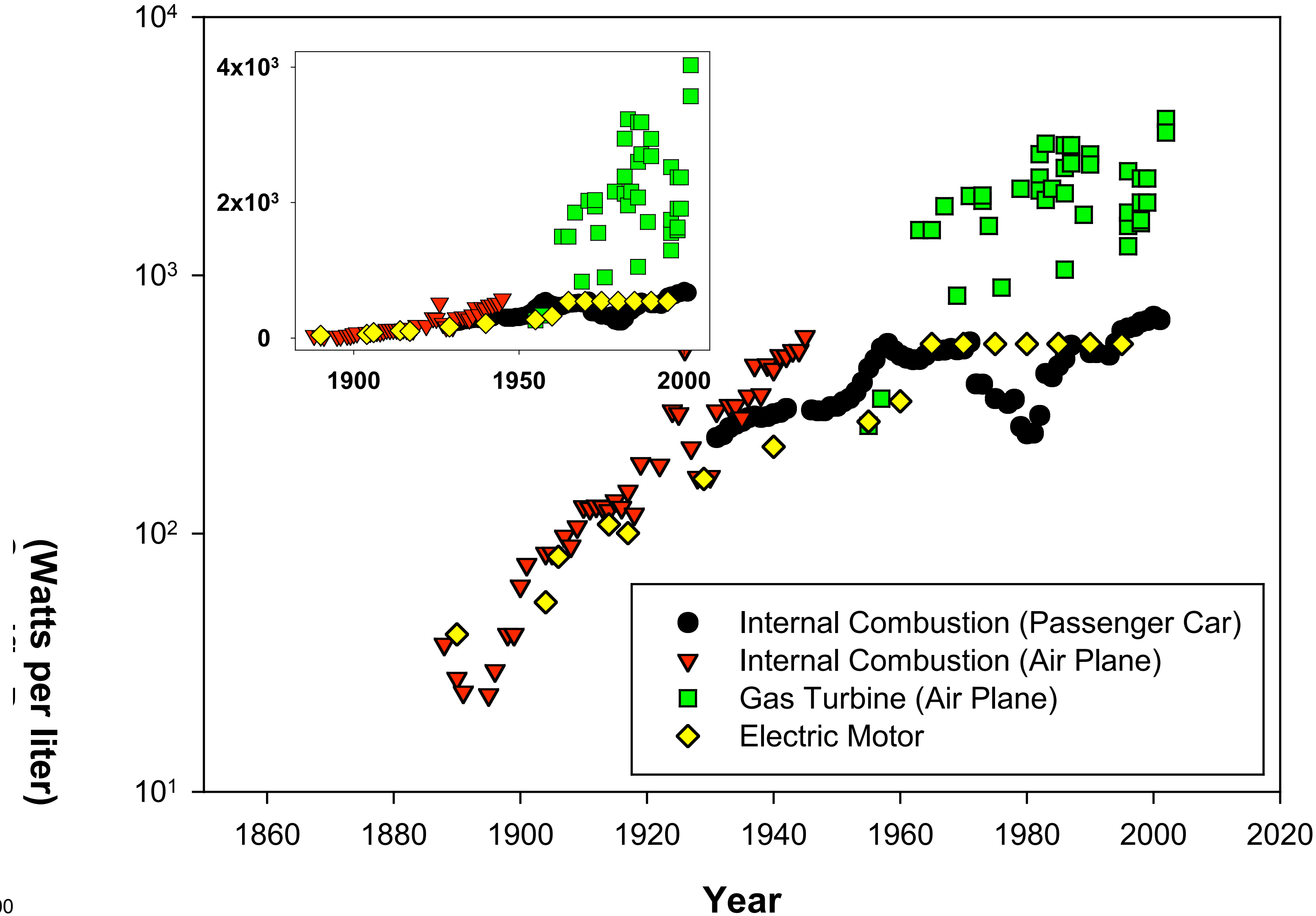
- He was implicitly predicting a trend that had been already followed for a number of years.
  - Empirically, from the functional perspective, his prediction was in accord with the previous 50 years of dynamics (a fact which he presumably was not aware of as he did not explicitly consider function).
- He was working in a functional area where the rate of change (and form?) was visible in just a few years (x10 in 3.5 years).
  - If he had been working on batteries or airplane engines..

(a)



10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year
Watt-hours per Liter
5x10²
4x10²
3x10²
2x10²
10²
0
1900
1950
2000
Year
Chemical
Lead Acid
Ni Cd
Ni MH
Li-ion
Li-Polymer
Electrical
Capacitor
Trend

(b)



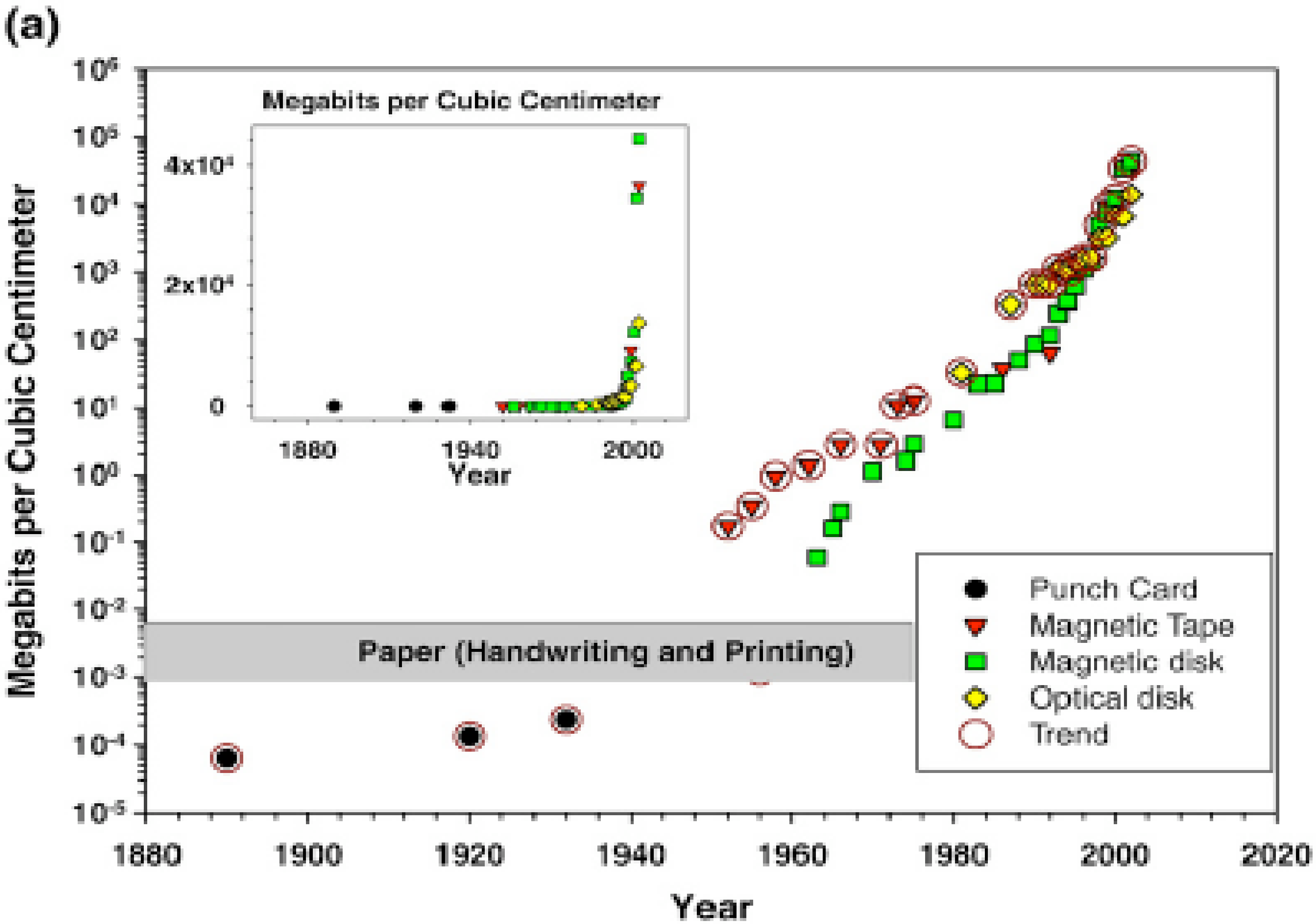
(Watts per liter)
10^4
10^3
10^2
10^1
4x10³
2x10³
0
1900
1950
2000
Internal Combustion (Passenger Car)
Internal Combustion (Air Plane)
Gas Turbine (Air Plane)
Electric Motor
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year

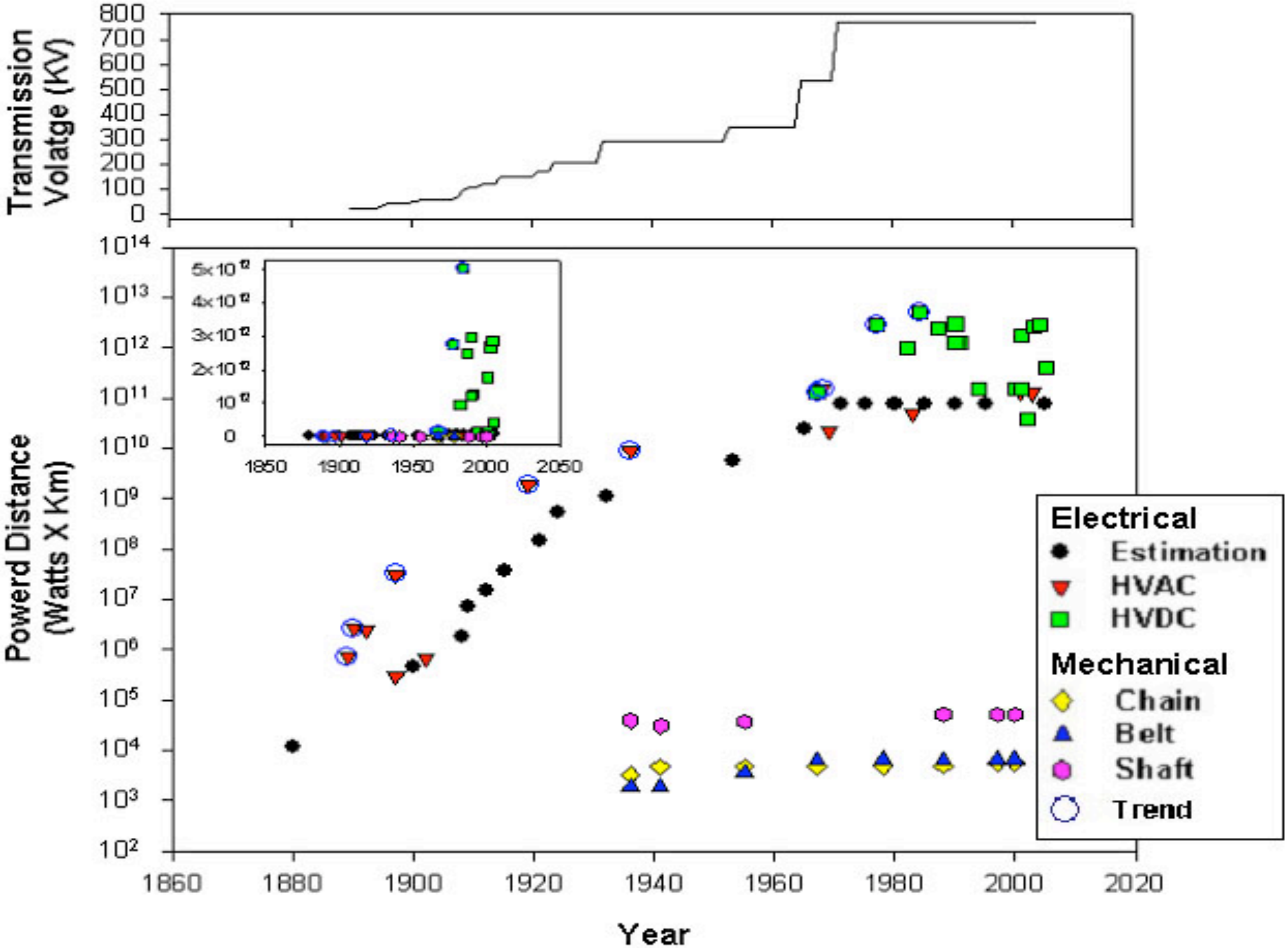
If not a self-fulfilling prophecy, then what could be the sources of Moore's "Luck"? II

- He was implicitly predicting a functional trend that had been already followed for a number of years.
- He was working in a functional area where the rate of change (and form?) was visible in just a few years.
  - Empirically, it appears that he would not have been able to see the amount of change he saw in less than 4 years unless he had spent a career ~40 years in batteries or turbines

Status of the self-fulfilling prophecy hypothesis

- Note evidence of exponential progress in areas away from Moore's "lucky" prediction
  - There is evidence of such a relationship in more than 40 long term cases that have been examined
  - The progress rates vary from ~1% to 45% and none but Moore's had been predicted/prophesied


(a)
Megabits per Cubic Centimeter
4x10⁴
2x10⁴
0
1880
1940
2000
Year
Megabits per Cubic Centimeter
10⁶
10⁵
10⁴
10³
10²
10¹
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
Paper (Handwriting and Printing)
Punch Card
Magnetic Tape
Magnetic disk
Optical disk
Trend
1880
1900
1920
1940
1960
1980
2000
2020
Year



Transmission Volatge (KV)
800
700
600
500
400
300
200
100
0
Powerd Distance (Watts X Km)
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
1860 1880 1900 1920 1940 1960 1980 2000 2020
Year
Electrical
Estimation
HVAC
HVDC
Mechanical
Chain
Belt
Shaft
Trend

Status of the self-fulfilling prophecy hypothesis

- Prophecy is not necessary for exponential relationships
- Prophecy nor SEMATECH nor roadmaps are necessary to get high rates of exponential progress
- Moore’s prediction was continuous (functionally for information transformation) with 7 orders of magnitude of prior progress.
- It is not parsimonious to invoke SFPH in Moore’s case - *Electronics* Magazine asked him to predict future
- Could “ a Moore prediction” of 35+% rate of progress for batteries in 1965 have resulted in us now having a 300 mile range EV battery that fits in your hand?
- Does anyone agree with my description of the hypothesis as “*The self fulfilling prophecy **fallacy***” wrto its application to Moore’s prediction?
- Is the application an example of Ross’ “Fundamental Attribution Error”?
- In any case, regularity exists well beyond Moore’s Law and variation in dynamics exists independent of predictions

If not a self-fulfilling prophecy, then what could be the sources of Moore's "Luck"? III

- He was implicitly predicting a functional trend that had been already followed for a number of years.
- He was working in a functional area where the rate of change (and form?) was visible in just a few years.
- He chose a *tradeoff* metric rather than a simpler figure of merit (transistor speed?)
- He avoided pinning his progress equation on cumulative production volume and instead stayed with the more *fundamental variable-time*

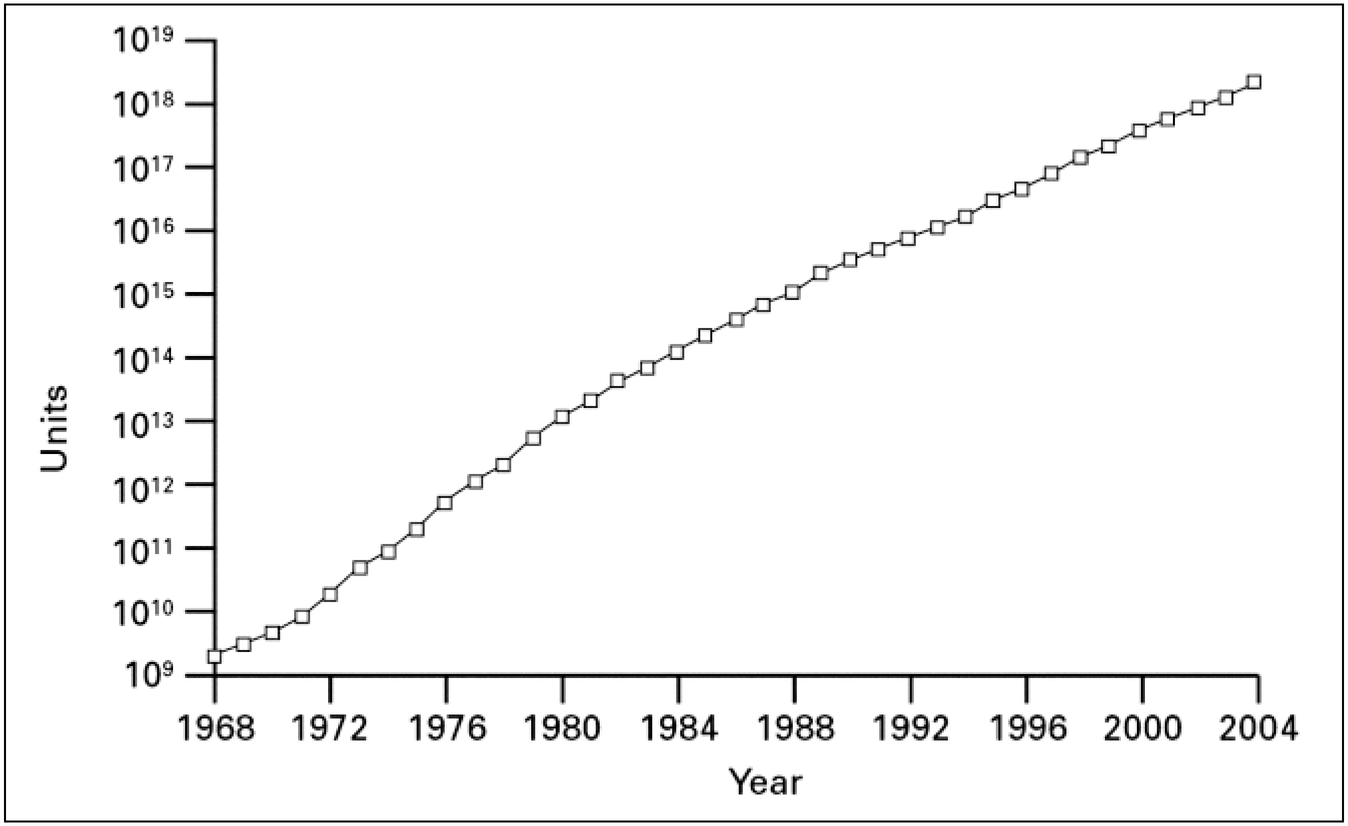
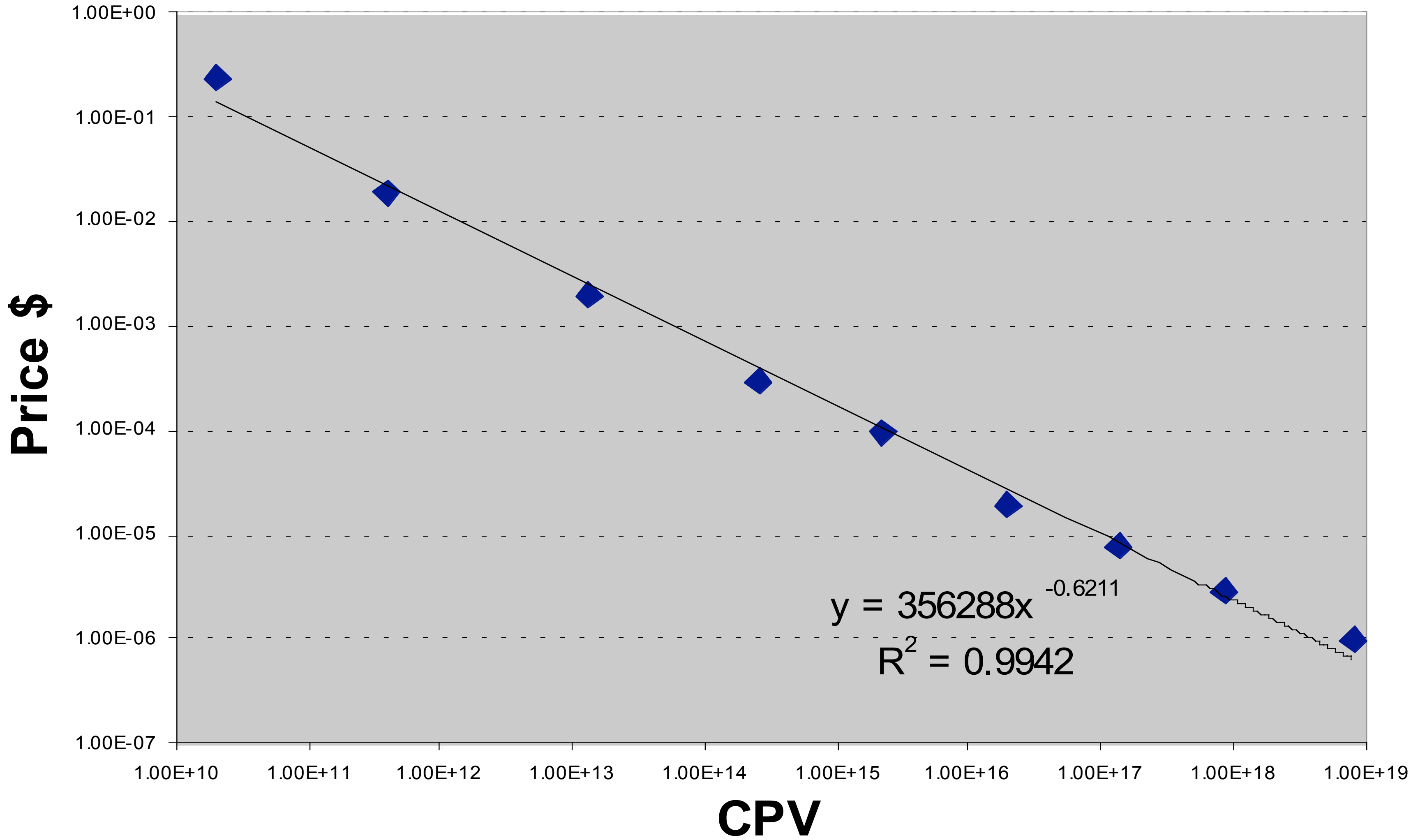


FIGURE 2. Total number of transistors shipped by the semiconductor industry (1968–2004). Source: Intel/WSTS, May 2005.

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

Learning

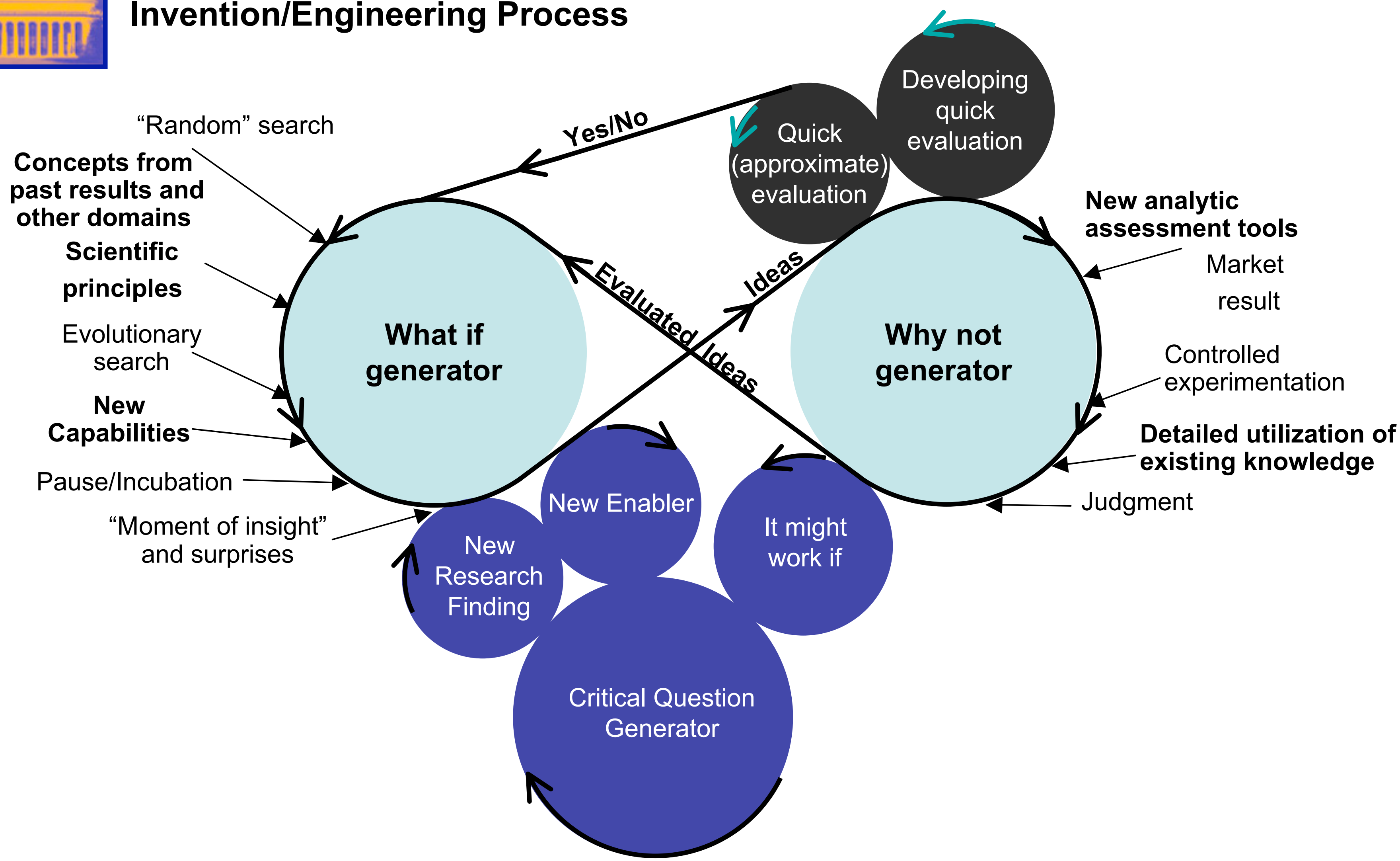


Price $
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
y = 356288x -0.6211
R2 = 0.9942
1.00E+10
1.00E+11
1.00E+12
1.00E+13
1.00E+14
1.00E+15
1.00E+16
1.00E+17
1.00E+18
1.00E+19
CPV

If not a self-fulfilling prophecy, then what could be the sources of Moore's "Luck"? IV

- He was implicitly predicting a functional trend that had been already followed for a number of years.
- He was working in a functional area where the rate of change (and form?) was visible in just a few years.
- He chose a *tradeoff* metric rather than a simpler figure of merit (transistor speed?)
- He was "lucky" (experienced) enough to avoid pinning his dynamics on cumulative production volume and instead stayed with the more *fundamental variable-time*
- He chose an exponential form but could have followed others in fitting his data to a logistic curve

Invention/Engineering Process



Accumulating Knowledge

- Search techniques
- Preparation or prototyping skill

- **New science**
- Critical questions
- Enabling approaches

- **New combinations**
- **New capabilities**
- **New design principles**

- **Results from assessing**
- Evaluation techniques
- Limits and tradeoffs

Invention/Engineering Process

"Random" search

Concepts from past results and other domains

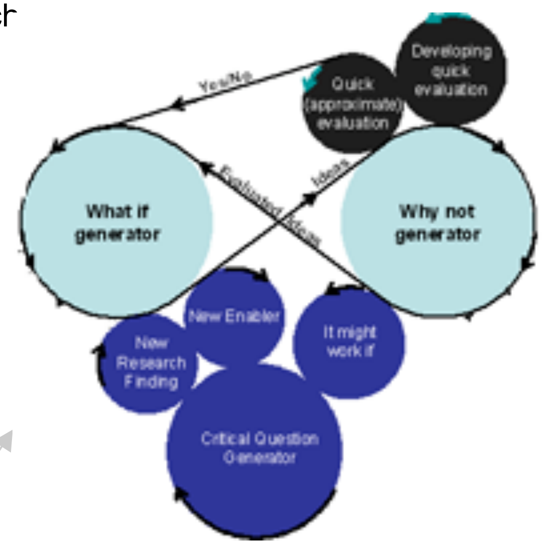
Scientific principles

Evolutionary search

New Capabilities

Pause/Incubation

"Moment of insight" and surprises



New analytic assessment tools

Market result

Controlled experimentation

Detailed utilization of existing knowledge

Judgment

Accumulating Knowledge

- **New 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

Technical capability time dependence

- TC = f(K) where K accumulates over time as TC advances
  - dTC/dt = α f(K) = α TC
  - TC = exp(α t); EXPONENTIAL ..or…
- dTC/dt = [α + β(TC_L -TC)]TC LOGISTIC
- The logistic curve applied to Moore's original data shows TC_L to be < 10^4
- we are now at ~10^9

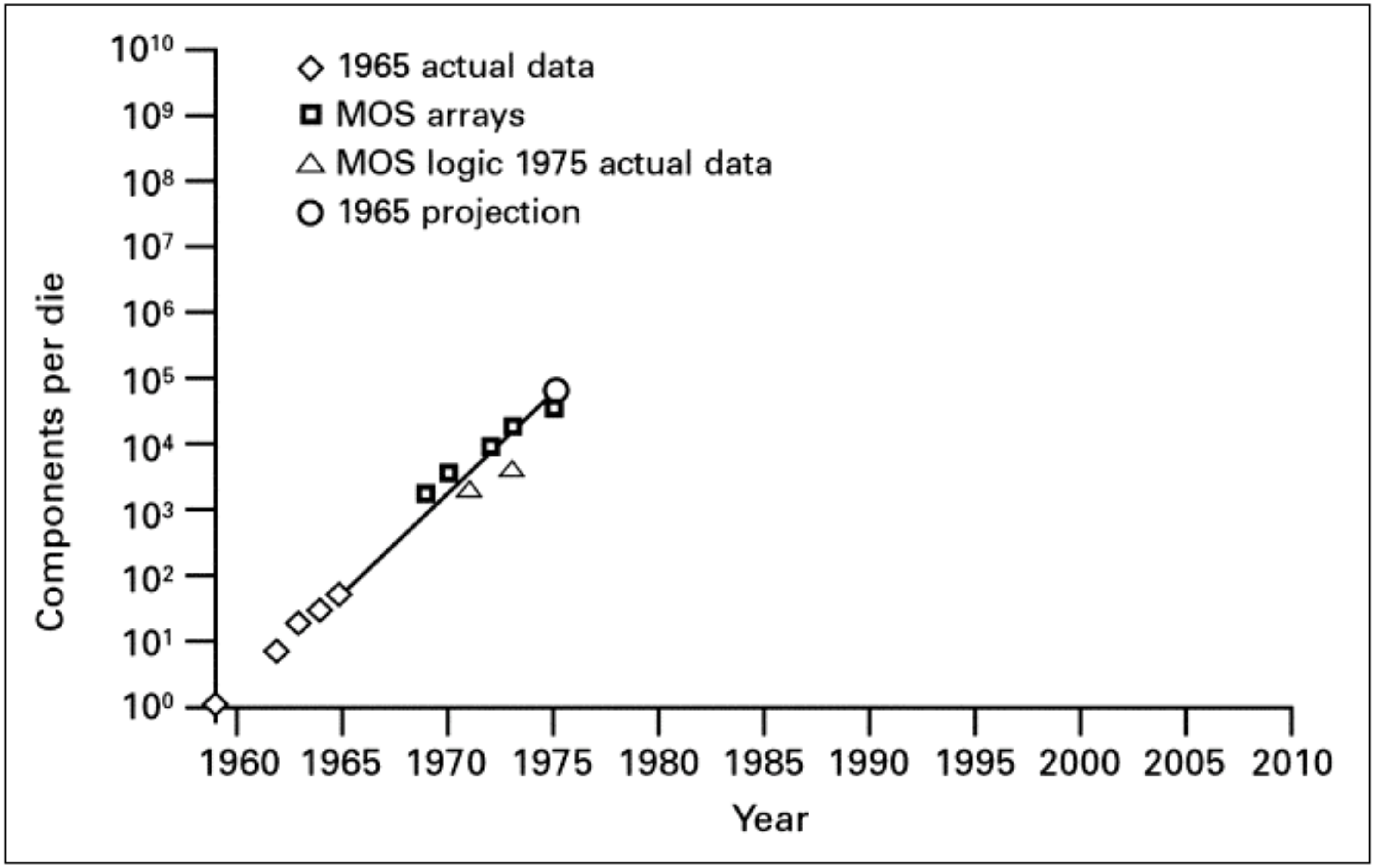


Figure 6. Integrated circuit complexity (1959–1975). Source: Intel.

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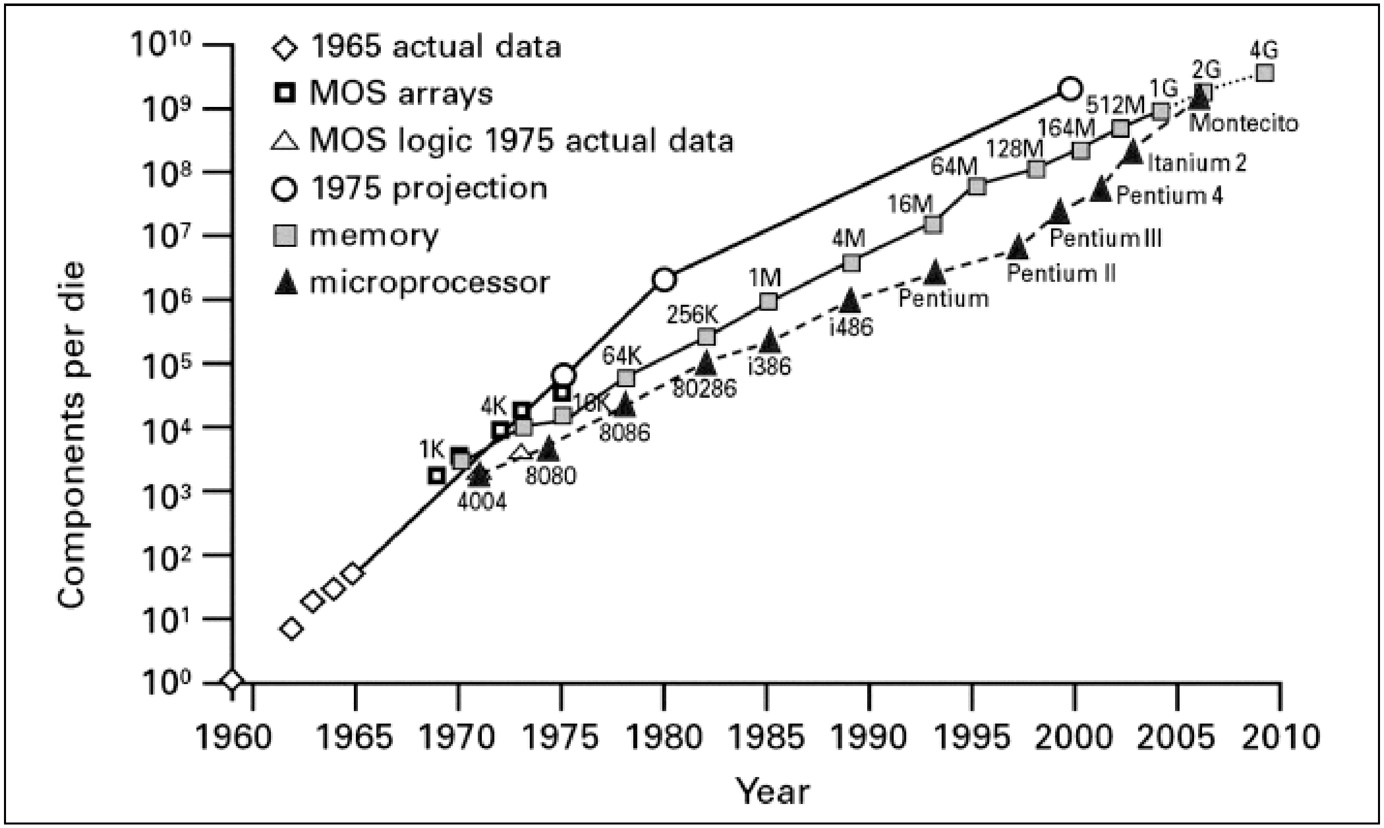

FIGURE 9. Integrated circuit complexity, actual data compared with 1975 projection. Source: Intel.

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Conclusions From Examining Gordon Moore's "Luck"

- Appropriate **Technical capability metrics** follow reasonably regular patterns
  - "Noisy" exponentials with time (**not** logistic curves or..)
  - Large variation in rates of progress among TASA and among functional categories (**not** for power laws with CPV)
- **Accumulation of capability** as the *active constraint on engineering innovation* is consistent with exponentials not logistic curves (or power laws with CPV)
- Modeling
  - Consistent with the invention process
  - Simple to model ignoring details
  - Regularity may actually be promoted by the highly irregular, creative and *adaptive* core process.

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- **Concluding Remarks**

Further research of interest

- For a ***cumulative process*** where the rate of improvement is proportional to current capability, an exponential relationship over time is expected-

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

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

- Understanding fully the ***differences in rates of progress (α) is the practical and theoretical point of most interest.***
- Goal from second slide -a “reasonably valid” model that explains/predicts why various technological approaches progress at such very different rates.
- Other issues are also important:
  - **limits** in technical capability;
  - Role of capability dynamic differences between TASA in substitution dynamics
  - linking properly defined metrics to demand and other economic variables;
  - linking metric dynamics to productivity growth overall and in sectors
  - Emergence of new TASA and their capability (metric) level

Influences on Rates of progress

- "maturity" – empirically great rate differences from "birth" are obvious and limits are not seen in many tradeoff metrics or any FPMs (yet?)- rated relatively unimportant
- CPV- empirically not mechanistically important; demand also questionable
- *R&D spending-* Since **human effort is essential to achieve progress**, "R&D spending" is needed to get progress. How much faster can one go with more R&D spending per year? Feedback and accumulation times are not necessarily reduced by having more participants.
- R&D spending tends to increase as revenue increases (in a given sector) and thus as FPMs improve, R&D spending will increase as an effect not a cause.
- How does R&D spending vary in sectors having different rates of progress?

R&D spending in selected sectors and times

Case	R&D 1965	R&D$/ Revenue$ 1965-2004	FPM improvement	R&D 2004
IC	125x 10^6 $	11% - 15%	35% 10^7	$28x10^9$ $
turbines	150x 10^6 $	19% - 9%	4% 10^1	$9x10^9$ $
Pharma drugs	150x 10^6 $	15% - 19%	~ < 1% ~ $<10^0$	$51x10^9$ $

Influences on Rates of progress II

- “maturity” – empirically eliminated
- CPV -empirically not important mechanistically but is cross-correlated with time through FPM improvement; demand also questionable
- *R&D spending*- empirical cross industry comparisons indicate little explanatory power. In market share competitive industries, R&D$ likely to exceed limits where increases are useful .
- Market structure for industry or sector
- Capability of people in different fields/sectors; superior firm organizational forms; differing prophecies
- “Weakness” of supporting science: also not strongly supported empirically (info vs. thermo).
- Something else

Influences on Rates of progress III

- "maturity" – empirically eliminated
- CPV
- *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
- Needed work
  - An objective direct method (and framework) for observing decomposability
  - Observation of decomposability for a large number of technical capability progress cases
  - Simulation/modeling of progress as a function of objectively observable decomposability
- Possible Utility…

Concluding remarks I

- One can envision a “real theory” for the progress in technical capability - Moore’s remarkable prediction and the **broad existence** of such laws
- Moreover, careful attention to **exponential time dependence** can help us recognize technical capability trends that **might** be relatively stable. Thus, “predictions” one might offer include:
  – Capacitors will be superior to batteries in energy storage in numerous applications by ~2015 and in almost all applications in about 30 years.
  – Solar PV will be superior to oil conversion for electricity generation in numerous applications by ~2020.

Concluding Remarks II

- We have argued
  - That the **self-fulfilling prophecy explanation** for technical capability dynamics is a fallacy
  - That **produced units and R&D$** are not the fundamental parameters
- Instead it is has been hypothesized that
  - **Technology structure and market structure** matter
  - **Seconds, meters, bits and ergs/watts** are the fundamental variables that matter
- Perhaps technology does provide some possibly important constraints on the **undeniably social process** of technological development.