Digital Integrated Circuit Design

CMPE 530/630

Introduction to Digital IC Design

Dr. Cory Merkel

A Little Bit About Me

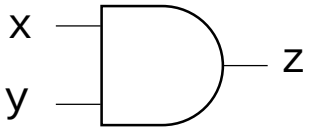
- From Rochester Area
- Ph.D. in Microsystems Engineering @ RIT
- 3 years at Air Force Research Lab
- Research Interests:
  - Brain-inspired/neuromorphic computing
  - AI at the Edge

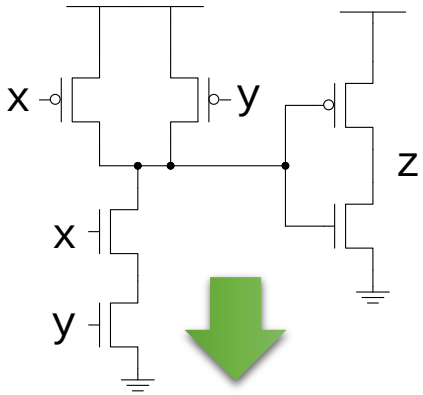
IC Design Flow

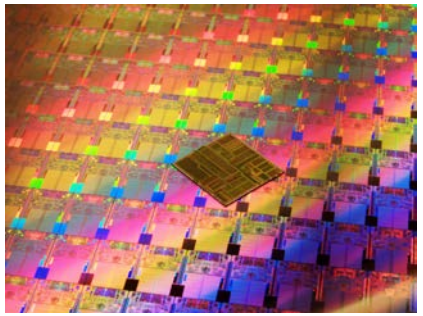
Design Specification → Functional Design → Logic Level Design → Transistor Level Design → Mask Design → Fabrication

"I need a chip that multiplies two 1-bit numbers."

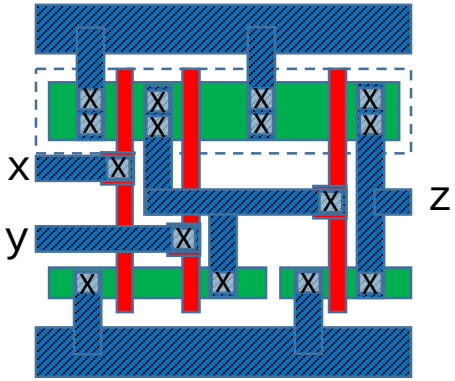
```
module my_chip(x,y,z);
input x,y,z;
assign z=x&y;
endmodule
```







Source: Intel



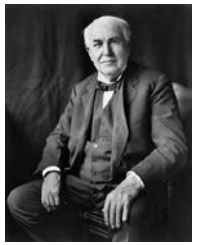
» Lots of intermediate steps not shown!

Course Goals

- Introduce students to IC design techniques
- Provide a strong foundation for students to explore advanced concepts on their own
- By the end of the course, students will be able to design custom integrated circuits from concept through tapeout!

A Little History…

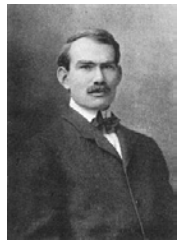
1879 — Thomas Edison Invents Light Bulb



1897 — J. J. Thomson Discovers the Electron

1904 — J. A. Fleming Invents the Fleming Valve & Explains the Edison Effect

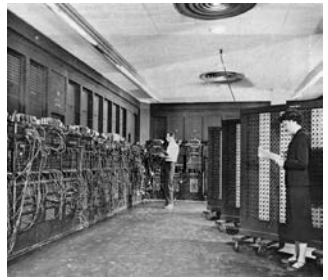
1906 — Lee de Forest Invents the Triode – Vacuum Tube Amplifier



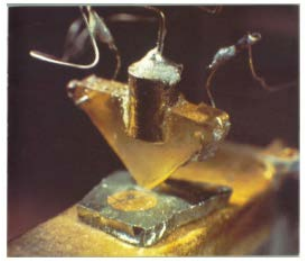
1930s — Semiconductor Crystals Used as Rectifiers in RADAR

1945 — ENIAC

- 1st general purpose electronic computer
- Filled whole room
- 17,468 vacuum tubes
- 70k res, 10k caps
- 6k manual switches



1947 — Walter Brittain, John Bardeen, and William Shockley invent point contact transistor at Bell Labs.

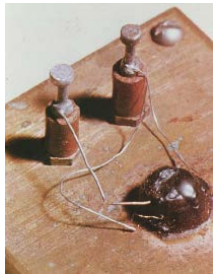


Winners of 1957 Nobel Prize in Physics

Images are from Wikipedia

A Little History…

First junction transistor invented by William Shockley at Bell Labs

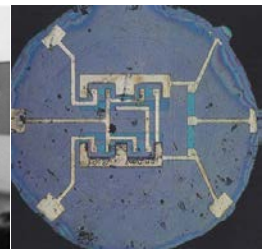


1948

TRADIC – 1st transistorized compute
- 3 cubic feet (ENIAC was 1000 ft²)
- 800 point-contact transistors
- 10k germanium crystal rectifiers
- 1M ops/sec @ < 100 W

1954

Bob Noyce Fairchild -1st useful integrated circuit and planar process.



1958

First integrated circuit 3-transitor phase-shift oscillator invented by Jack Kilby at TI

1960

Winner of 2000 Nobel Prize in Physics

1974

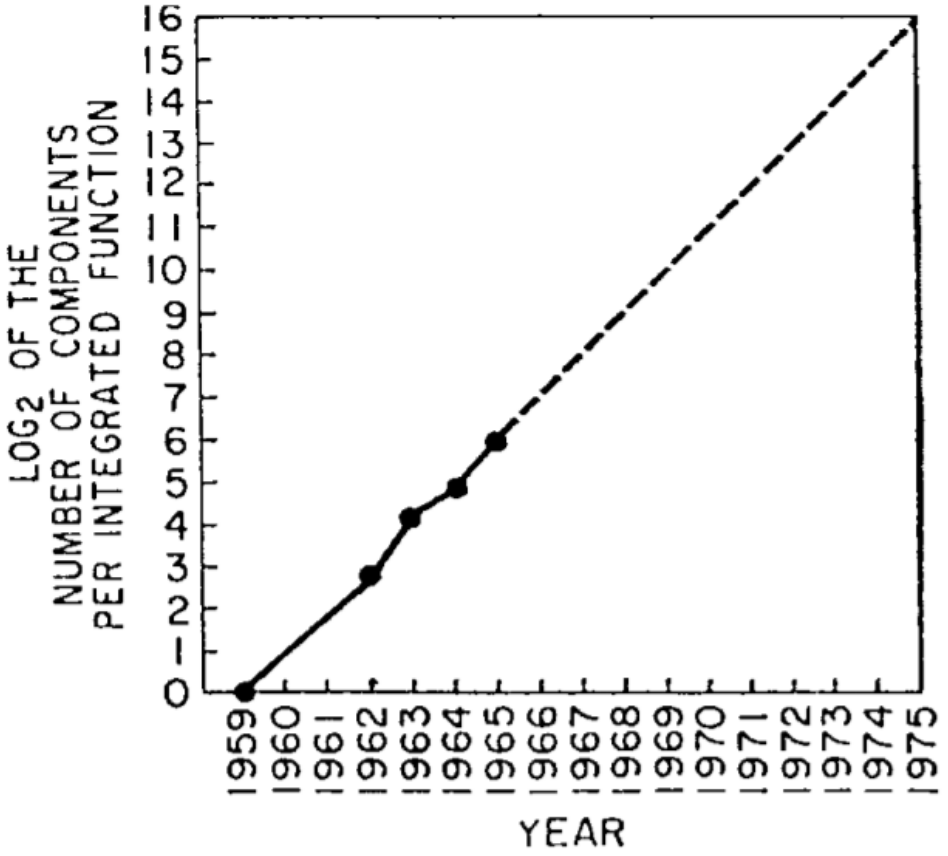
Robert Dennard introduces Dennard Scaling (IBM)

Images are from Wikipedia

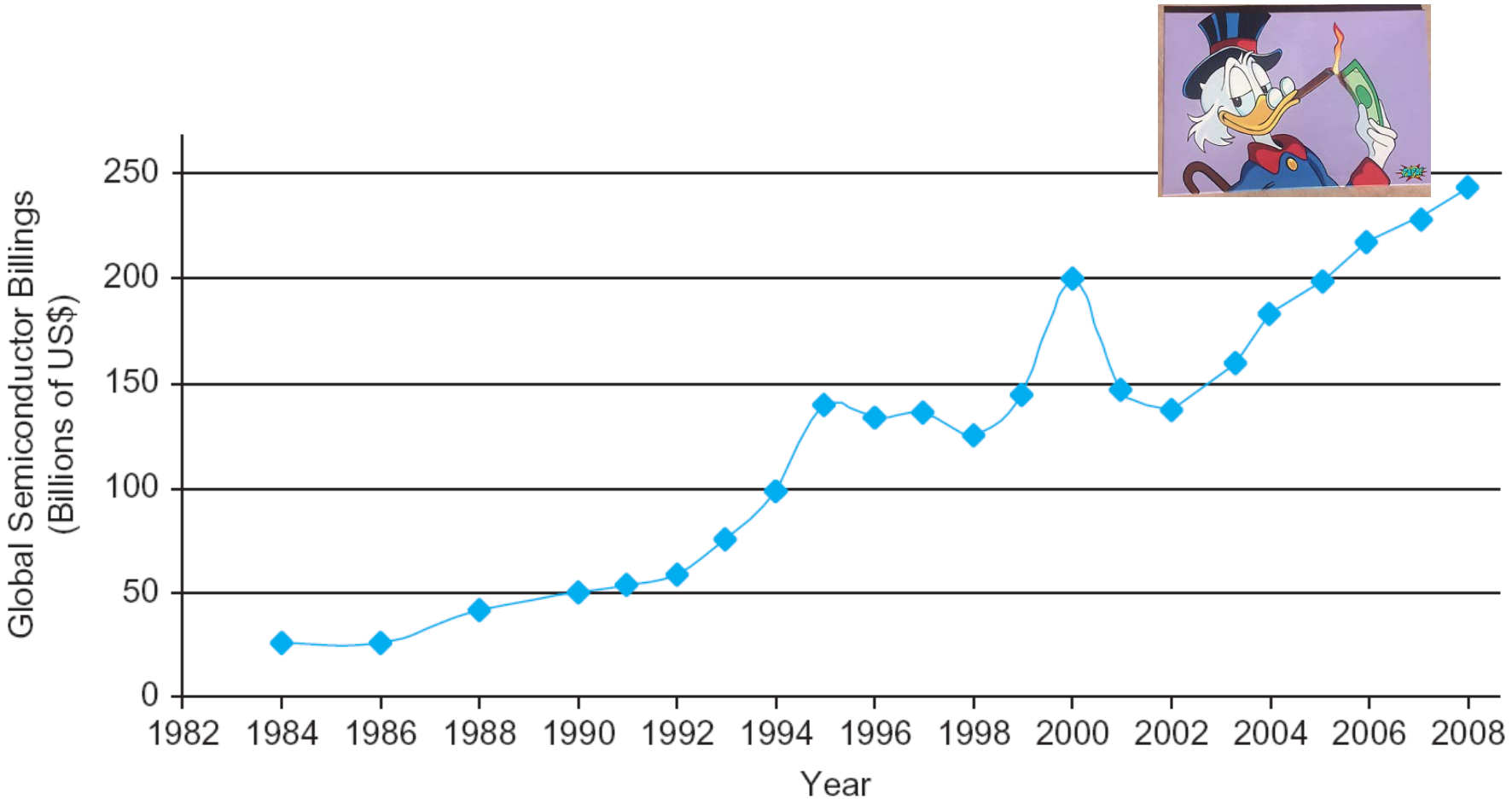
» Why Integration?
- Overcame the "tyranny of numbers"
  - Before ICs, Had to wire million of connections by hand
- Enabled unparalleled growth in IC industry for 50+years

Moore's Law and Scaling

» 1965 – Gordon Moore: "Cramming More Components onto Integrated Circuits,"



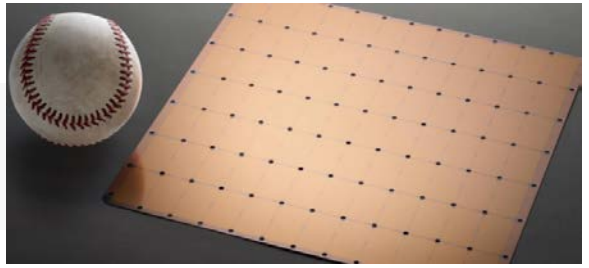
Size of Worldwide Semiconductor Market

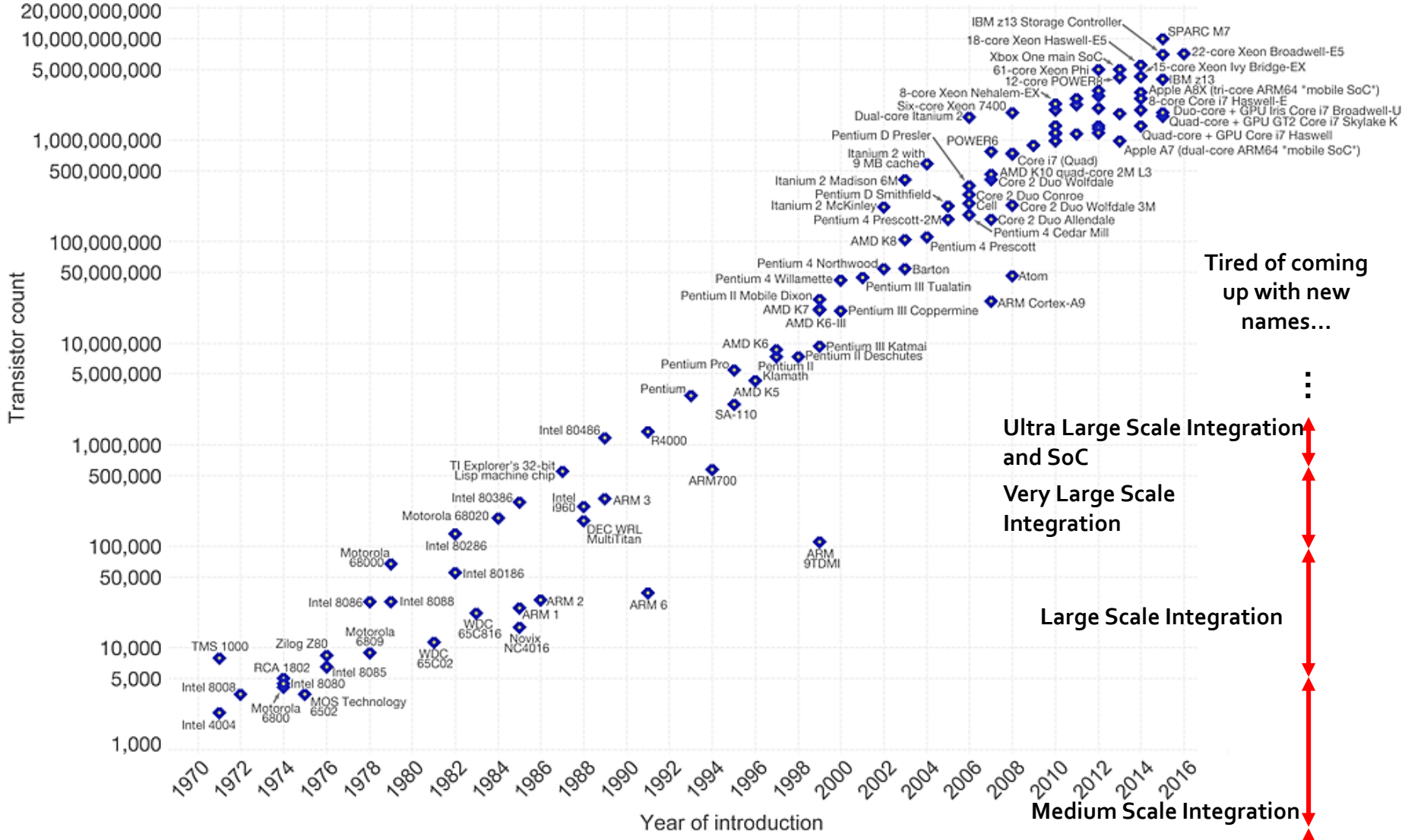


- Currently valued at over 0.5 Trillion dollars!

Transistor Counts

2020: Cerebras Systems AI Chip—1.2 Trillion Transistors!





Tired of coming up with new names…

⋮

Ultra Large Scale Integration and SoC

Very Large Scale Integration

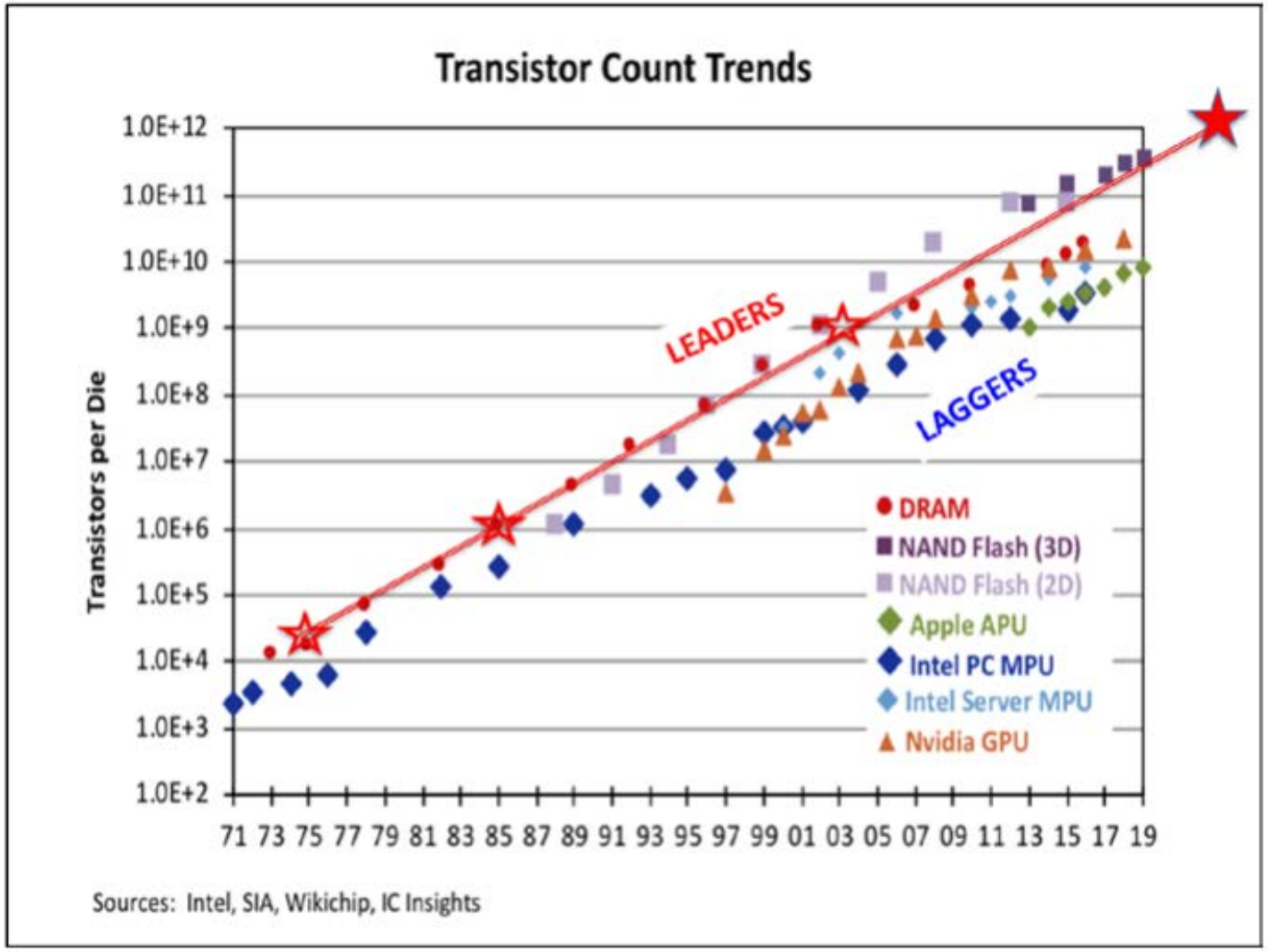
Large Scale Integration

Medium Scale Integration

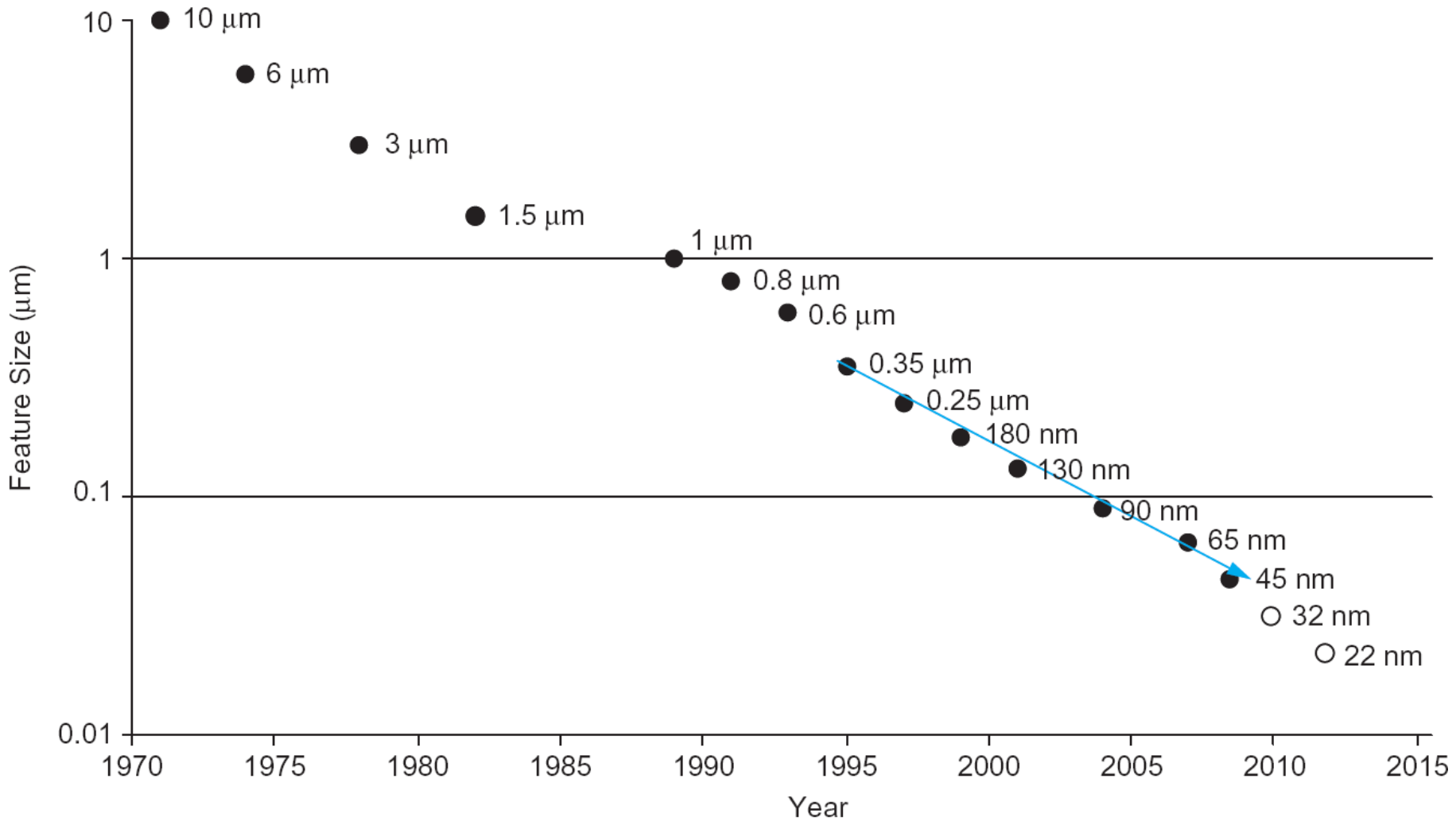
Small Scale Integration

Source: ourworldindata.org

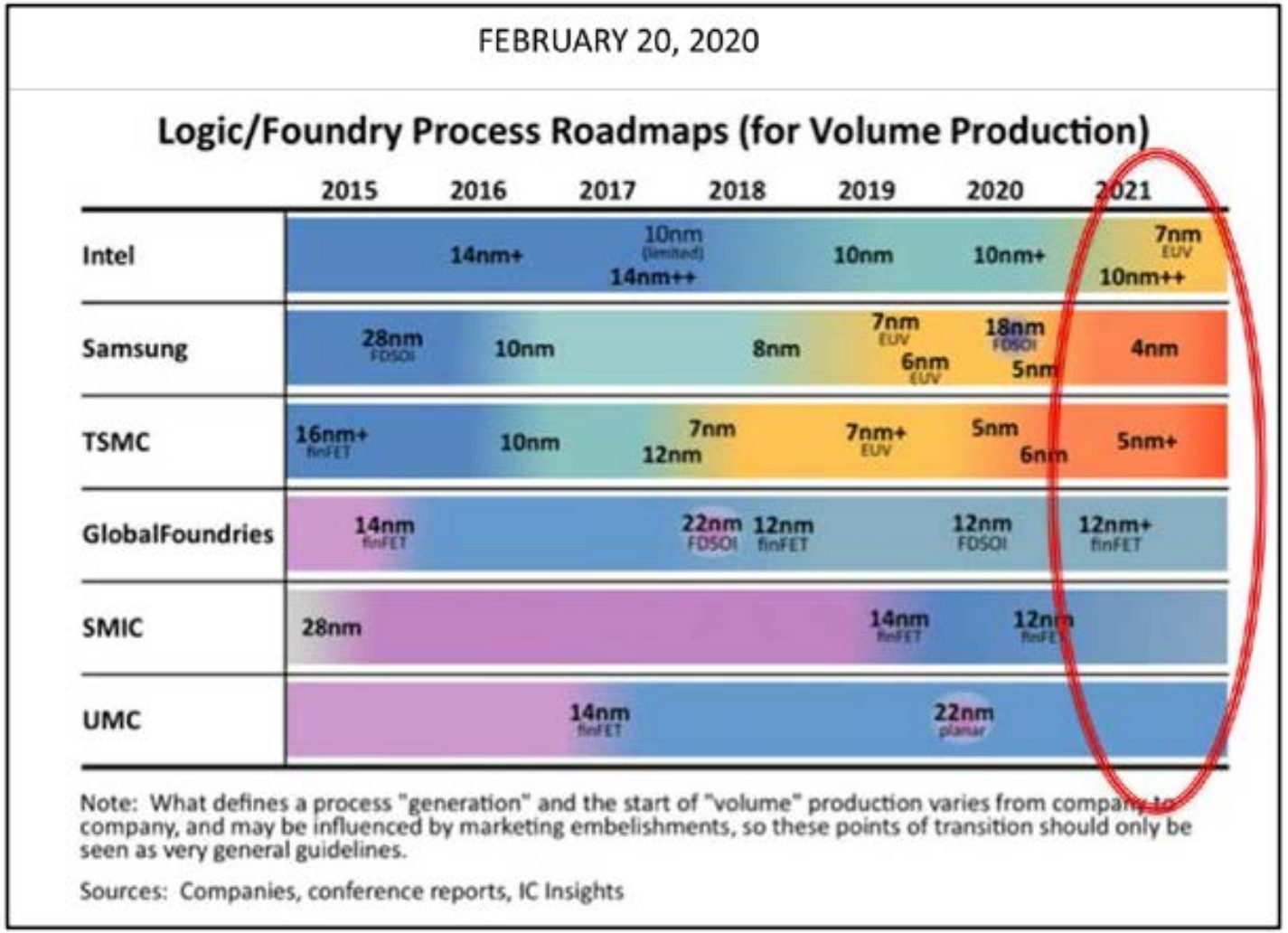
Transistor Counts (Another Look)



Shrinking Transistor Sizes

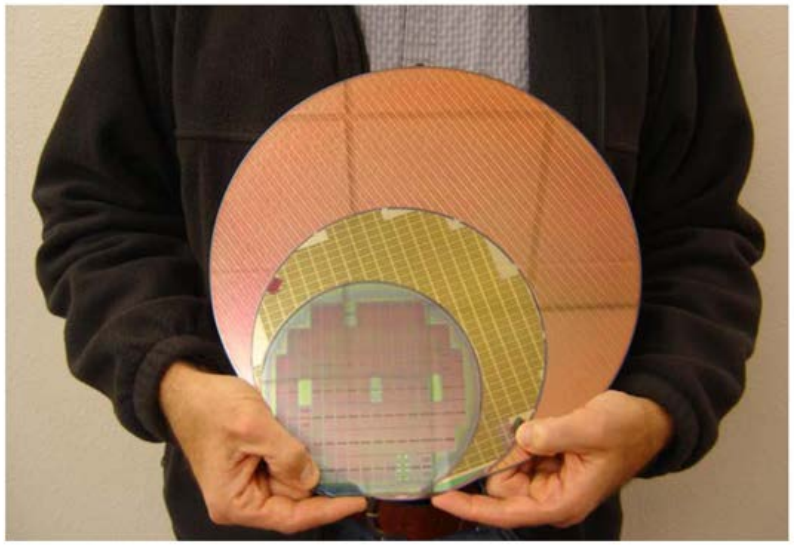


Shrinking Transistor Sizes



Wafer Sizes

- Larger wafers allow more die to be produced in parallel:

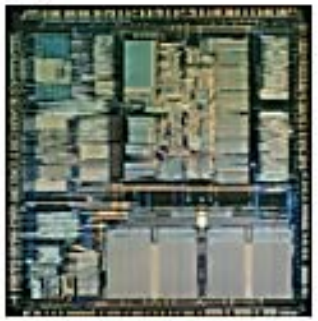


R. J. Baker, "CMOS: Circuit design, layout, and simulation," 2019.

- Each die is identical

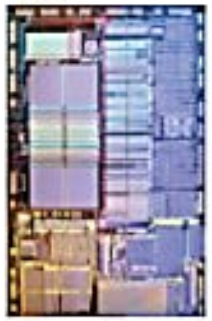
Intel Processors Over the Years

1985



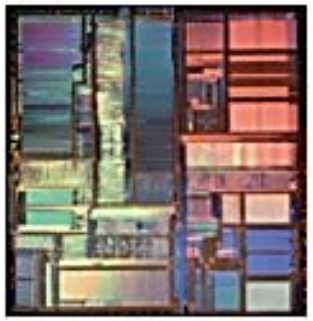
Intel386™ processor
Initial clock speed: 16MHz
Transistors: 275,000
Manufacturing technology: 1.5 micron

1989



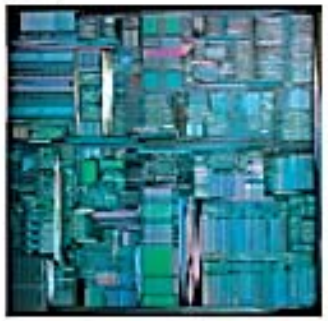
Intel486™ processor
Initial clock speed: 25MHz
Transistors: 1.2 million
Manufacturing technology: 1 micron

1993



Intel® Pentium® processor
Initial clock speed: 60MHz
Transistors: 3.1 million
Manufacturing technology: 0.8 micron

1995

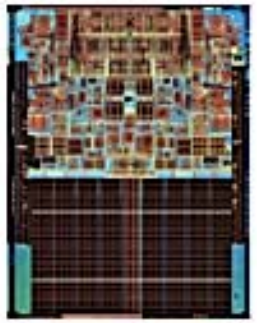


Intel® Pentium® Pro processor
Initial clock speed: 200MHz
Transistors: 5.5 million
Manufacturing technology: 0.35 micron

2003

Intel® Pentium® M processor
Initial clock speed: 1.7GHz
Transistors: 55 million
Manufacturing technology: 90nm

2006



Intel® Core™2 Duo processor
Initial clock speed: 2.66GHz
Transistors: 291 million
Manufacturing technology: 65nm

2008

Intel® Core™2 Duo processor
Initial clock speed: 2.4GHz
Transistors: 410 million
Manufacturing technology: 45nm

2008

Intel® Atom™ processor
Initial clock speed: 1.86GHz
Transistors: 47 million
Manufacturing technology: 45nm

2010

2nd generation Intel® Core™ processor
Initial clock speed: 3.8GHz
Transistors: 1.16 billion
Manufacturing technology: 32nm

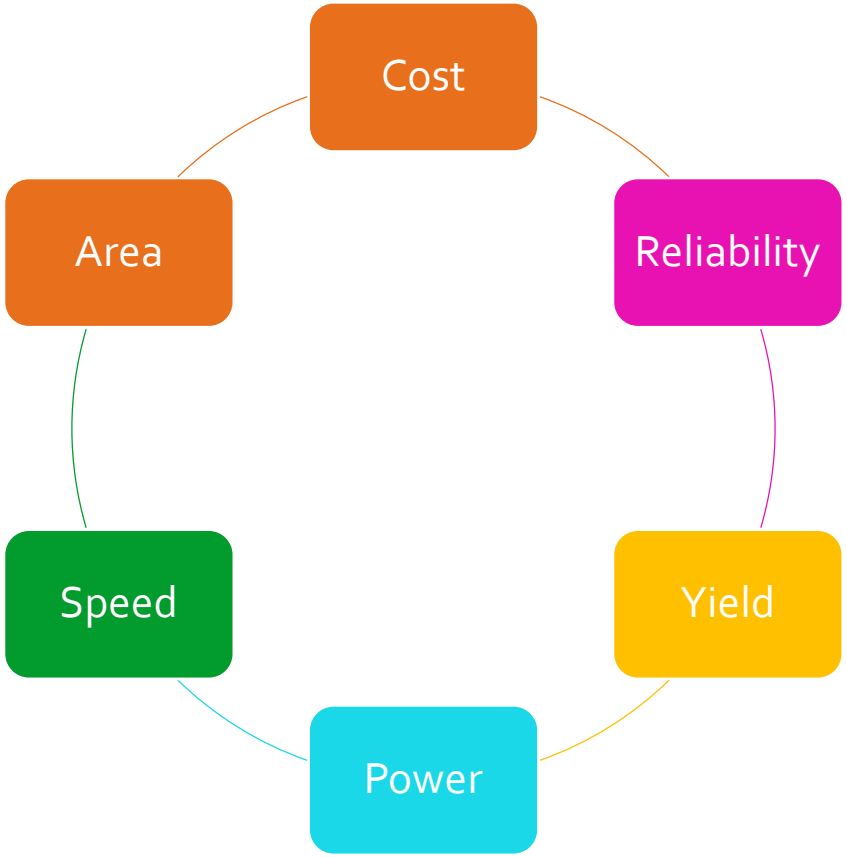
2012

3rd generation Intel® Core™ processor
Initial clock speed: 2.9GHz
Transistors: 1.4 billion
Manufacturing technology: 22nm

Source: Intel

Evaluating Digital ICs

- What are the tradeoffs?
- What influences what?



Shrinking Transistor Sizes

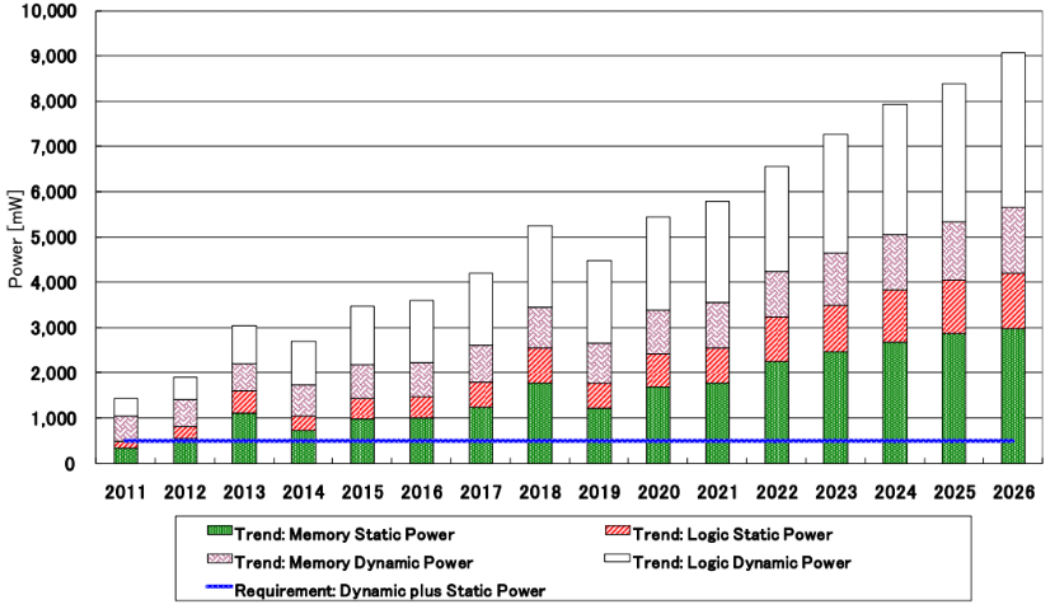
» Why does the IC industry want to scale?

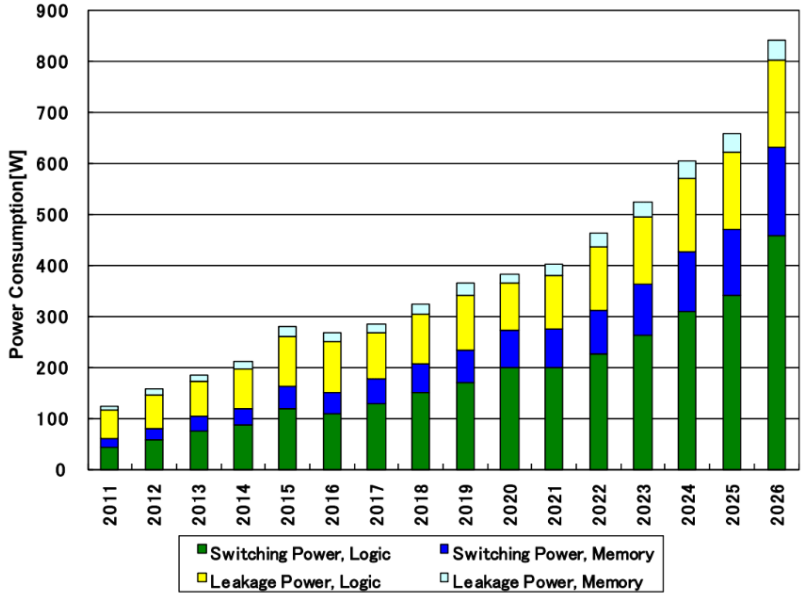
Parameter	Sensitivity	Dennard Scaling	Constant Voltage	Lateral Scaling
L: Length		1/S	1/S	1/S
W: Width		1/S	1/S	1
t_{ox}: gate oxide thickness		1/S	1/S	1
V_{DD}: supply voltage		1/S	1	1
V_t: threshold voltage		1/S	1	1
NA: substrate doping		S	S	1
β	$W/(Lt_{ox})$	S	S	S
I_{on}: ON current	$\beta(V_{DD}-V_t)^2$	1/S	S	S
R: effective resistance	V_{DD}/I_{on}	1	1/S	1/S
C: gate capacitance	WL/t_{ox}	1/S	1/S	1/S
τ: gate delay	RC	1/S	$1/S^2$	$1/S^2$
f: clock frequency	$1/\tau$	S	S^2	S^2
E: switching energy / gate	CV_{DD}^2	$1/S^3$	1/S	1/S
P: switching power / gate	Ef	$1/S^2$	S	S
A: area per gate	WL	$1/S^2$	$1/S^2$	1
Switching power density	P/A	1	S^3	S
Switching current density	I_{on}/A	S	S^3	S

Faster, more energy-efficient chips @ lower cost

Adverse Effects of Scaling

» Power Consumption





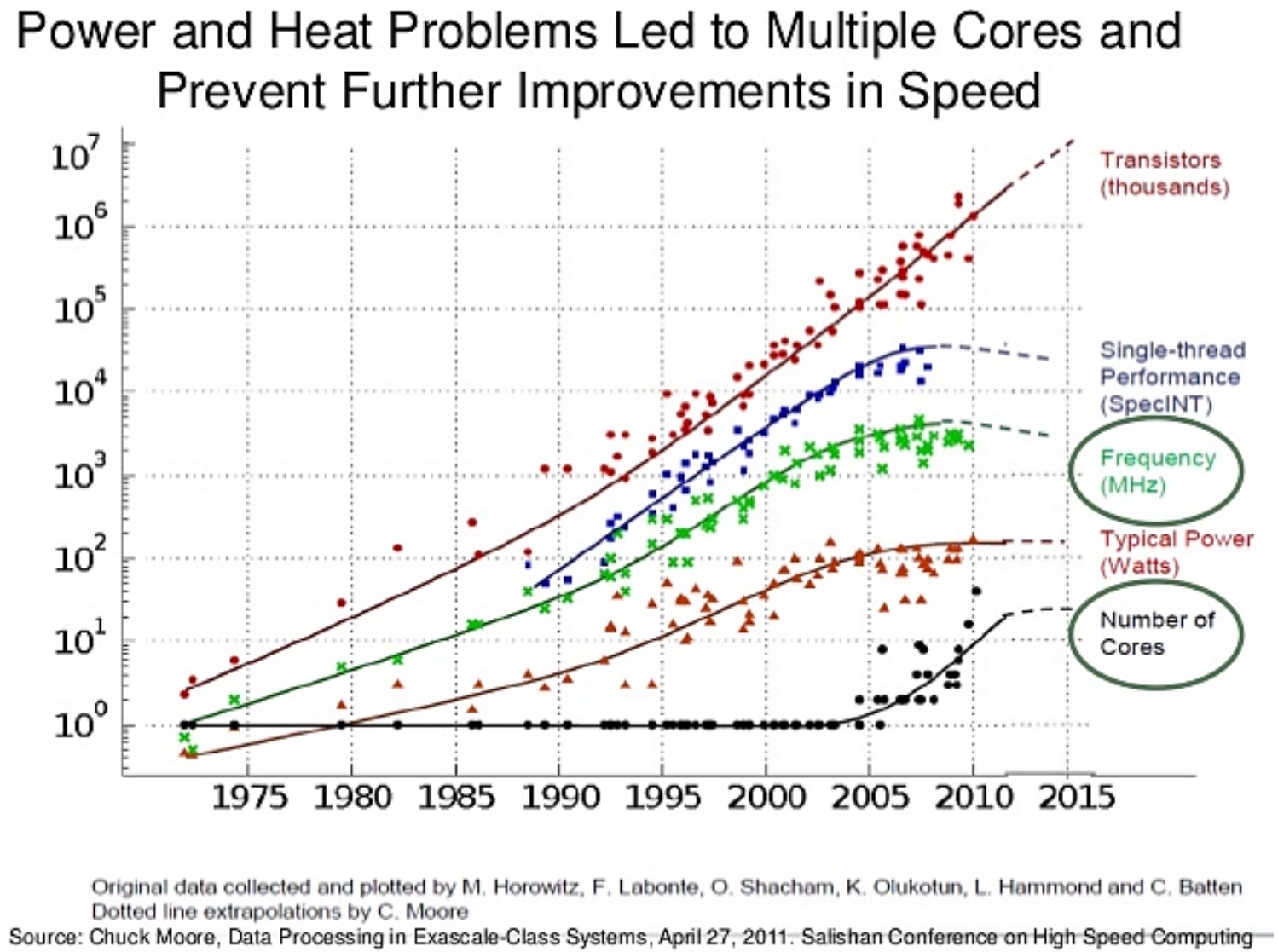
Source: ITRS

» More transistors/chip → More dynamic power

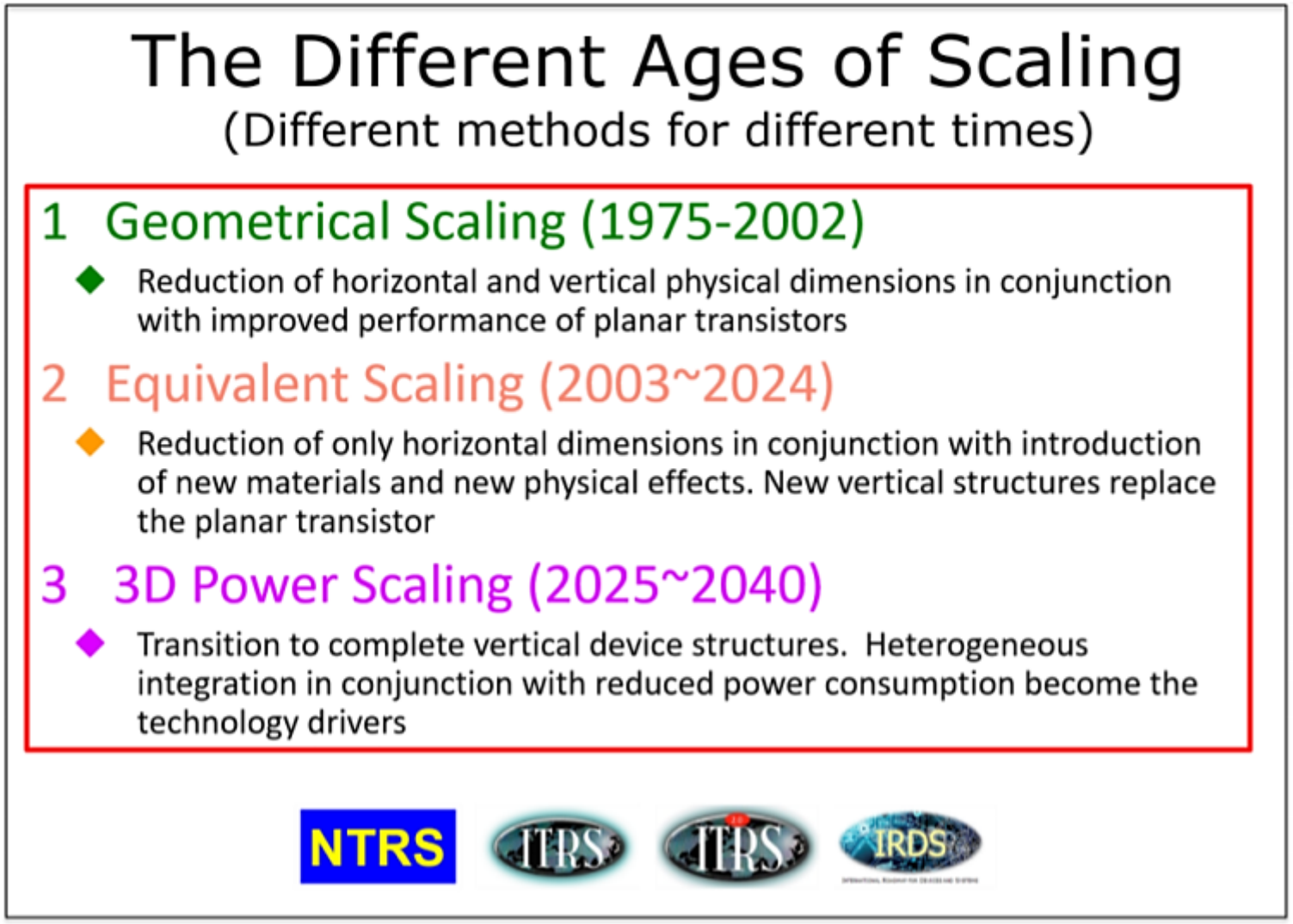
» As threshold voltages are reduced, transistors become more "leaky"

- Large static power consumption

The Death of Moore's Law ☹



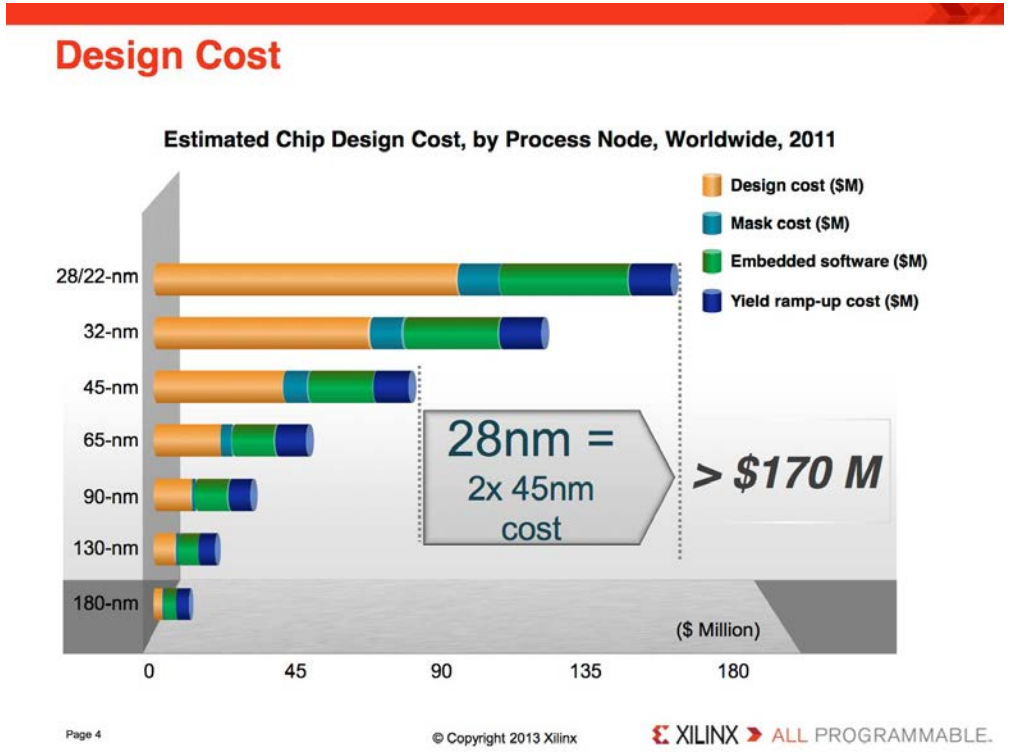
Eras of Scaling



Source: IRDS

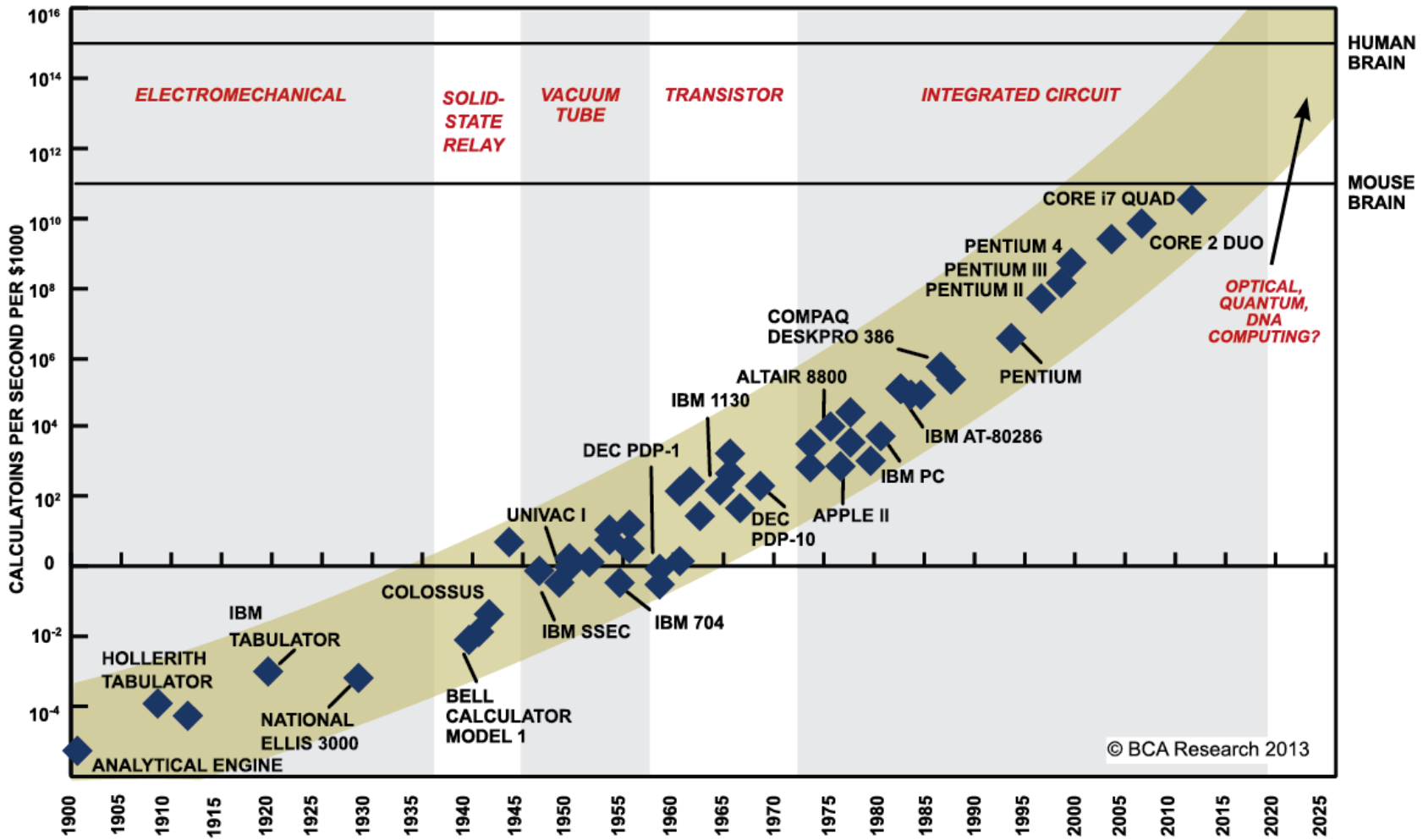
Adverse Effects of Scaling

- Reliability
- Design/manufacturing cost
  - Barrier to entry for new businesses
  - SOC design cost approaching $500M



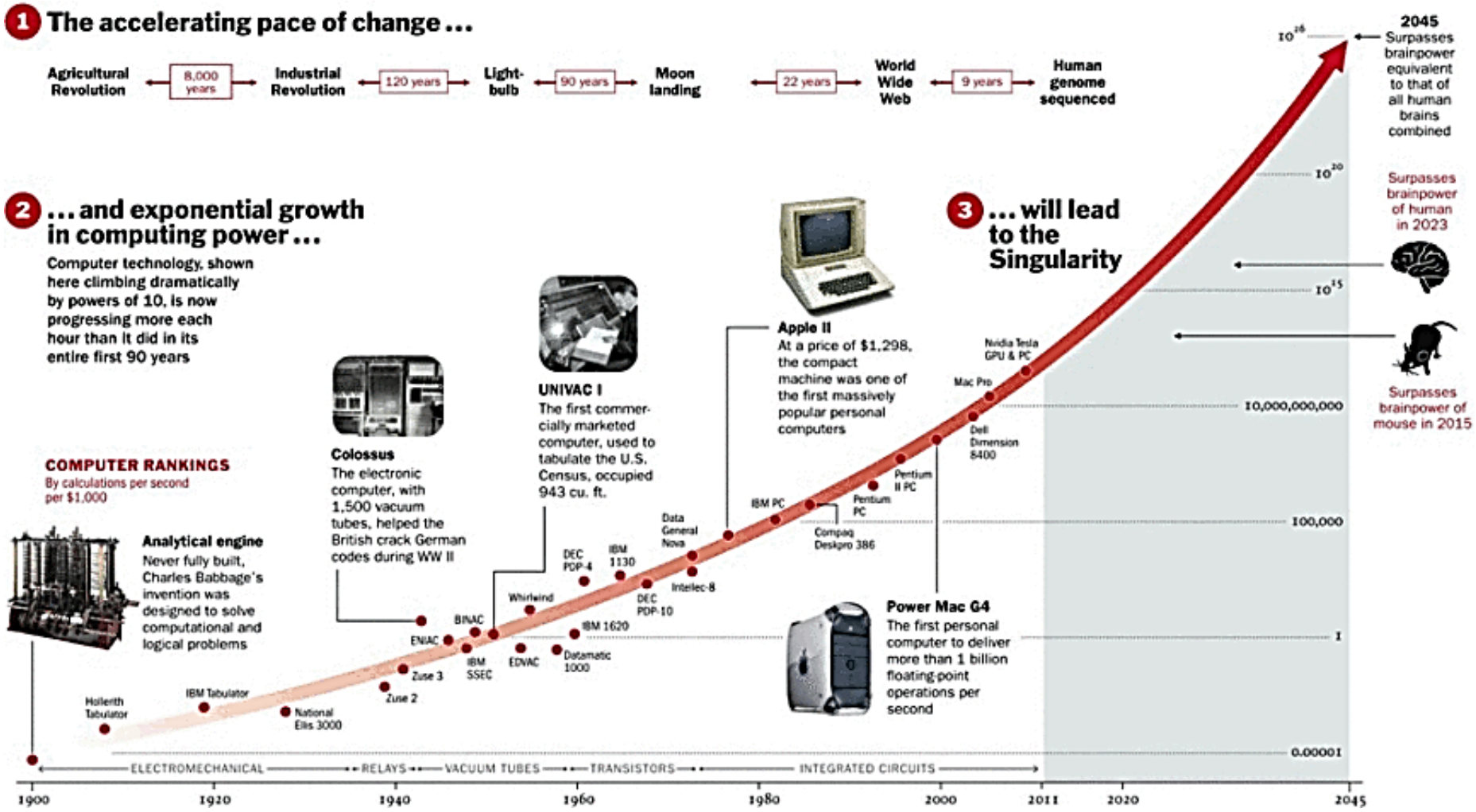
Source: Xilinx

Another View of Moore's Law



SOURCE: RAY KURZWEIL, "THE SINGULARITY IS NEAR: WHEN HUMANS TRANSCEND BIOLOGY", P.67, *THE VIKING PRESS*, 2006. DATAPOINTS BETWEEN 2000 AND 2012 REPRESENT BCA ESTIMATES.

Another View of Moore's Law



Source: needull.com

Back to Our 1-bit Multiplier Example

- There are lots of approaches we could use:
  - Full Custom
    - Every gate is custom designed
      - Most flexible for efficiency
      - Too difficult these days with billions of gates
  - Application Specific Integrated Circuit
    - Gates come from a library, most effort goes into floorplanning, routing
  - System-on-Chip (SOC)
    - Many heterogeneous functionalities on one die
    - Analog/digital/RF, etc.
  - System-in-Package (SIP)
    - Several dice integrated into one package

Additional Reading

- International Technology Roadmap for Semiconductors (ITRS)
  - www.itrs2.net/
- International Roadmap for Devices and Systems
  - https://irds.ieee.org/
- Moore, G. E. (1998). Cramming more components onto integrated circuits. *Proceedings of the IEEE*, *86*(1), 82-85.
- Feynman, R. P. (2012). There's plenty of room at the bottom: An invitation to enter a new field of physics. In *Handbook of Nanoscience, Engineering, and Technology, Third Edition* (pp. 26-35). CRC Press.
- *Crystal Fire* by Michael Riordan and Lillian Hoddeson
- *The Chip* by T. R. Reid
- http://www.computerhistory.org/timeline