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ICTP Latin-American Basic Course on FPGA Design for Scientific Instrumentation

15 - 31 March 2010

Introduction to VLSI Digital Design

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Introduction to VLSI Digital Design

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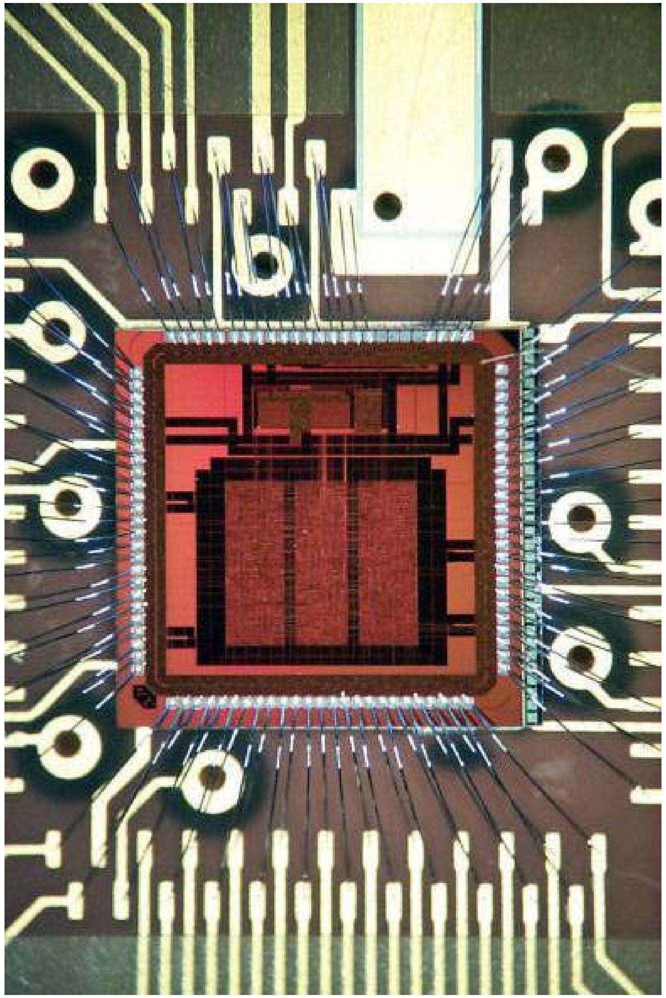
Mar del Plata, Argentina, 15 – 31 March, 2010

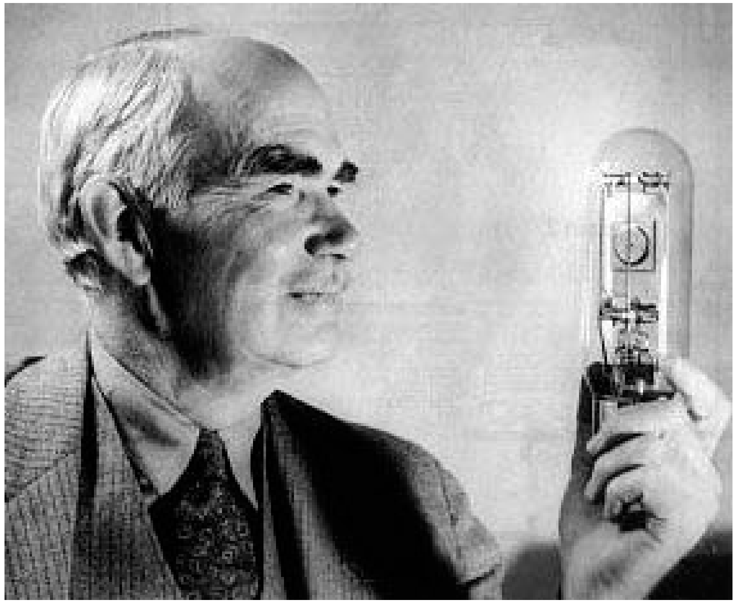
Outline

- Introduction
- Transistors
- The CMOS inverter
- Technology
- Scaling
- Gates
- Sequential circuits
- Storage elements
- Phase-Locked Loops
- Example



History

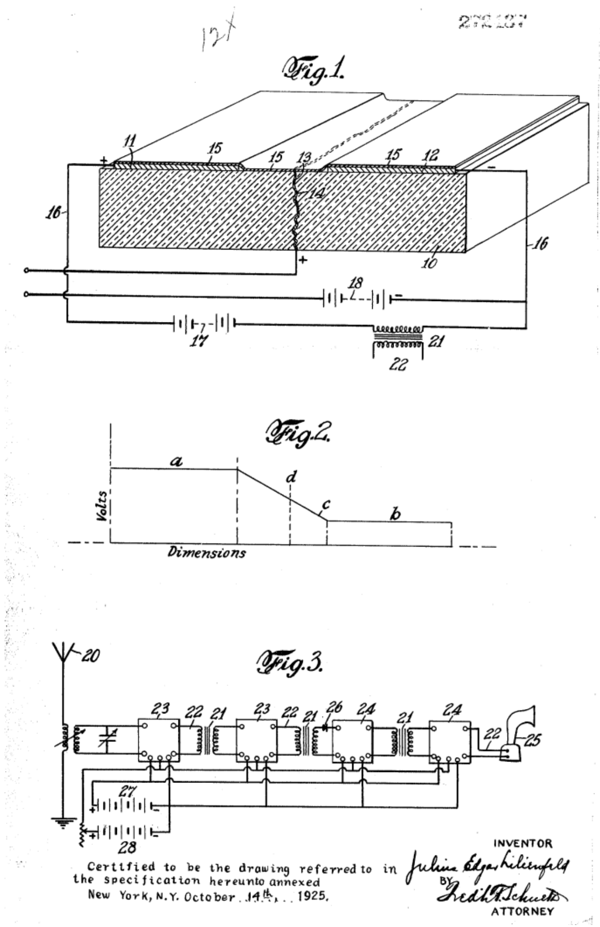
1906



Audion (Triode)
1906, Lee De Forest

- 1883 Thomas Alva Edison ("*Edison Effect*")
  - While experimenting with light bulbs, Edison found that a current can flow through vacuum from the lighted filament to a positively biased metal plate but it does not flow to a negatively biased one.
- 1904 John Ambrose Fleming ("Fleming Diode")
  - Recognizes the importance of Edison's discovery.
  - Demonstrates the rectification of alternating current signals.
  - Applies the principle to radio reception.
- 1906 Lee de Forest ("Triode")
  - Adds an electrode (the "grid") to the Fleming diode between the anode and the cathode.
  - With the grid the "diode" becomes an active device. That is, it can be used for the amplification of signals. (Anode current controlled by the grid.)
- Vacuum tube devices continued to evolve
  - They dominated the radio and TV industry till the sixties.
  - They have coexisted with the transistor and even with integrated circuits (you might still have one as your TV screen or computer monitor)
  - By the way, they are miniature particle accelerators
  - They were the "genesis" of today's huge electronics industry.
  - They were however, fragile, relatively large, power hungry, and costly to manufacture. The industry needed something better.

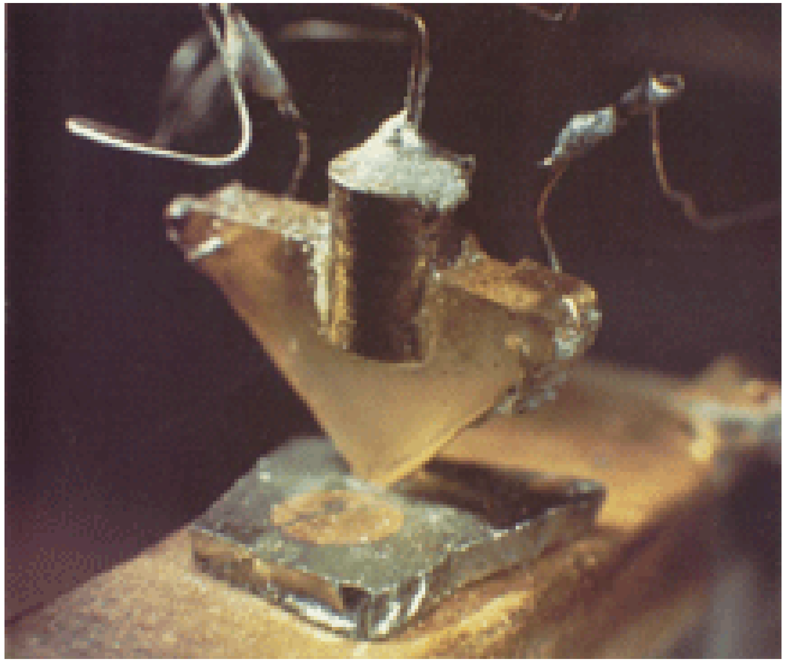
History



- 1925 J. Lilienfeld ("MESFET")
  - Canada patent was filed in 1925 and granted in 1927. The device described is what today would be called a Metal Semiconductor Field Effect Transistor.
  - Patent CA272437 : "Method and apparatus for controlling electric current"
- 1928 J. Lilienfeld ("MOSFET")
  - US patent filed in 1928 and granted in 1933. The device proposed is similar to a modern Metal Oxide Semiconductor FET. The dielectric proposed was the Aluminum Oxide
  - Patent US1900018: "Device for controlling electric current"
- It was necessary to wait till 1960 to have a technology capable of producing working devices!

History

1947

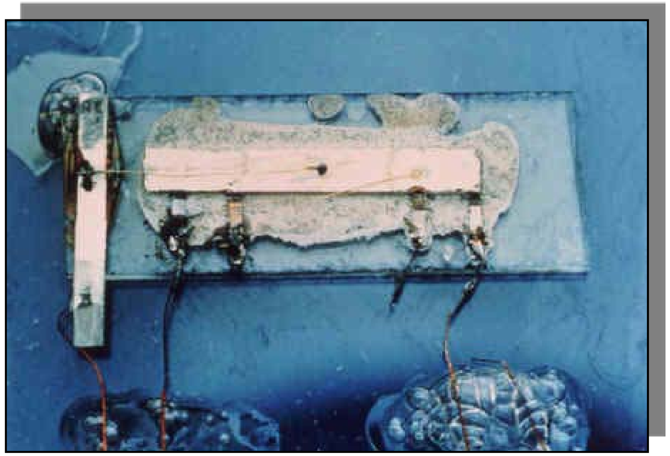


First point contact transistor (germanium)
1947, John Bardeen and Walter Brattain
Bell Laboratories

- 1940 Russel Ohl (PN junction)
  - The PN junction is developed at Bell Labs. The device produces 0.5 V across the junction when exposed to light.
- 1947 Bardeen and Brattain (Transistor)
  - 1945 Bell labs establish a group to develop an alternative to the vacuum tube. The group was lead by William Shockley.
  - Bardeen and Brattain succeeded in creating an amplifying circuit utilizing a point-contact "transfer resistance" device (the transistor).
  - The transistor was built on germanium.
  - U.S. patent # 2,524,035 (1950)
- 1950 William Shockley (Junction transistor)
  - Higher manufacturability yield than the point-contact transistor.
  - By the mid fifties the junction transistor replaces the point-contact transistor
  - Main use: telephone systems
- 1952 Single crystal silicon is fabricated
- 1954 First commercial silicon transistor
  - Texas instruments
- 1954 First transistor radio (Regency TR-1)
  - Industrial Development: Engineer Associates
  - Four germanium transistors from Texas Instruments
- 1955 First field effect transistor
  - Bell Labs

History

1958

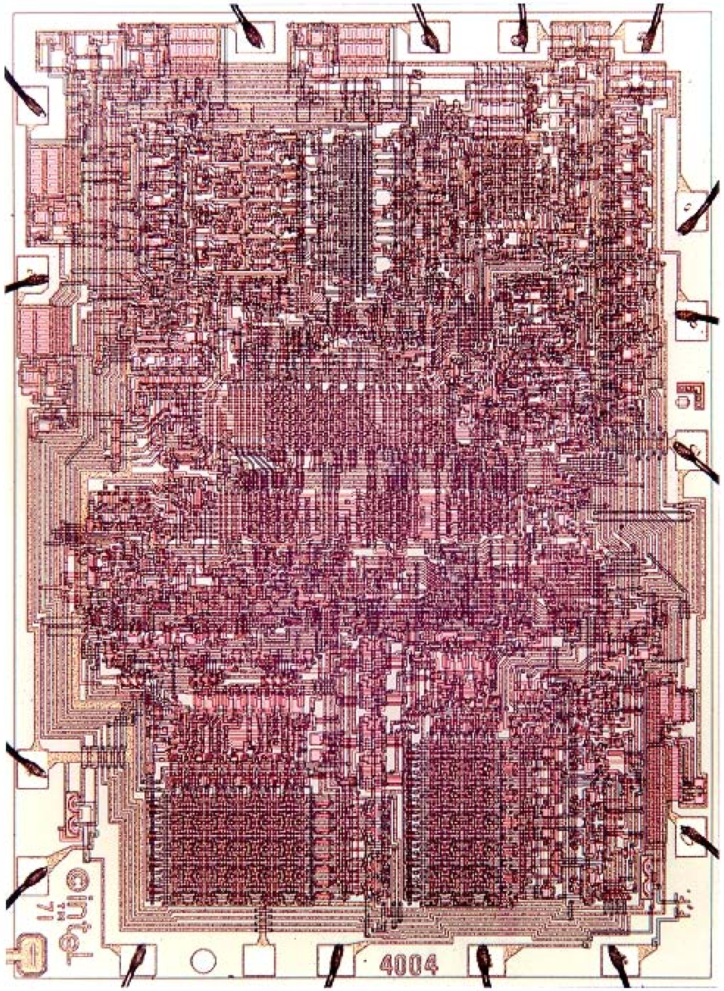


First integrated circuit (germanium), 1958
Jack S. Kilby, Texas Instruments

Contained five components, three types: transistors resistors and capacitors

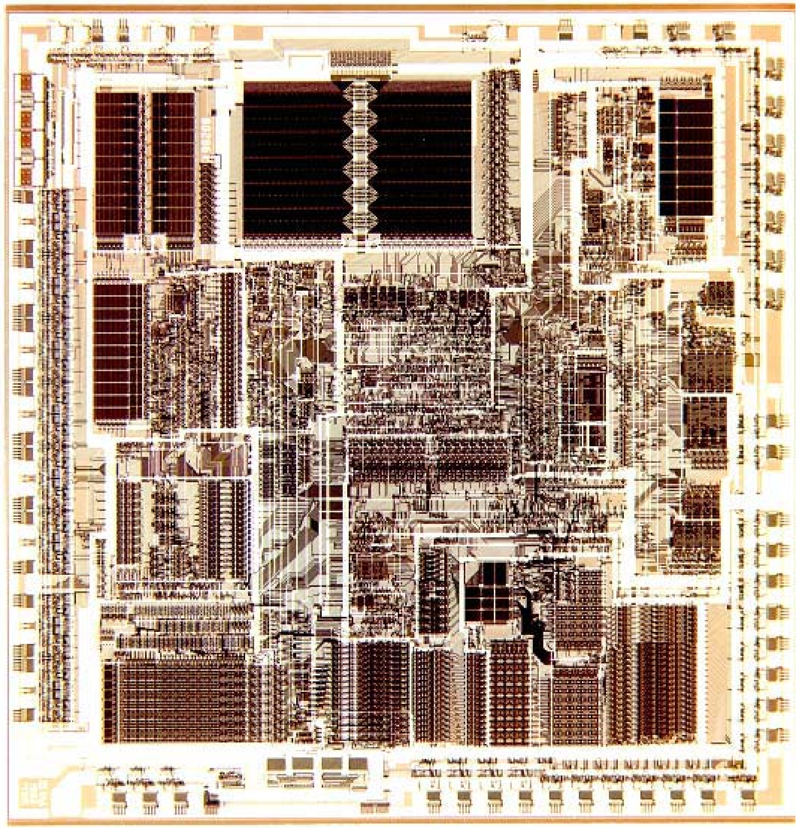
- 1952 Geoffrey W. A. Dummer (IC concept)
  - 1952 IC concept published
  - 1956 Failed attempt
- 1954 Oxide masking process developed
  - Developed at Bell Labs this is the foundation of IC production
  - The process involves: oxidation, photo-masking, etching and diffusion
- 1958 Jack Kilby (Integrated circuit)
  - Working at Texas Instruments Kilby built a simple oscillator IC with five integrated components
  - U. S. patent # 3,138,743 (1959)
- 1959 Planar technology invented
  - The planar technology was developed from the contributions of: Jean Hoerni and Robert Noyce (Fairchild) and Kurt Lehovec (Sprag Electric)
  - The planar technology is still the process used today.
- 1960 First MOSFET fabricated
  - At Bell Labs by Kahng
- 1961 First commercial ICs
  - Fairchild and Texas Instruments
- 1962 TTL invented
- 1963 First PMOS IC produced by RCA
- 1963 CMOS invented
  - Frank Wanlass at Fairchild Semiconductor
  - U. S. patent # 3,356,858
  - Standby power reduced by six orders of magnitude

History



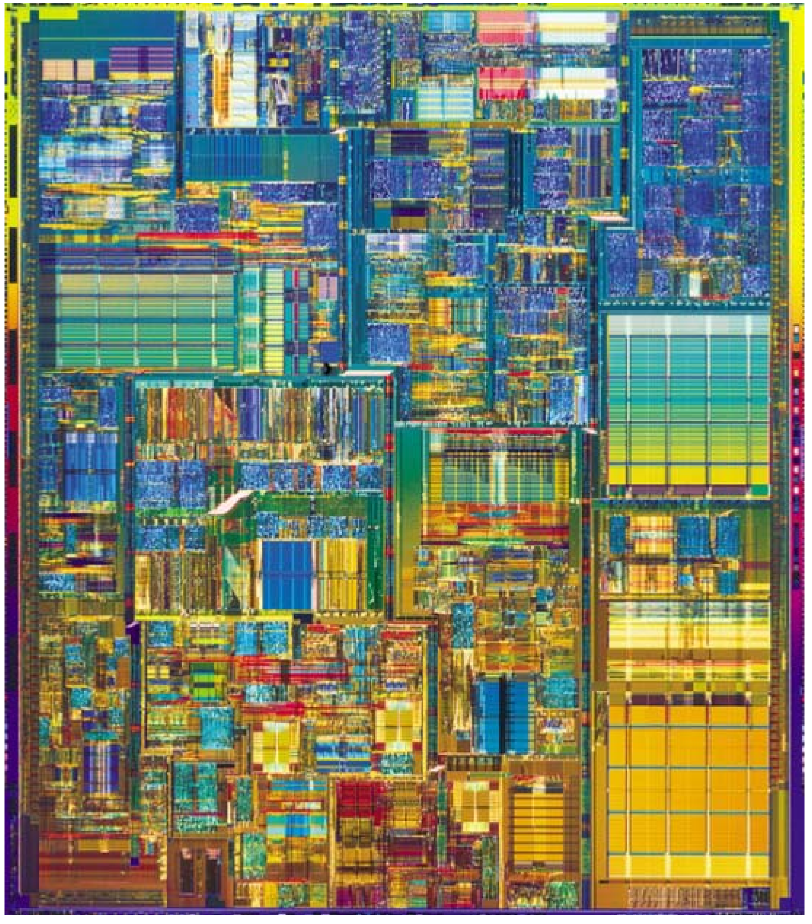
- 1971 Microprocessor invented
  - Intel produces the first 4-bit microprocessor the 4004
  - The 4004 was a 3 chip set
    - 2 kbit ROM IC
    - 320 bit RAM IC
    - 4-bit processor
    - Each housed in a 16-pin DIP package
  - Processor:
    - 10 μm silicon gate PMOS process
    - ~2300 transistors
    - Clock speed: 0.108 MHz
    - Die size: 13.5 mm^2

History



- 1982 Intel 80286
  - 1.5 μm silicon gate CMOS process
  - 1 polysilicon layer
  - 2 metal layers
  - 134,000 transistors
  - 6 to 12 MHz clock speed
  - Die size 68.7 mm^2

History



- 2000 Pentium 4
  - 0.18 μm silicon gate CMOS process
  - 1 polysilicon layer
  - 6 metal layers
  - Fabrication: 21 mask layers
  - 42,000,000 transistors
  - 1,400 to 1,500 MHz clock speed
  - Die size 224 mm^2

History

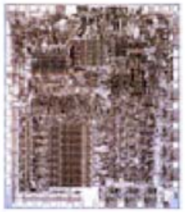
1950s
Silicon Transistor

1 Transistor

1960s
TTL Quad Gate

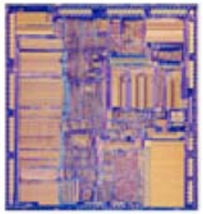
16 Transistors

1970s
8-bit Microprocessor



4500 Transistors

1980s
32-bit Microprocessor



275,000 Transistors

1990s
32-bit Microprocessor

3,100,000 Transistors

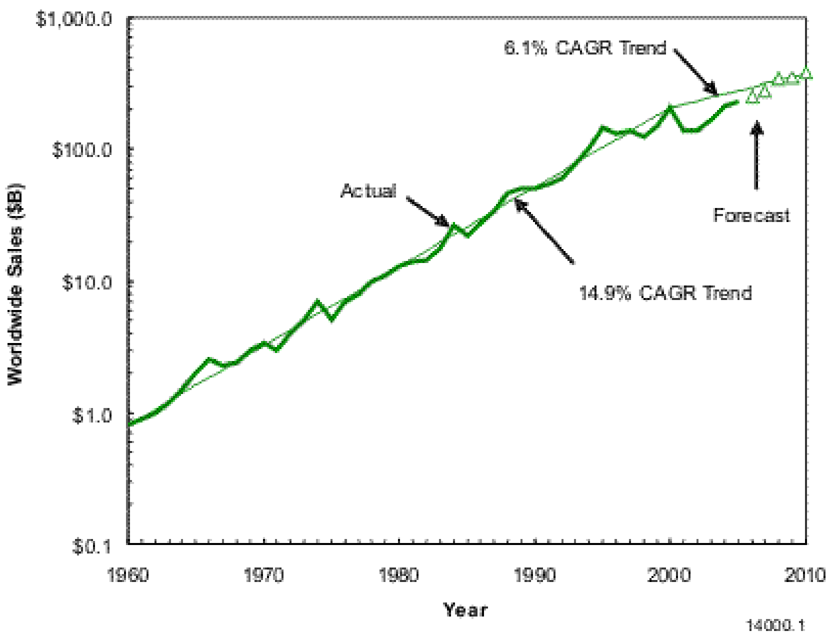
2000s
64-bit Microprocessor

592,000,000 Transistors

(Borrowed from A. Marchioro / CERN)

"Moore's Law"

- In 1965 Gordon Moore (then at Fairchild Corporation) noted that:
  - *"Integration complexity doubles every three years"*
  - This statement is commonly know as "Moore's Law"
  - It has proven to be "correct" till this day

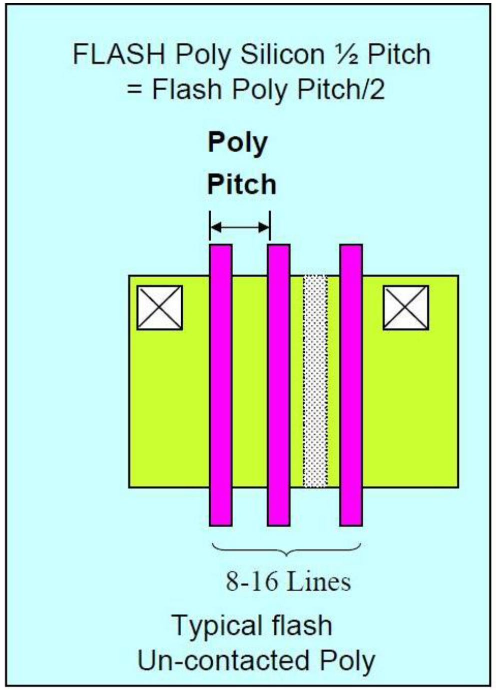


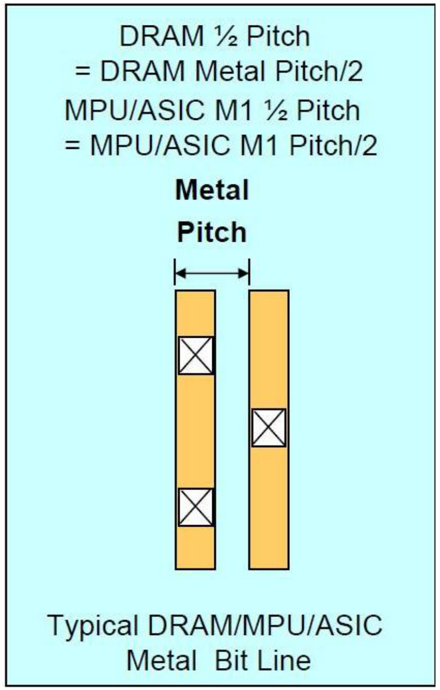
- What is behind this fantastic pace of development of the IC technologies?
  - Is it the "technological" will and motivation of the people involved?
  - Or/and is it the economical drive the main force?
  - Semiconductor industry sales:
    - 1962 > $1 - billion
    - 1978 > $10 - billion
    - 1994 > $100 - billion
    - 2007 > $268 - billion
    - 2009 > $226 - billion (-11.4% than in 2008)

From 1960 until 2000, worldwide semiconductor revenues have increased an average of 14.9% per year!

Source: IC Knowledge LLC, "Revenue trends," September 4, 2006

ITRS 2009 - Half- Pitch Definition

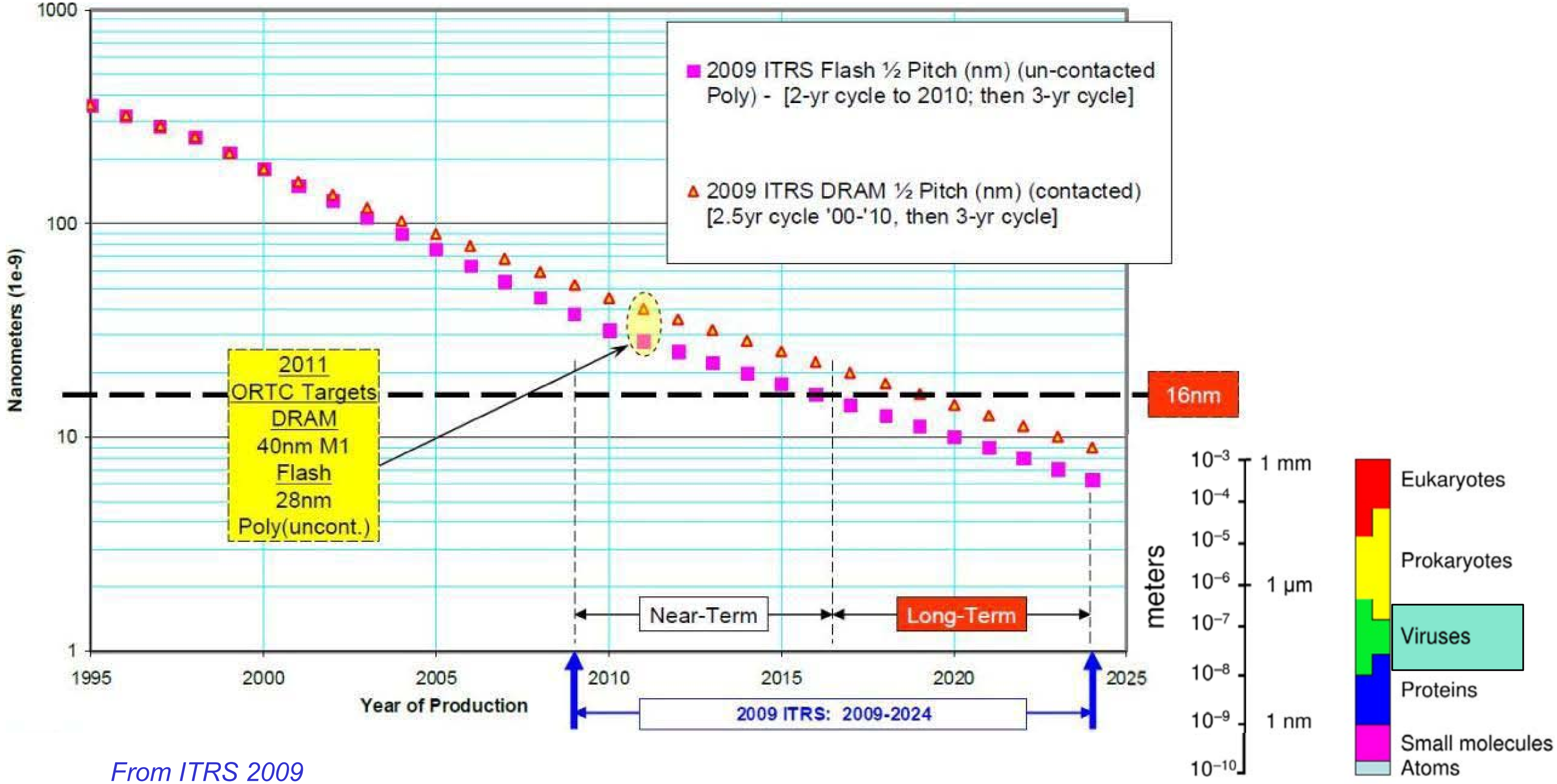




YEAR OF PRODUCTION	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*
Flash Uncontacted Poly Si ½ Pitch (nm)	38	32	28	25	23	20	18	15.9
DRAM stagger-contacted Metal 1 (M1) ½ Pitch (nm)	52	45	40	36	32	28	25	22.5
MPU/ASIC stagger-contacted Metal 1 (M1) ½ Pitch (nm)	54	45	38	32	27	24	21	18.9
MPU Printed Gate Length (nm)	47	41	35	31	28	25	22	19.8
MPU Physical Gate Length (nm)	29	27	24	22	20	18	17	15.3

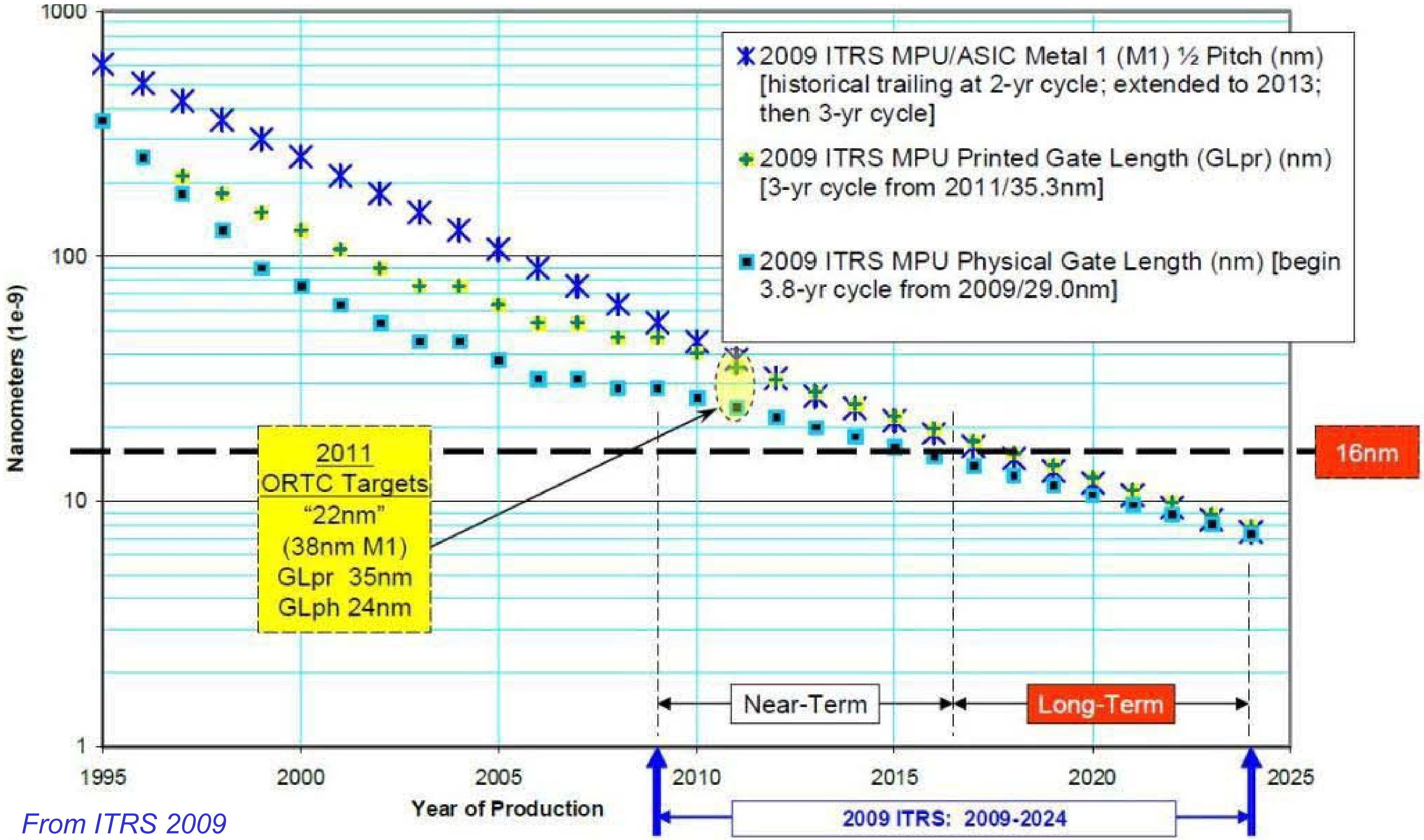
ITRS = International Technology Roadmap for Semiconductors

ITRS 2009 - Memory Scaling



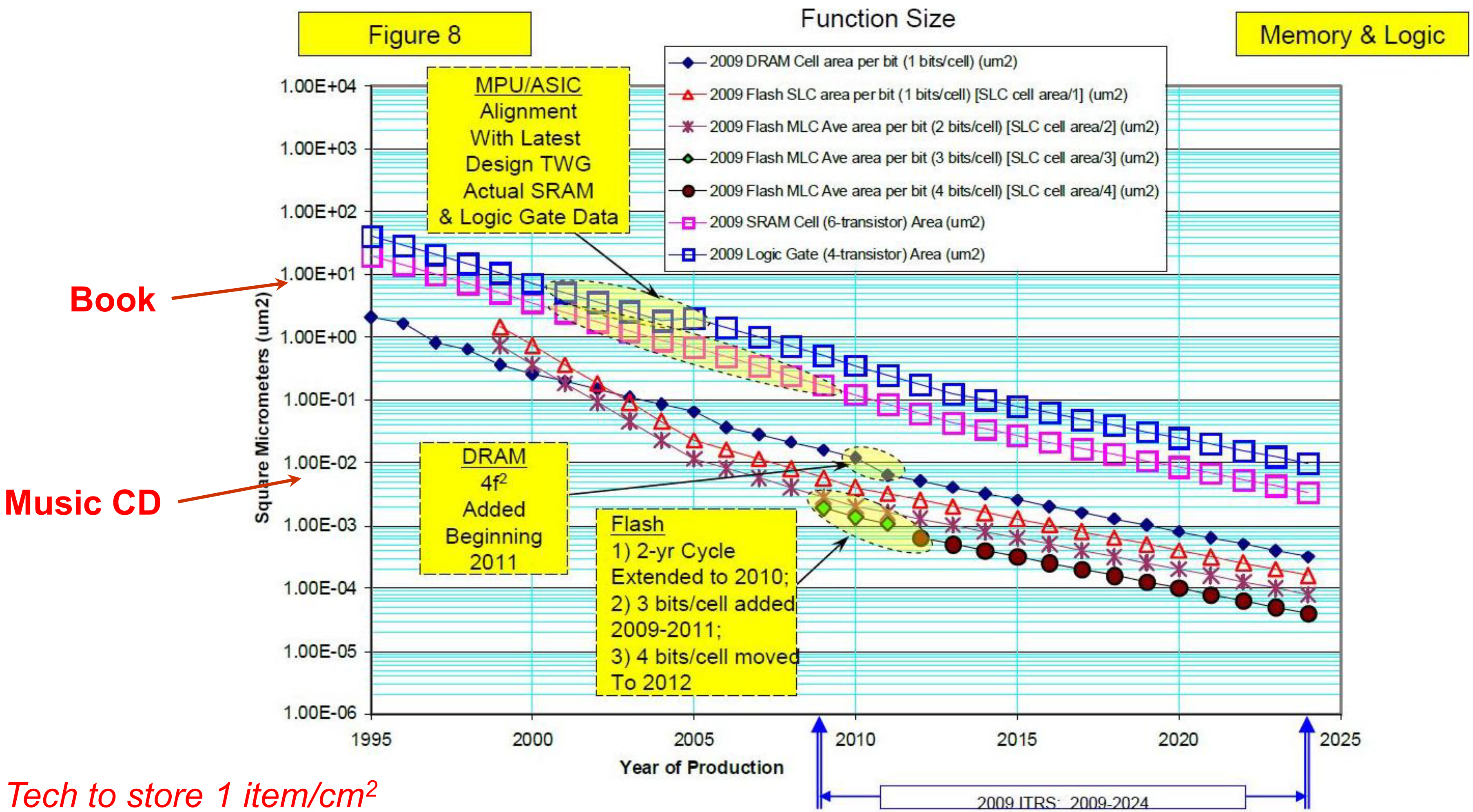
From ITRS 2009
http://www.itrs.net

ITRS 2009 - MPU Scaling



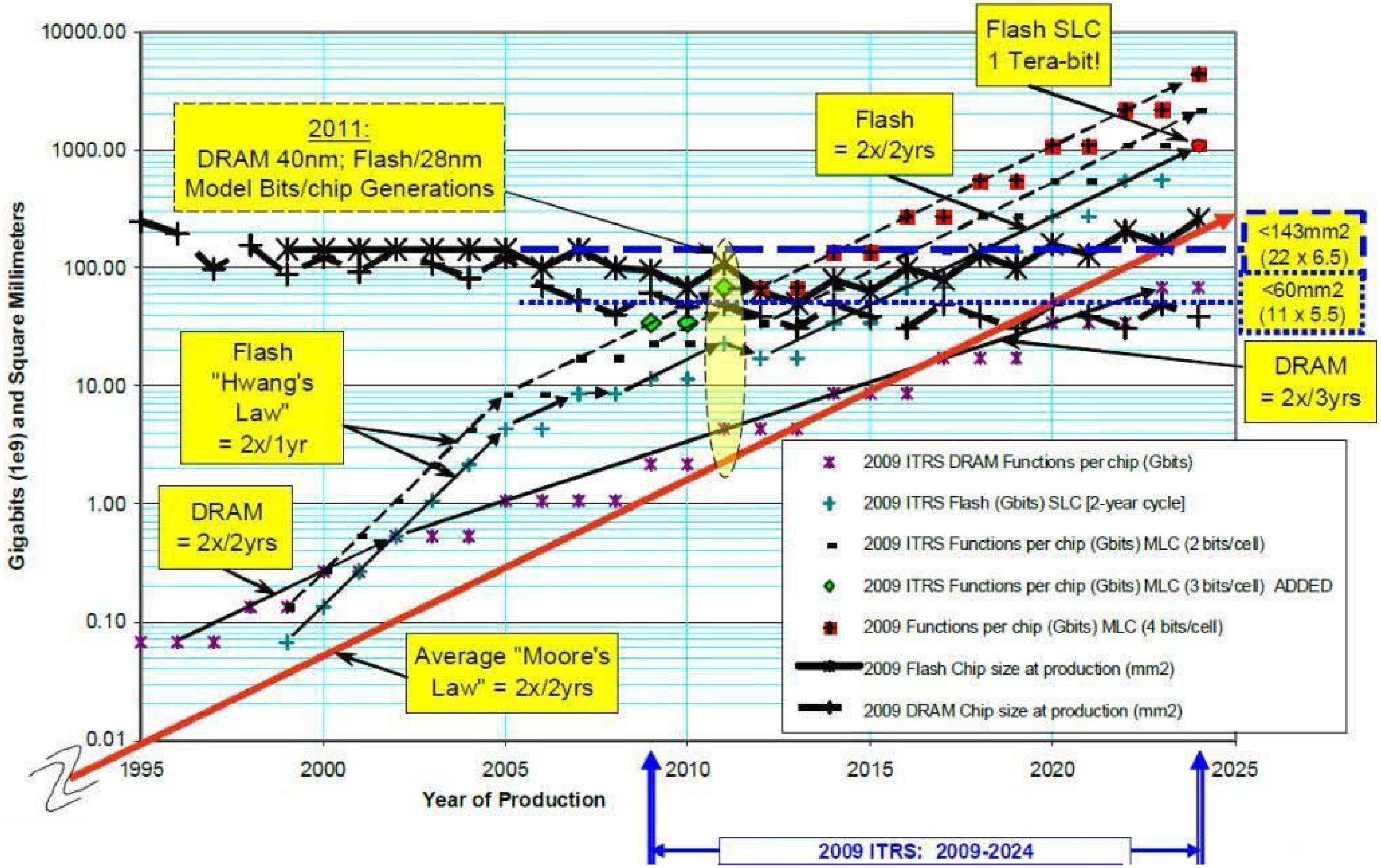
From ITRS 2009
http://www.itrs.net

ITRS 2009 - Memory-Cell Size

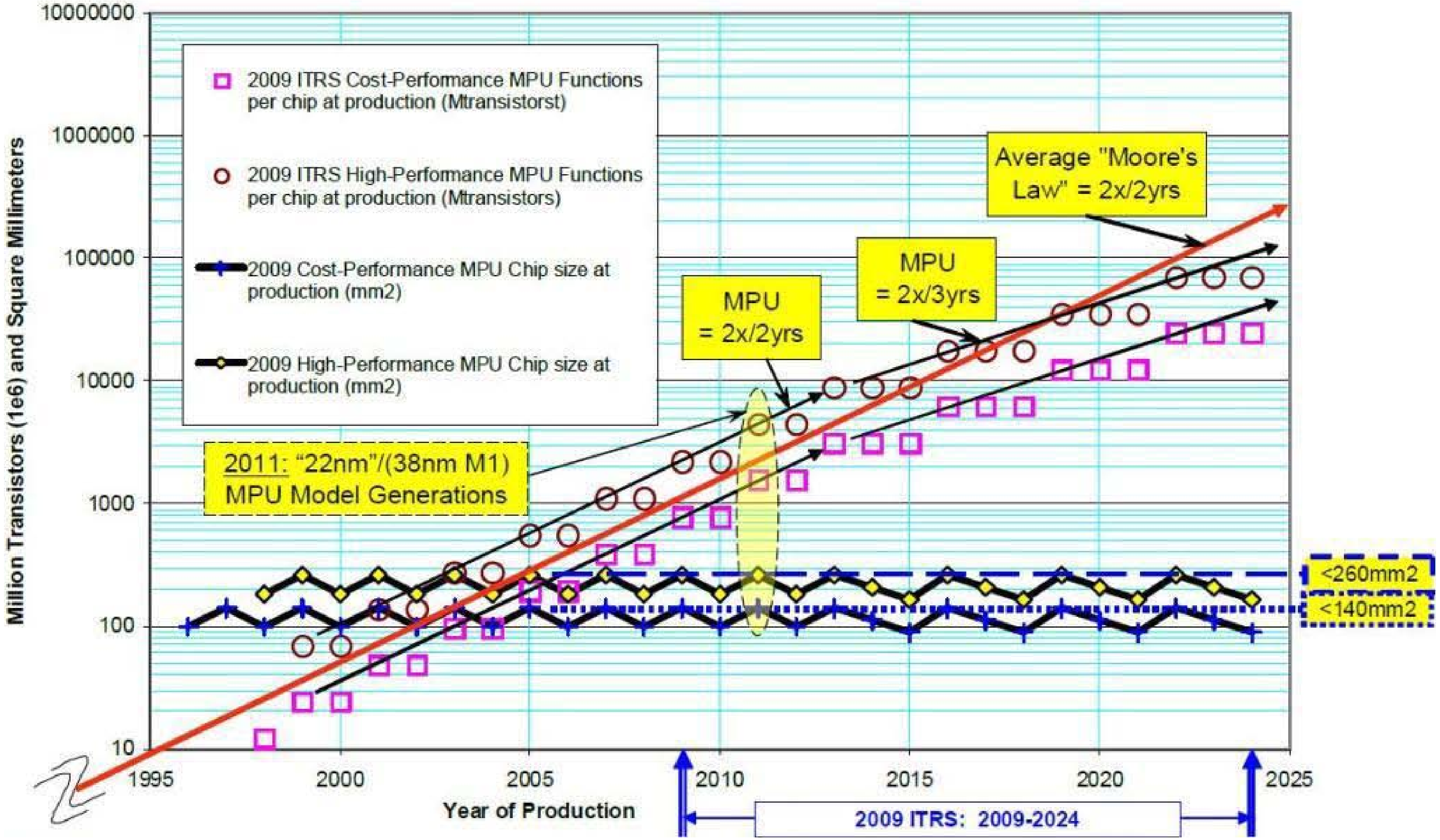


Tech to store 1 item/cm²

ITRS 2009 – Memory Size



ITRS 2009 – MPU Size

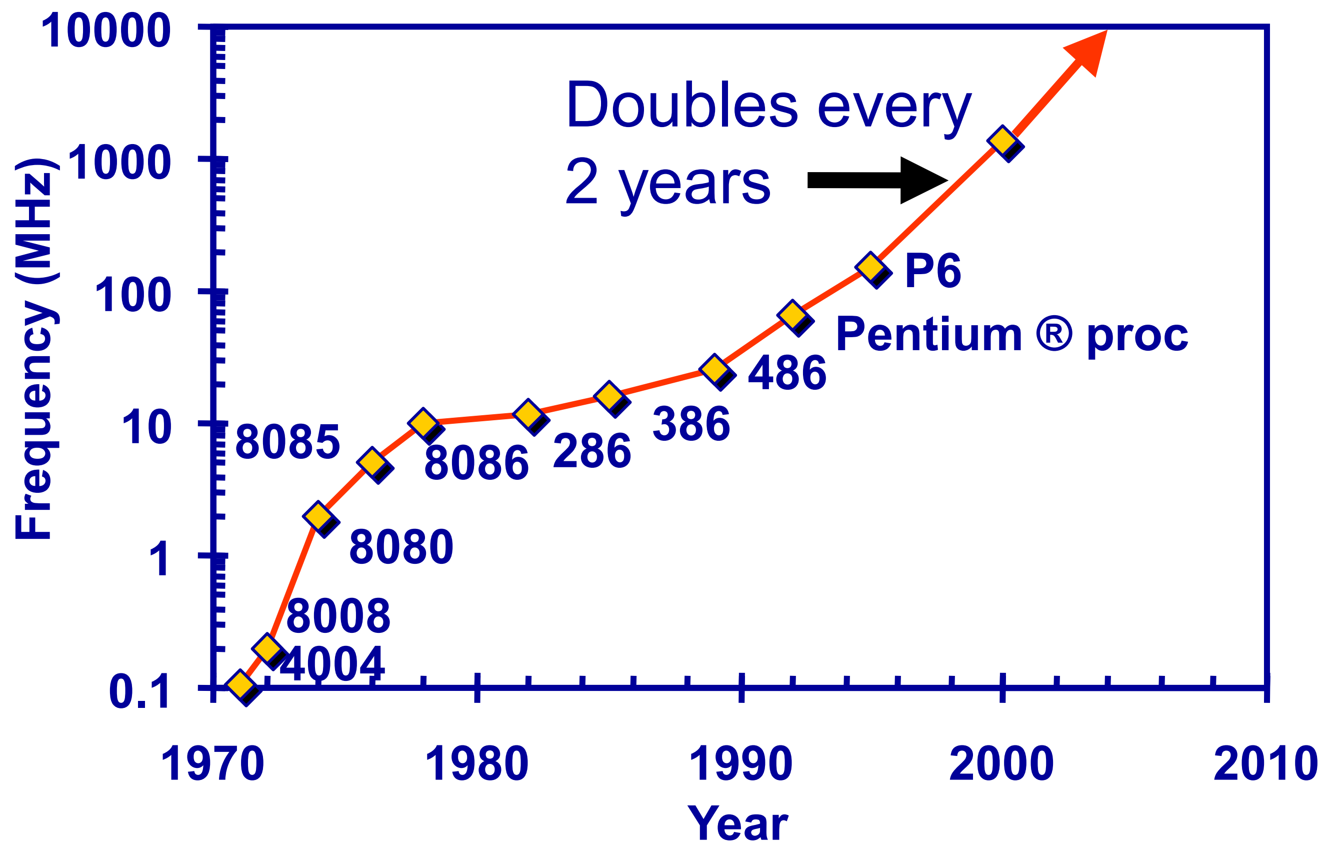


Transistor Count is not all

	Intel Core Duo	Human Brain
Power	5 – 70 W	10 – 40 W
Typical Frequency	1 GHz	0.1 Hz
Number of Elements	~ 10^9	~ 10^{11}
Interconnections per element	2-4 In / 1-3 out	/ ~10,000 Out
Elementary operation	Simple, Boolean	Complex, Nonlinear (choice)
Capacitance per interconnection	0.2 pF /mm	~1 pF

(Borrowed from A. Marchioro / CERN)

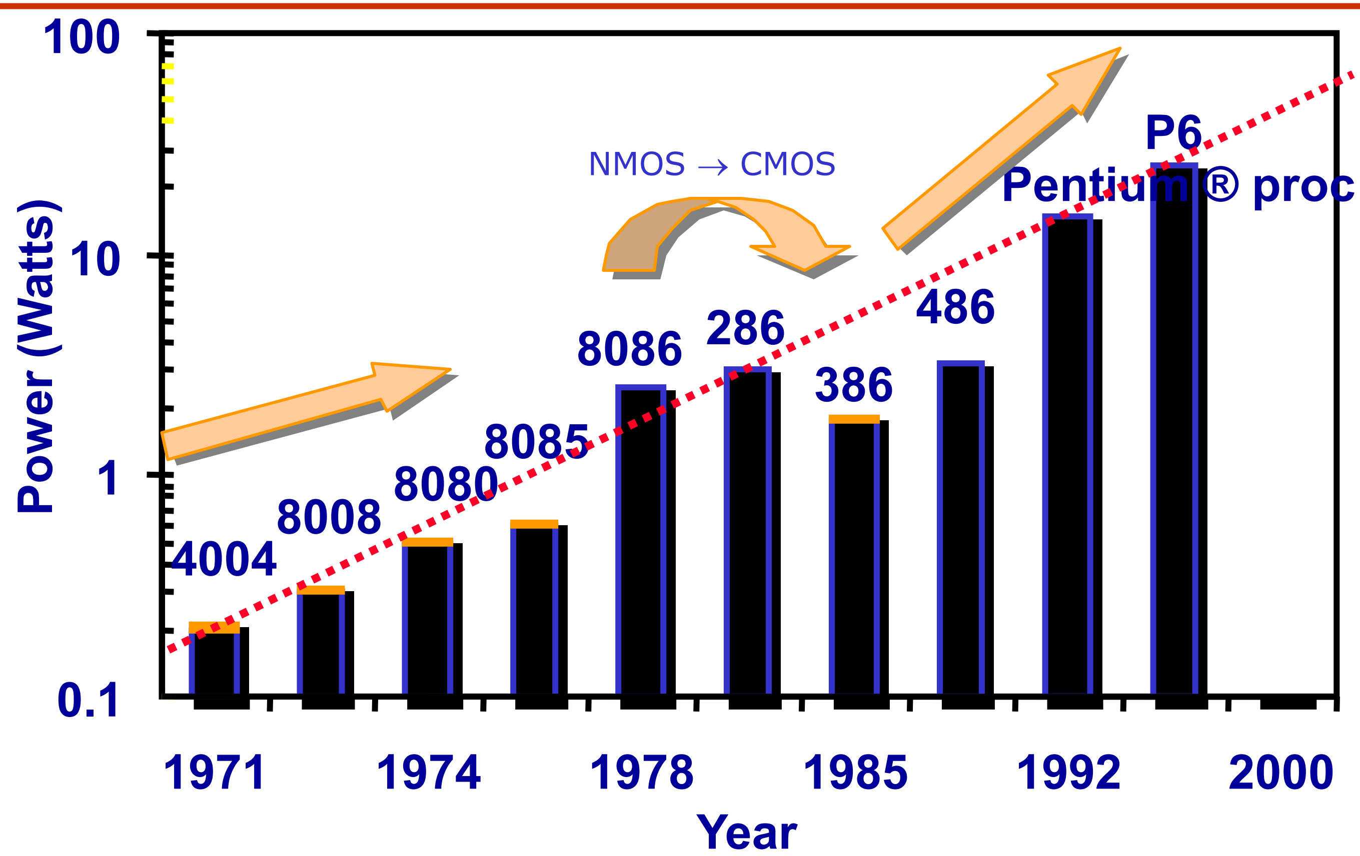
Frequency



Lead Microprocessors frequency doubles every 2 years

(Borrowed from A. Marchioro / CERN)

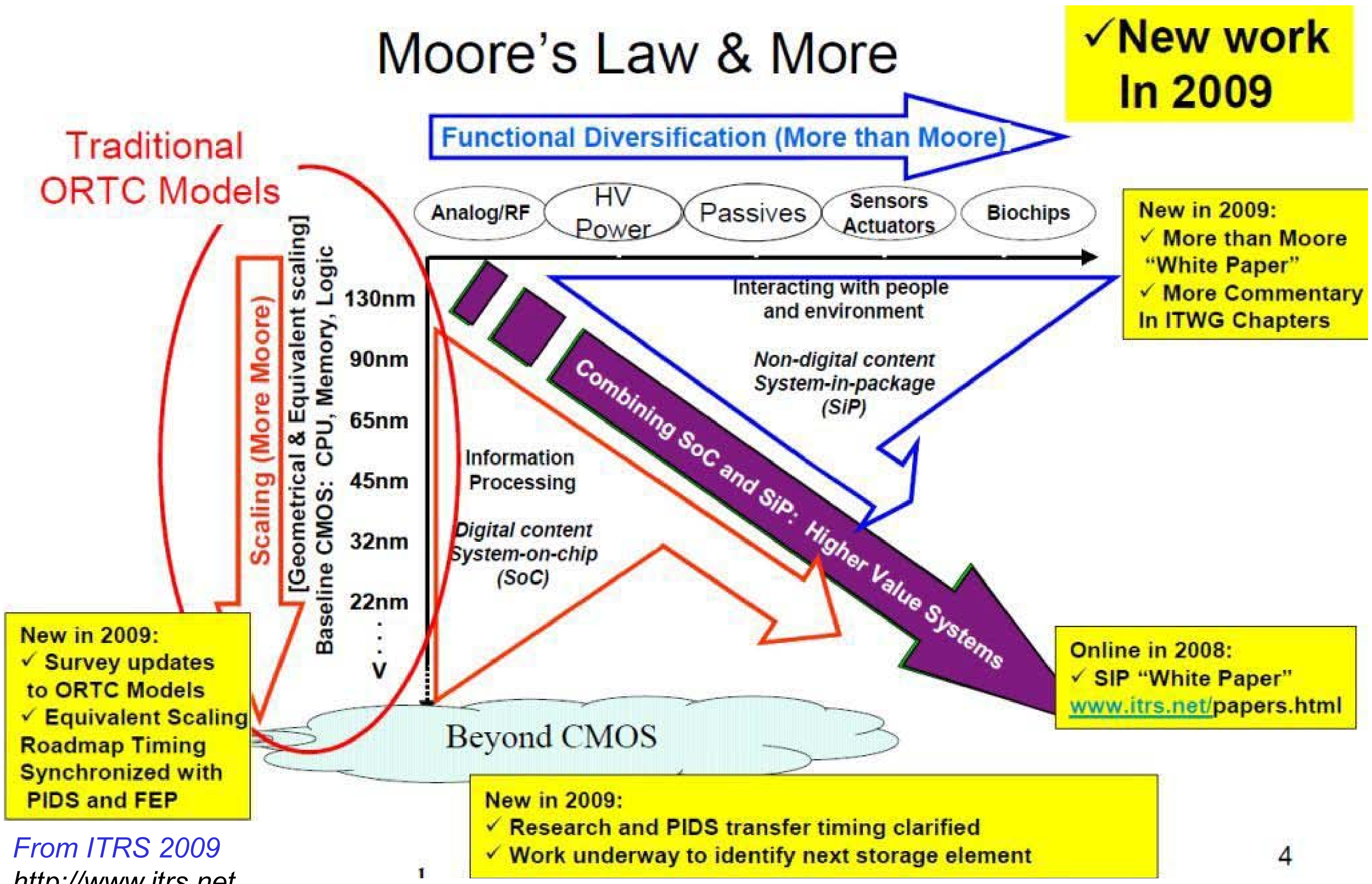
Power Dissipation



Lead Microprocessors power continues to increase

(Borrowed from A. Marchioro / CERN)

"More than Moore"



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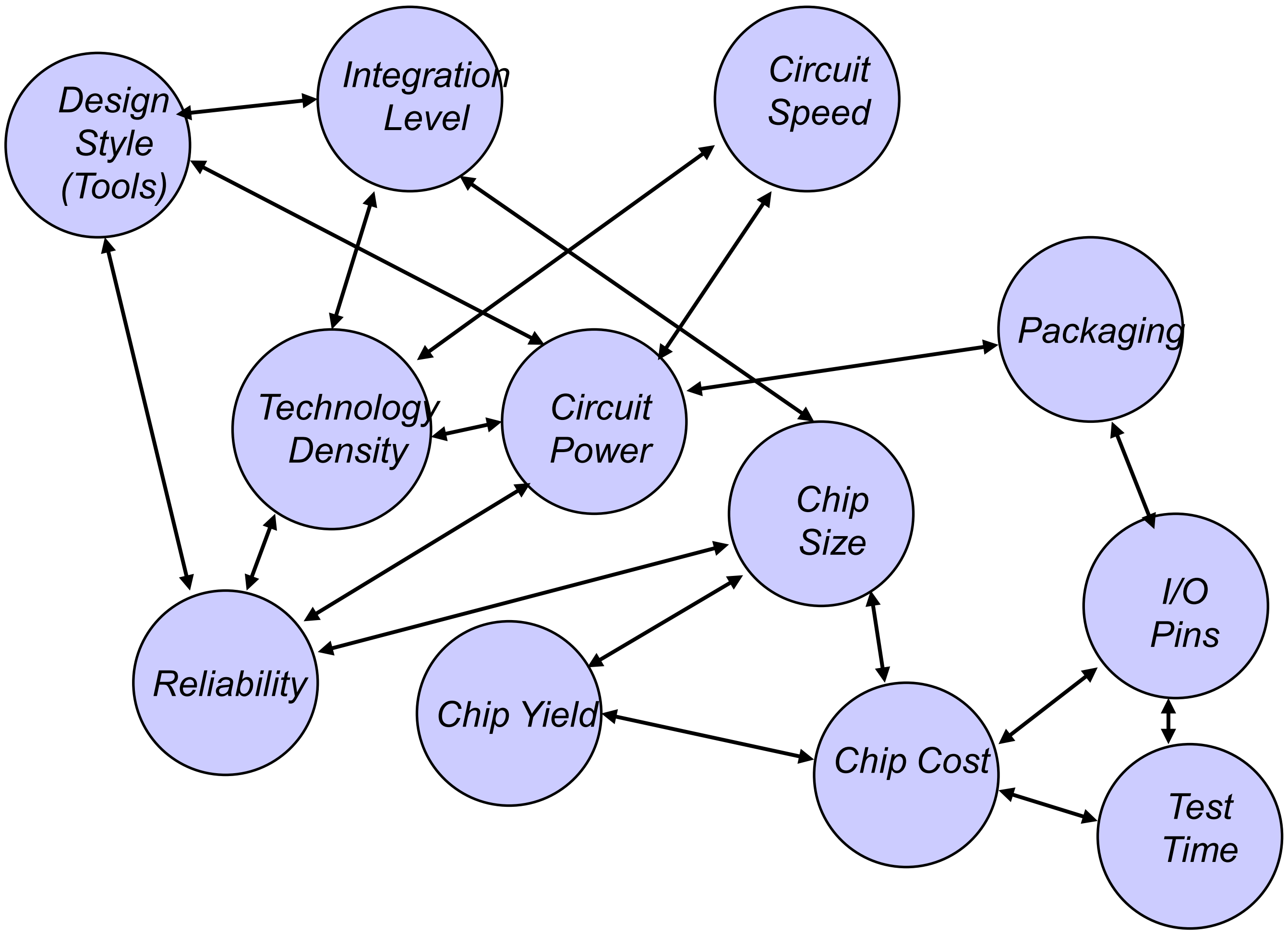
Design Trade-Offs



(Borrowed from A. Marchioro / CERN)

Driving force: Economics

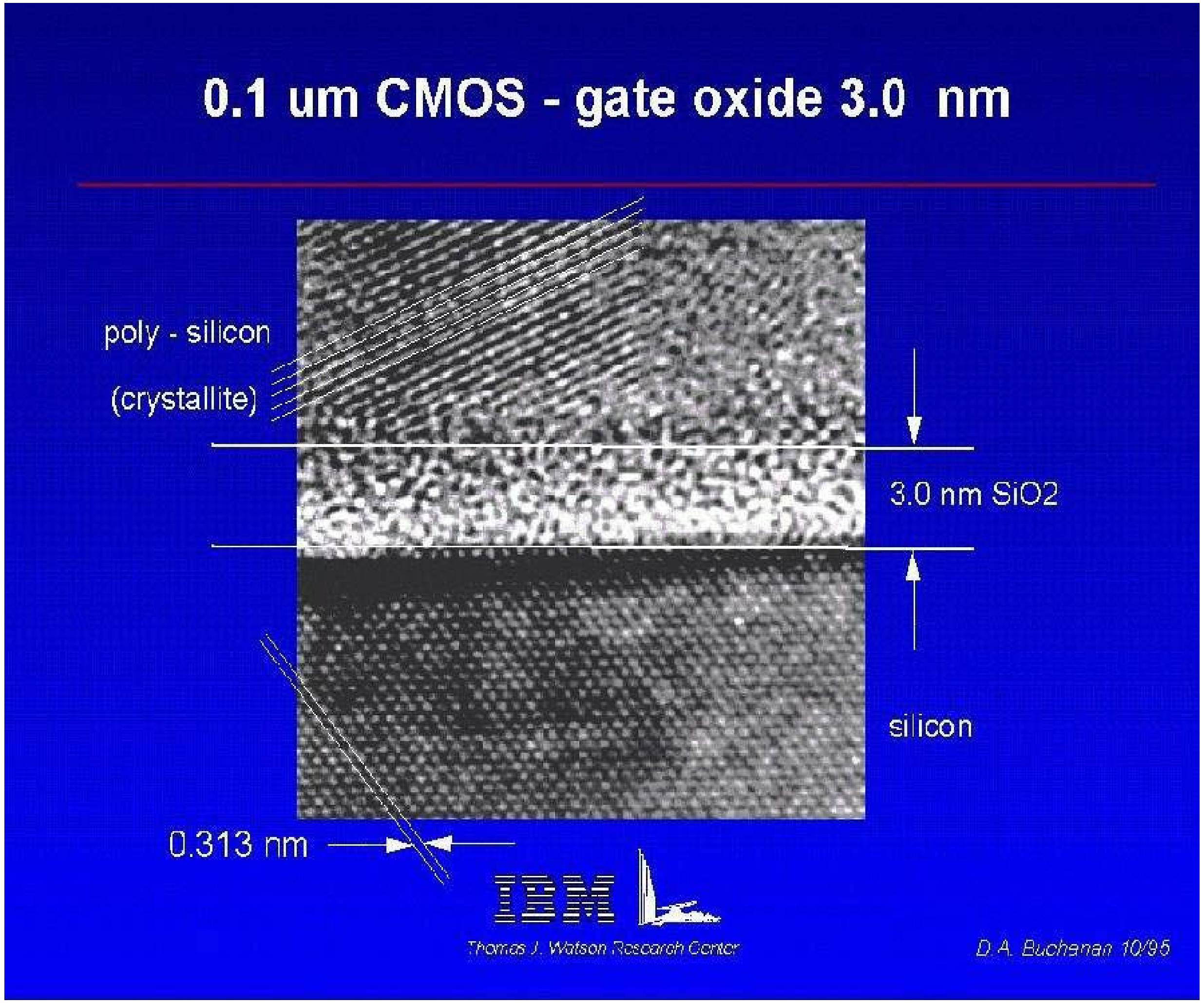
- Traditionally, the cost/function in an IC is reduced by 25% to 30% a year.
  - **This allows the electronics market to growth at ~17% / year**
    - **[Recent economic crisis has resulted in 2009 revenues of just more than $200 billion, which was the approximate size of the market nine years before in 2000!]**
- To achieve this, the number of functions/IC has to be increased. This demands for:
  - Increase of the transistors count
    - increased functionality
  - Increase of the clock speed
    - more operations per unit time = increased functionality
  - Decrease of the feature size
    - contains the area increase = contains price
    - improves performance

Driving force: Economics

- Increase productivity:
  - Increase equipment throughput
  - Increase manufacturing yields
  - Increase the number of chips on a wafer:
    - reduce the area of the chip:
      - smaller feature size & redesign
  - Use the largest wafer size available

Example of a cost effective product (typically DRAM): the initial IC area is reduced to 50% after 3 years and to 35% after 6 years.

VLSI Advanced Technology



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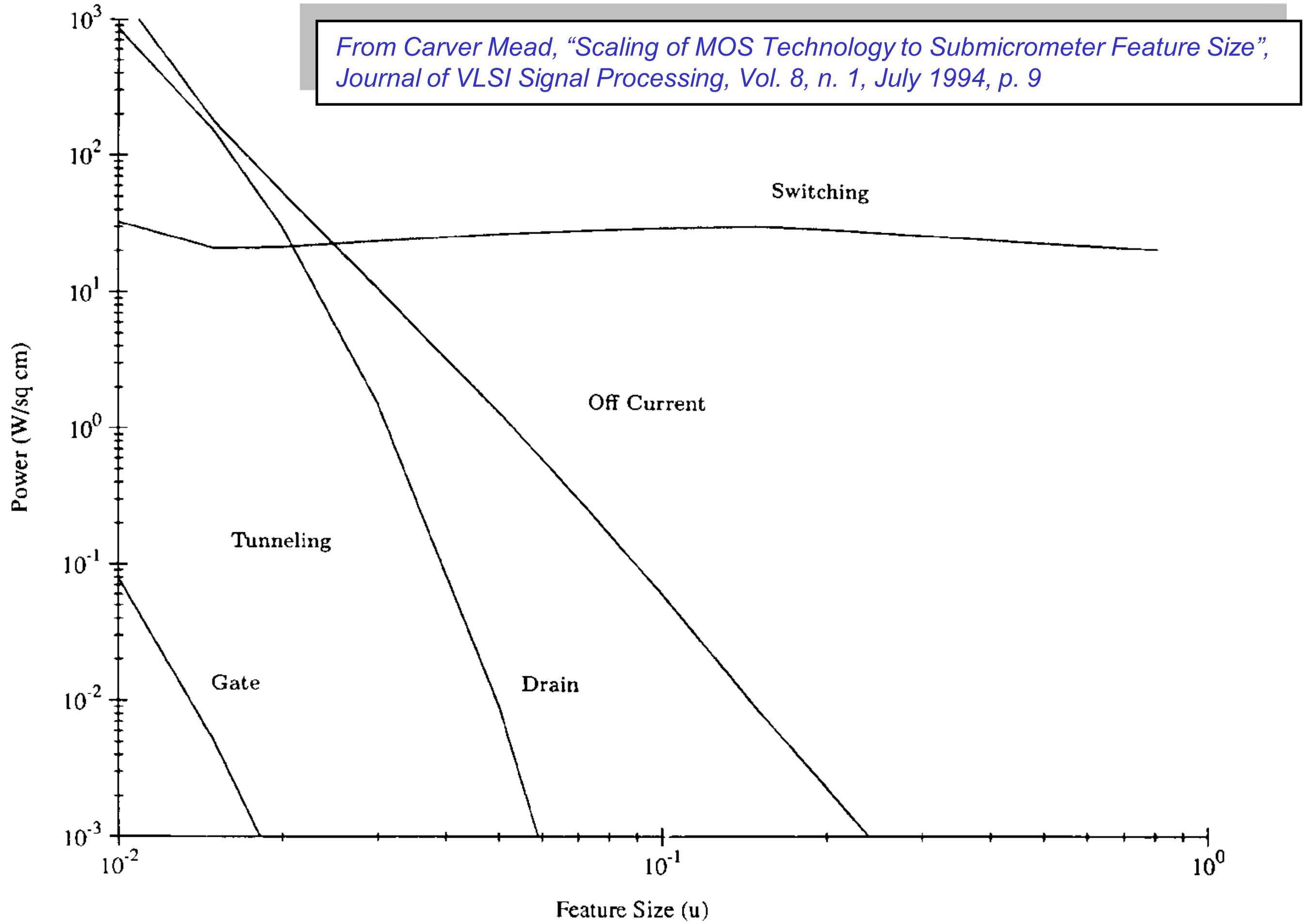
"Is there a limit?"



(Borrowed from A. Marchioro / CERN)

“Is there a limit?”

- High volume factory:
  - Total capacity: 40K Wafer Starts Per Month (WSPM) (180 nm)
  - Total capital cost: $2.7B
    - Production equipment: 80%
    - Facilities: 15%
    - Material handling systems: 3%
    - Factory information & control: 2%
- Worldwide semiconductor market revenues in 2009: ~$226B
  - Semiconductor market growth rate: ~15% / year
  - Equipment market growth rate: ~19.4% / year
  - Forecast for 2010:
    - Semiconductor spending: $40B
    - Equipment spending: $29B

Design abstraction levels