Lecture 1: VLSI Overview

CSCE 5730
Digital CMOS VLSI Design

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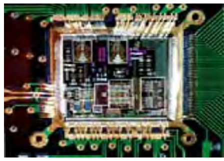


Lecture Outline

- Historical development of computers
- Introduction to a basic digital computer
- Five classic components of a computer
- Microprocessor
- IC design abstraction level
- Intel processor family
- Developmental trends of ICs
- Moore's Law

Introduction to Digital Circuits

What is a digital Computer ?

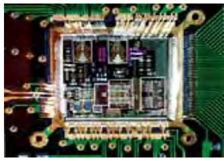
A fast electronic machine that accepts digitized input information, processes it according to a list of internally stored instruction, and produces the resulting output information.

List of instructions → Computer program

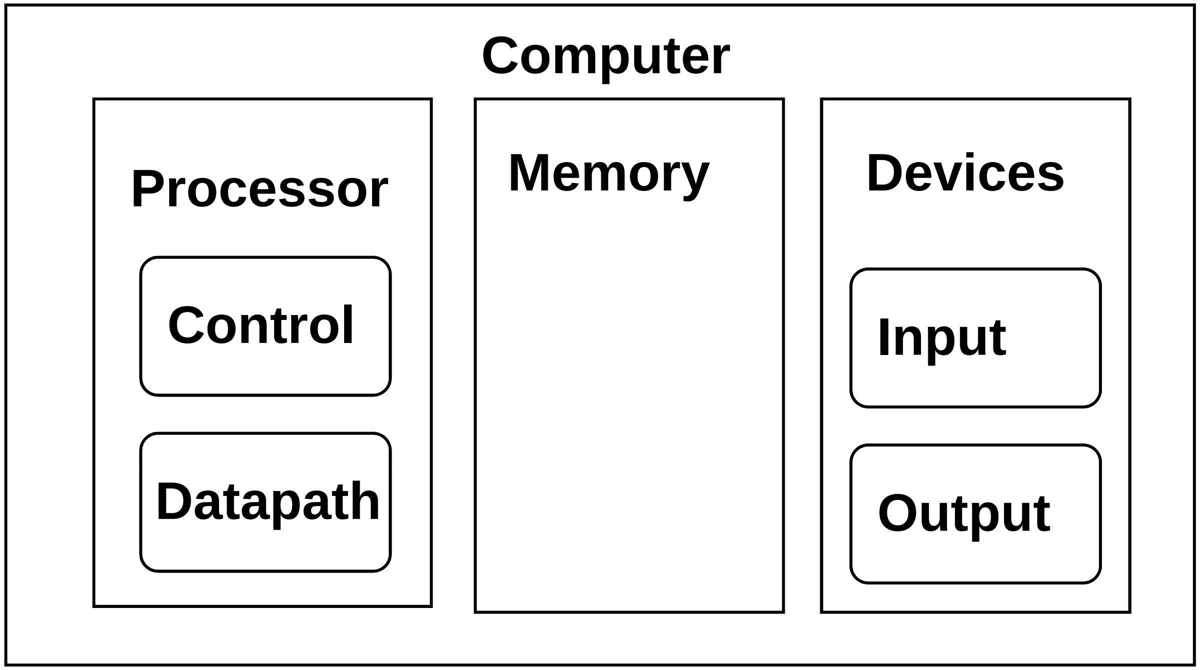
Internal storage → Memory

Different Types and Forms of Computer

- Personal Computers (Desktop PCs)
- Notebook computers (Laptop computers)
- Handheld PCs
- Pocket PCs
- Workstations (SGI, HP, IBM, SUN)
- ATM (Embedded systems)
- Supercomputers



Five classic components of a Computer



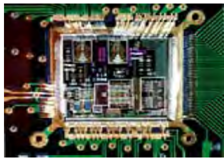
(1) Input, (2) Output, (3) Datapath, (4) Controller, and (5) Memory

What is a microprocessor ?

- **A microprocessor is an integrated circuit (IC) built on a tiny piece of silicon.** It contains thousands, or even millions, of transistors, which are interconnected via superfine traces of aluminum. The transistors work together to store and manipulate data so that the microprocessor can perform a wide variety of useful functions. The particular functions a microprocessor performs are dictated by software. (source : Intel)

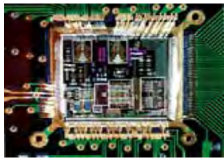
- Simply speaking, microprocessor is the CPU on a single chip. CPU stands for “central processing unit” also known as processor.

- Processor can be “general purpose” or “special purpose”. A special purpose processor is also known as “application specific integrated circuit” (ASIC).

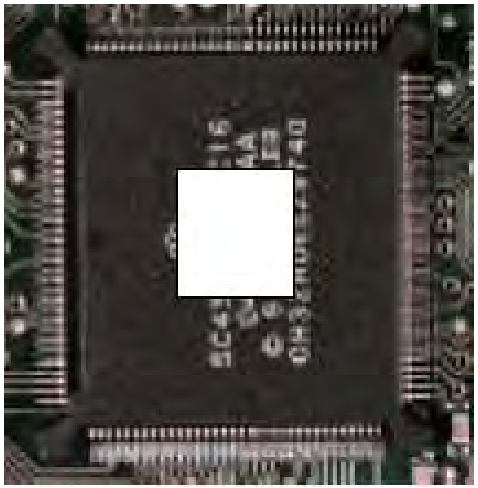


What is an Integrated Circuit ?

- An integrated circuits is a silicon semiconductor crystal containing the electronic components for digital gates.
- Integrated Circuit is abbreviated as IC.
- The digital gates are interconnected to implement a Boolean function in a IC .
- The crystal is mounted in a ceramic/plastic material and external connections called “pins” are made available.
- ICs are informally called chips.

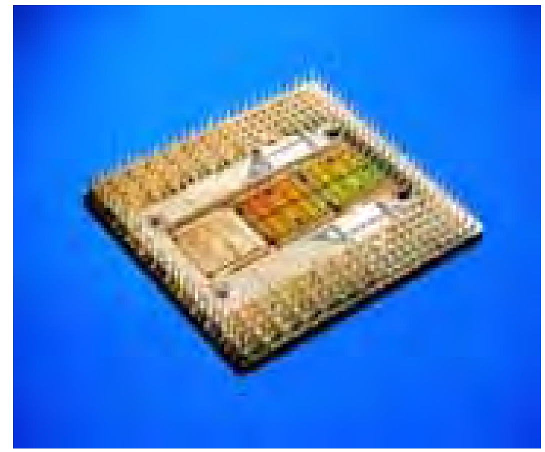


How does a microprocessor look?



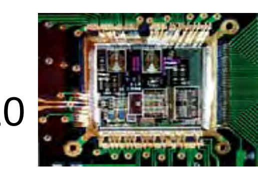
(1) ASIC

(2) Sun UltraSparc



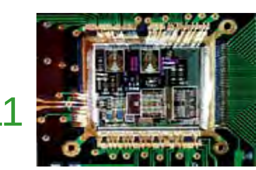
(3) PentiumPro

Historical Development



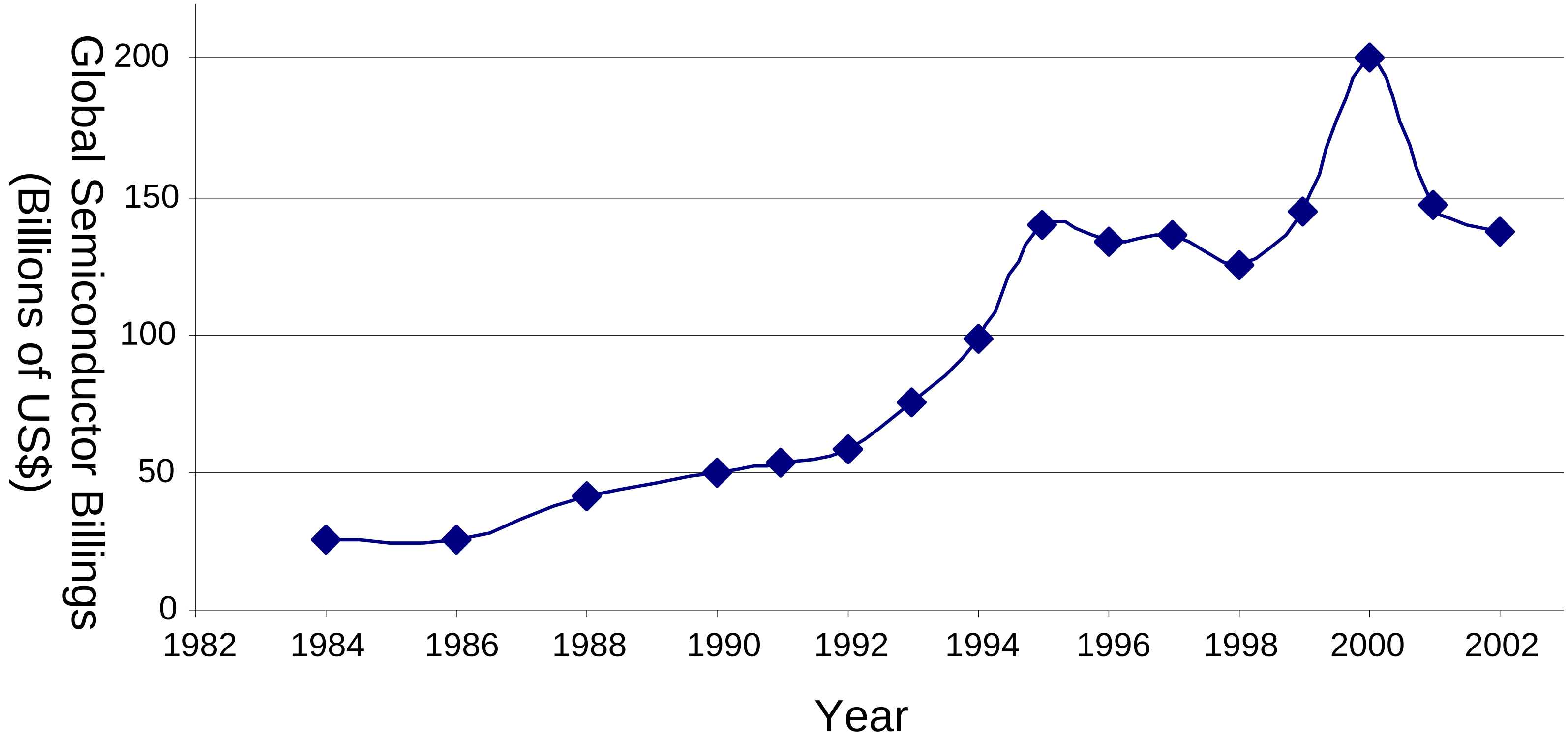
VLSI Technology: Highest Growth in History

- 1958: First integrated circuit
  - Flip-flop using two transistors
  - Built by Jack Kilby at Texas Instruments
- 2003
  - Intel Pentium 4 μprocessor (55 million transistors)
  - 512 Mbit DRAM (> 0.5 billion transistors)
- 53% compound annual growth rate over 45 years
  - No other technology has grown so fast so long
- Driven by miniaturization of transistors
  - Smaller is cheaper, faster, lower in power!
  - Revolutionary effects on society



VLSI Industry : Annual Sales

- 10^{18} transistors manufactured in 2003
  - – 100 million for every human on the planet
- 340 Billion transistors manufactured in 2006. (World population 6.5 Billion!)



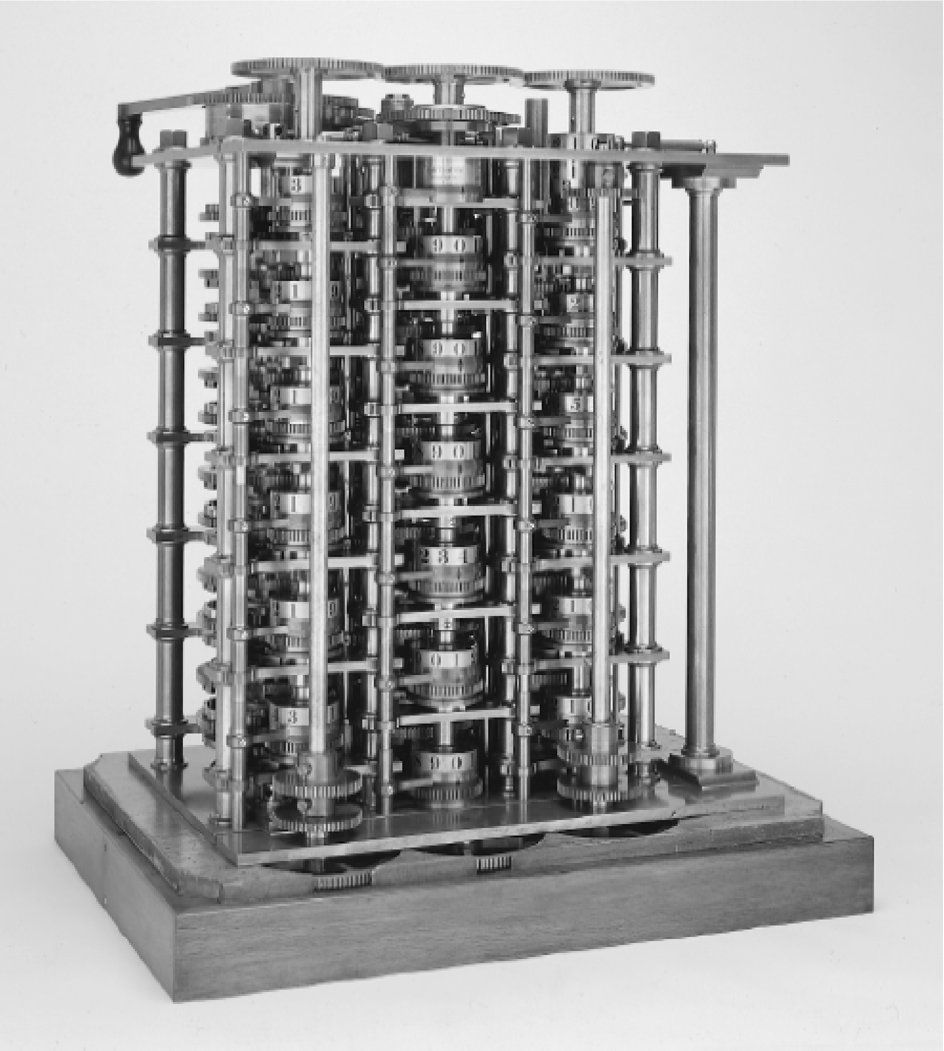
Invention of the Transistor

- Invention of transistor is the driving factor of growth of the VLSI technology
- Vacuum tubes ruled in first half of 20^{th} century Large, expensive, power-hungry, unreliable
- 1947: first point contact transistor
  - John Bardeen and Walter Brattain at Bell Labs
  - Earned Nobel prize in 1956

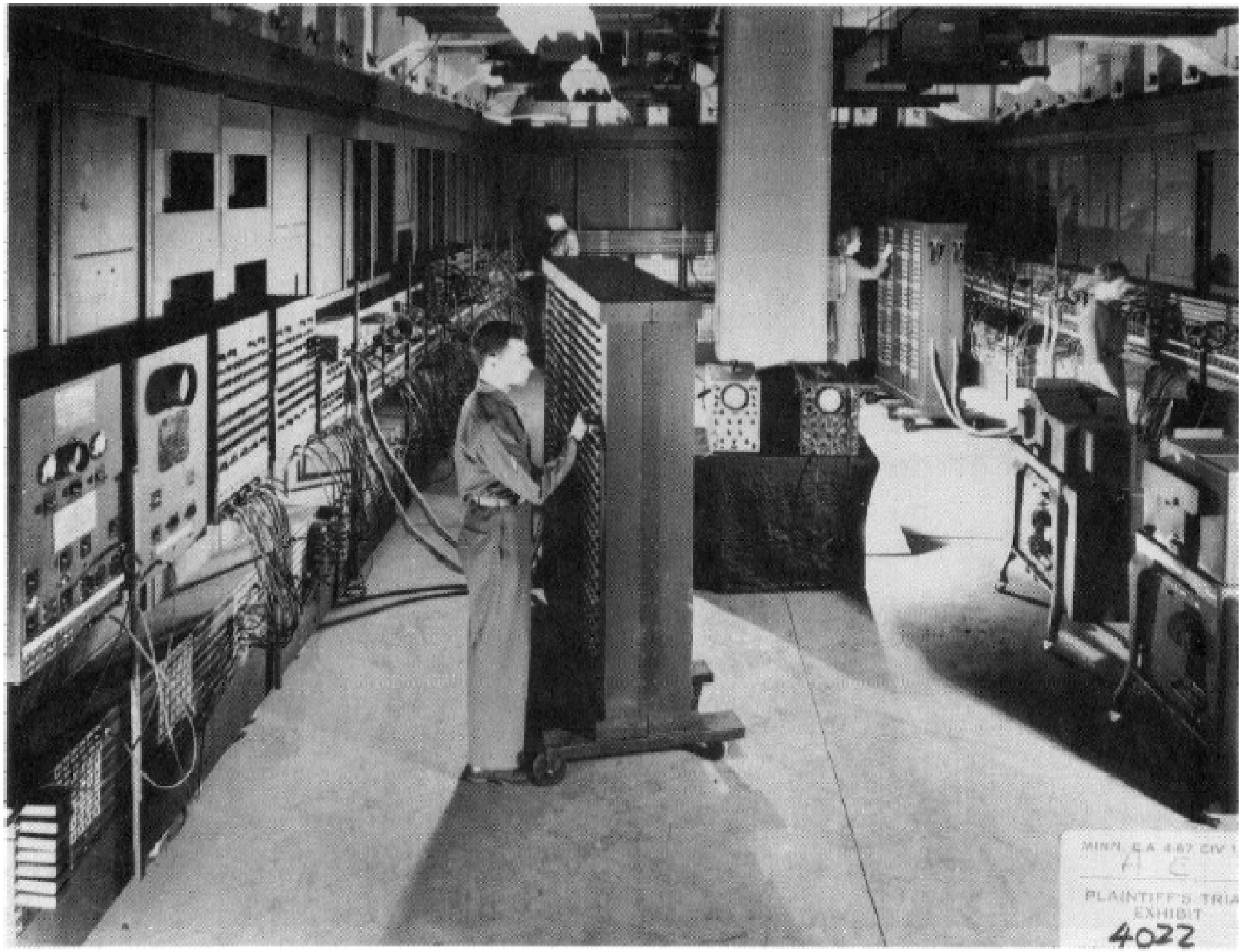
Transistor Types

- Bipolar transistors
  - n-p-n or p-n-p silicon structure
  - Small current into very thin base layer controls large currents between emitter and collector
  - Base currents limit integration density
- Metal Oxide Semiconductor Field Effect Transistors (MOSFET)
  - nMOS and pMOS MOSFETS
  - Voltage applied to insulated gate controls current between source and drain
  - Low power allows very high integration

The Babbage Difference Machine in 1832



The First Electronic Computer in 1946 (ENIAC)



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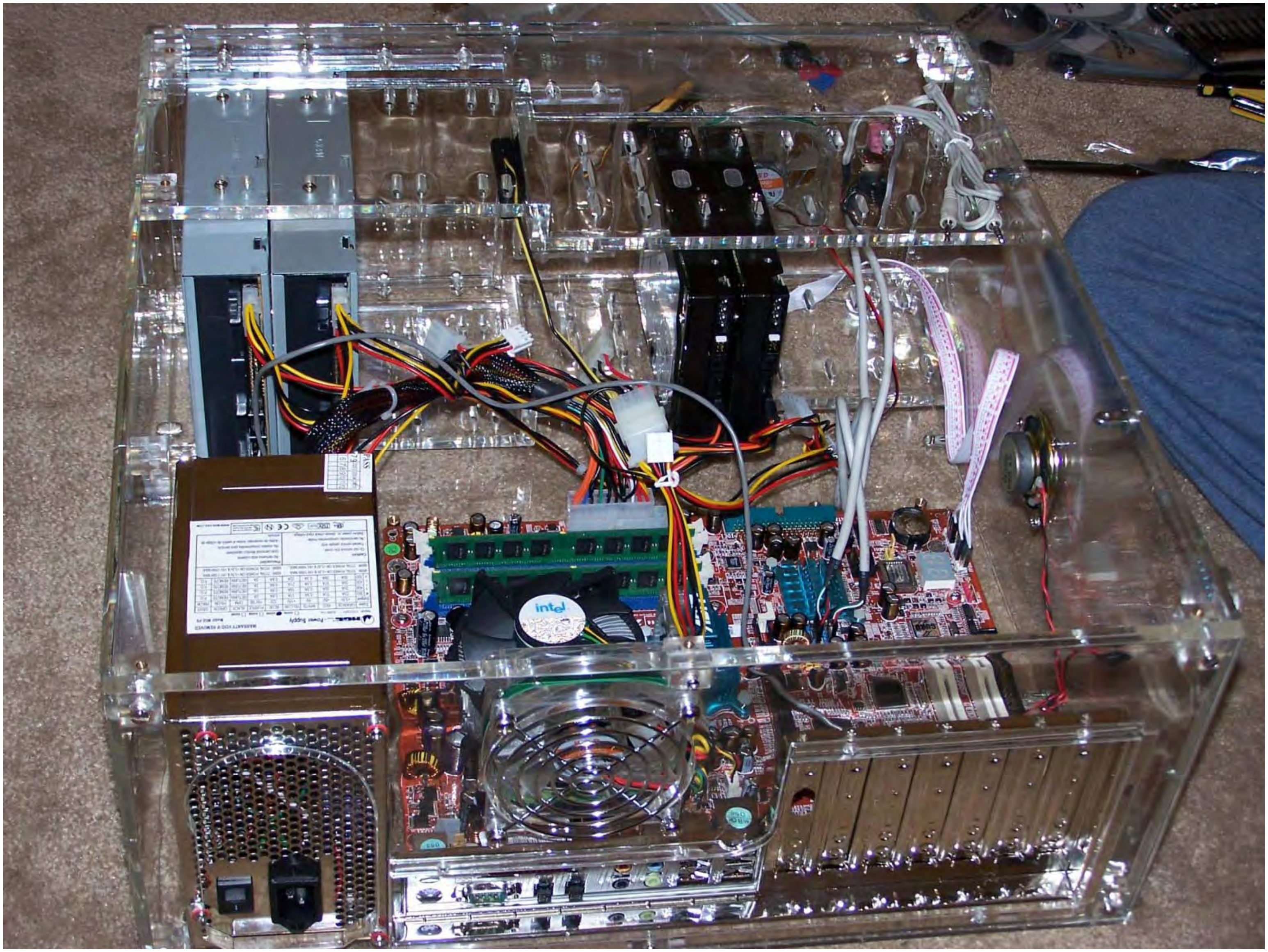
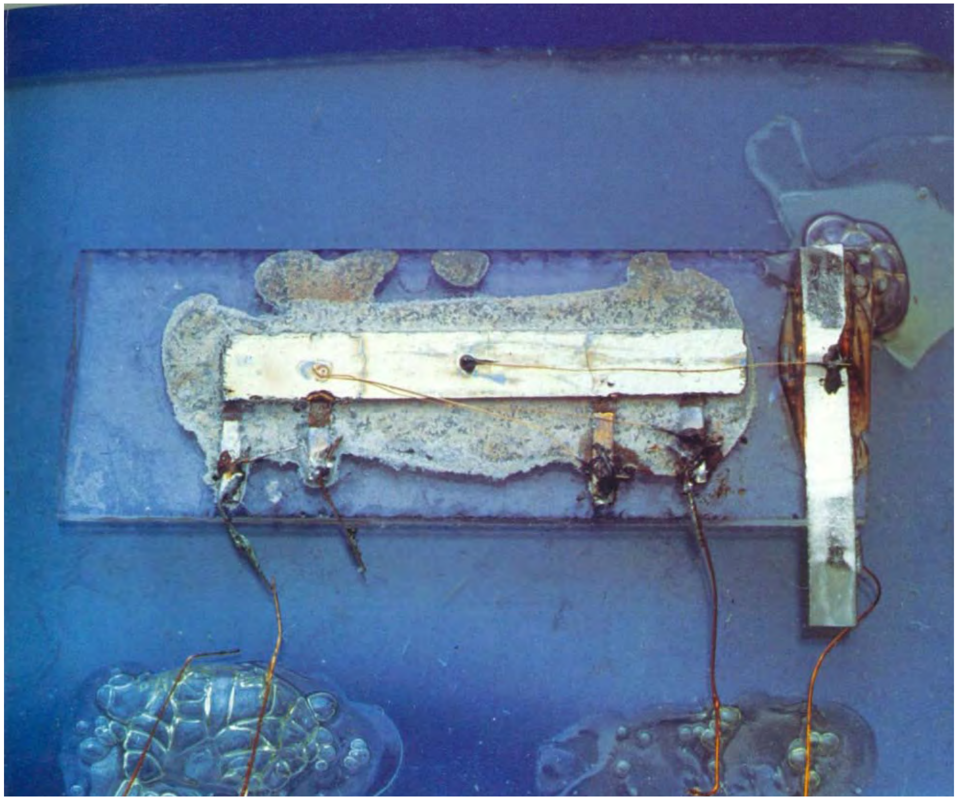
Discover the power of ideas

How a Home PC Looks Today??



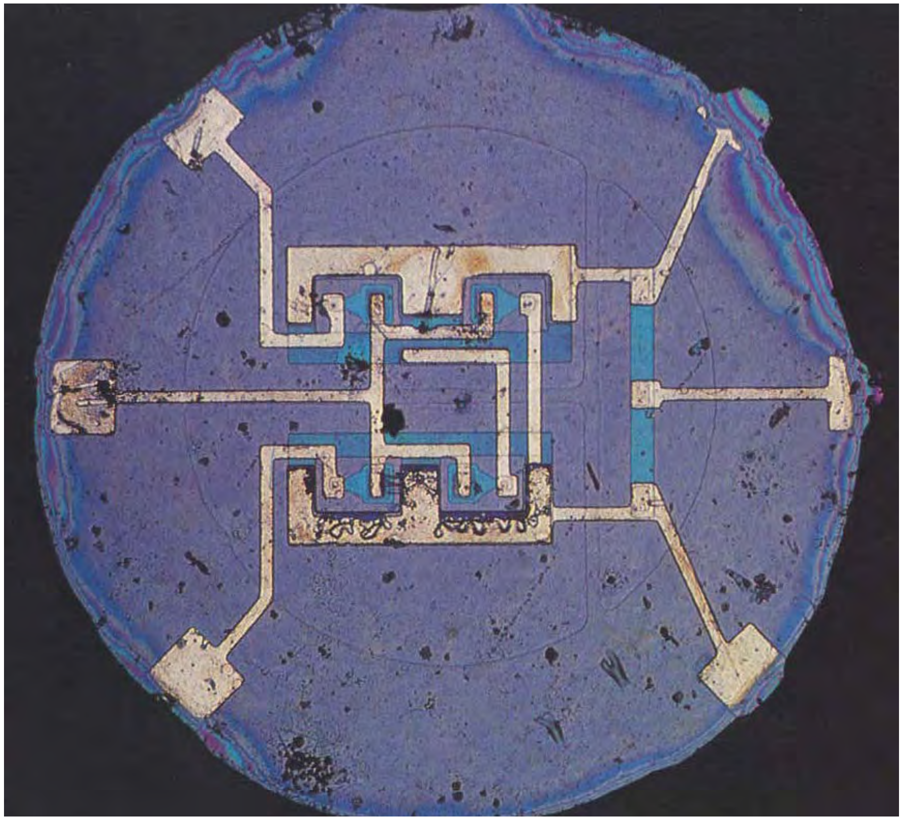
First Integrated Circuit - 1958

The First Integrated Circuit – Jack Kilby, Texas Instruments
1 Transistor and 4 Other Devices on 1 Chip
Winner of the 2000 Nobel Prize

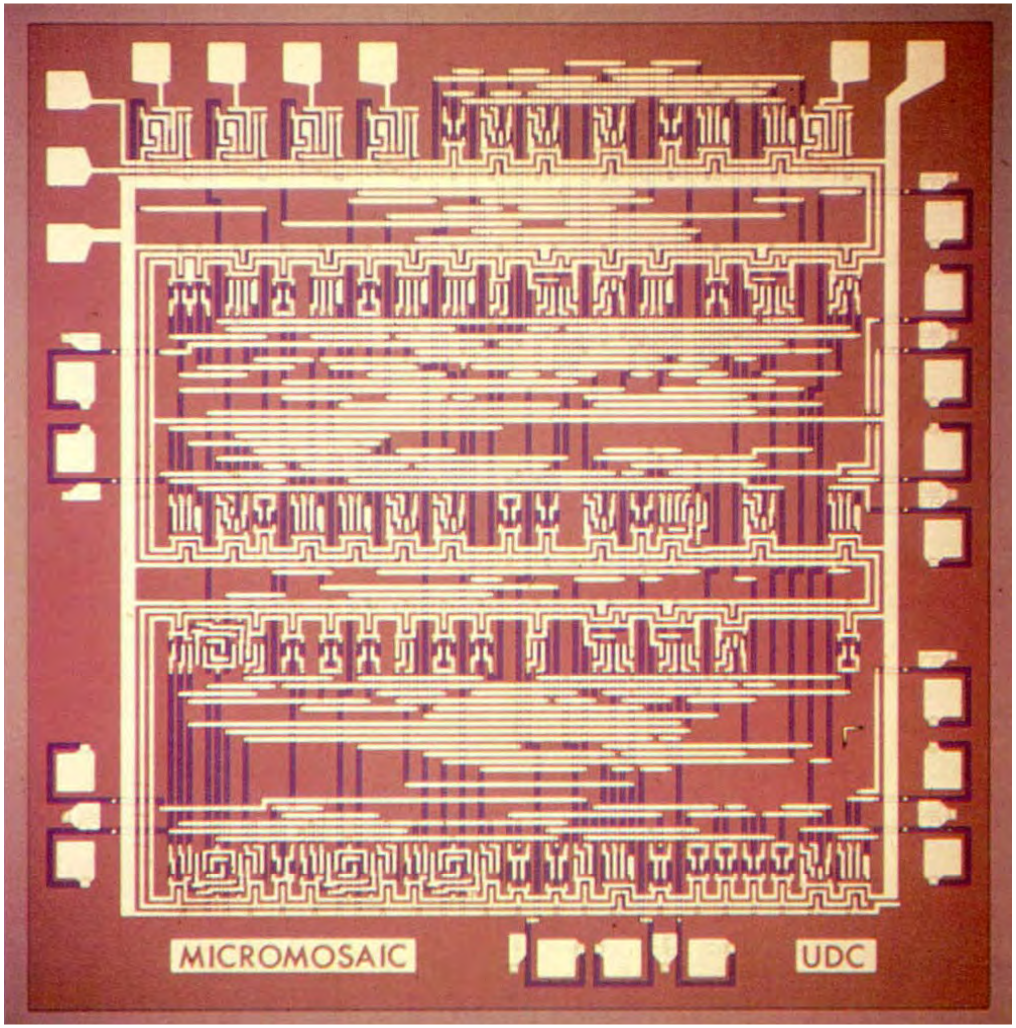


First Commercial Planar IC - 1960

Fairchild -- One Binary Digital (Bit) Memory Device on a Chip
4 Transistors and 5 Resistors
Start of Small Scale Integration (SSI)!! We are in VLSI!!

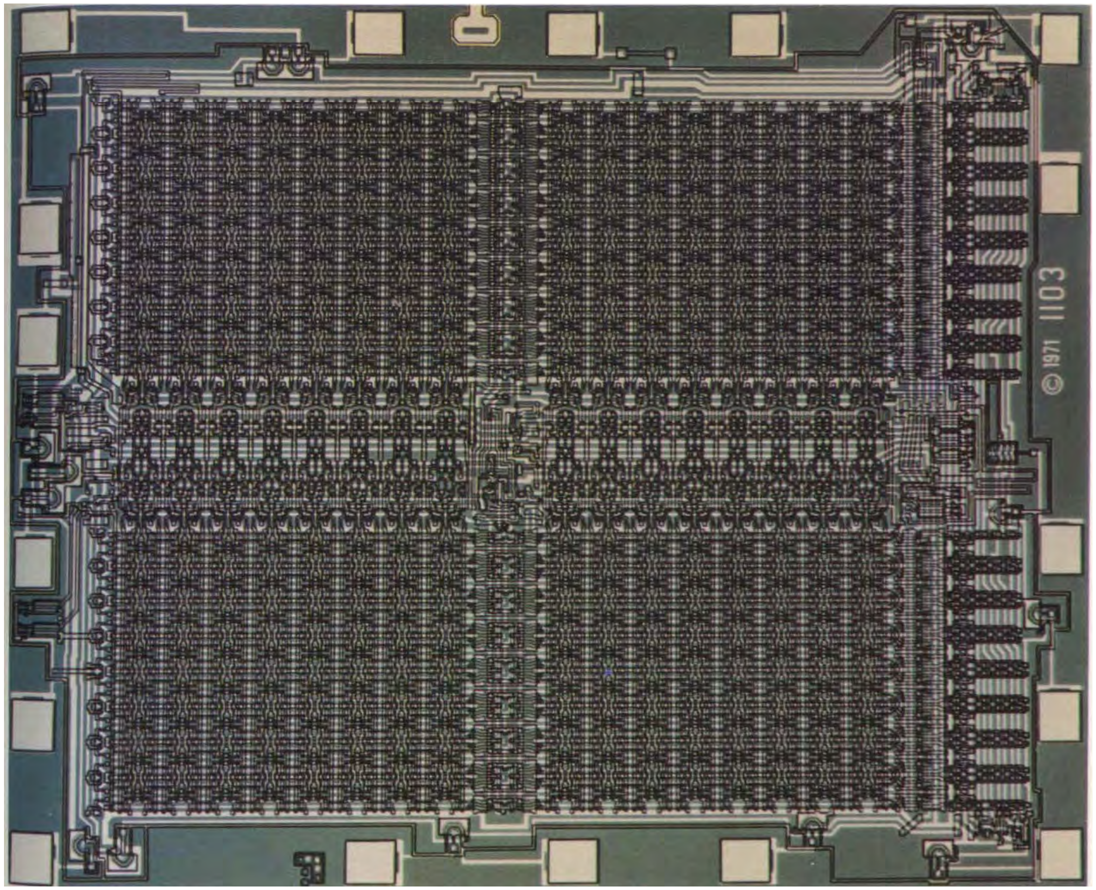


First IC Created with Computer-Aided Design Tools -- 1967



μMOSAIC – Fairchild

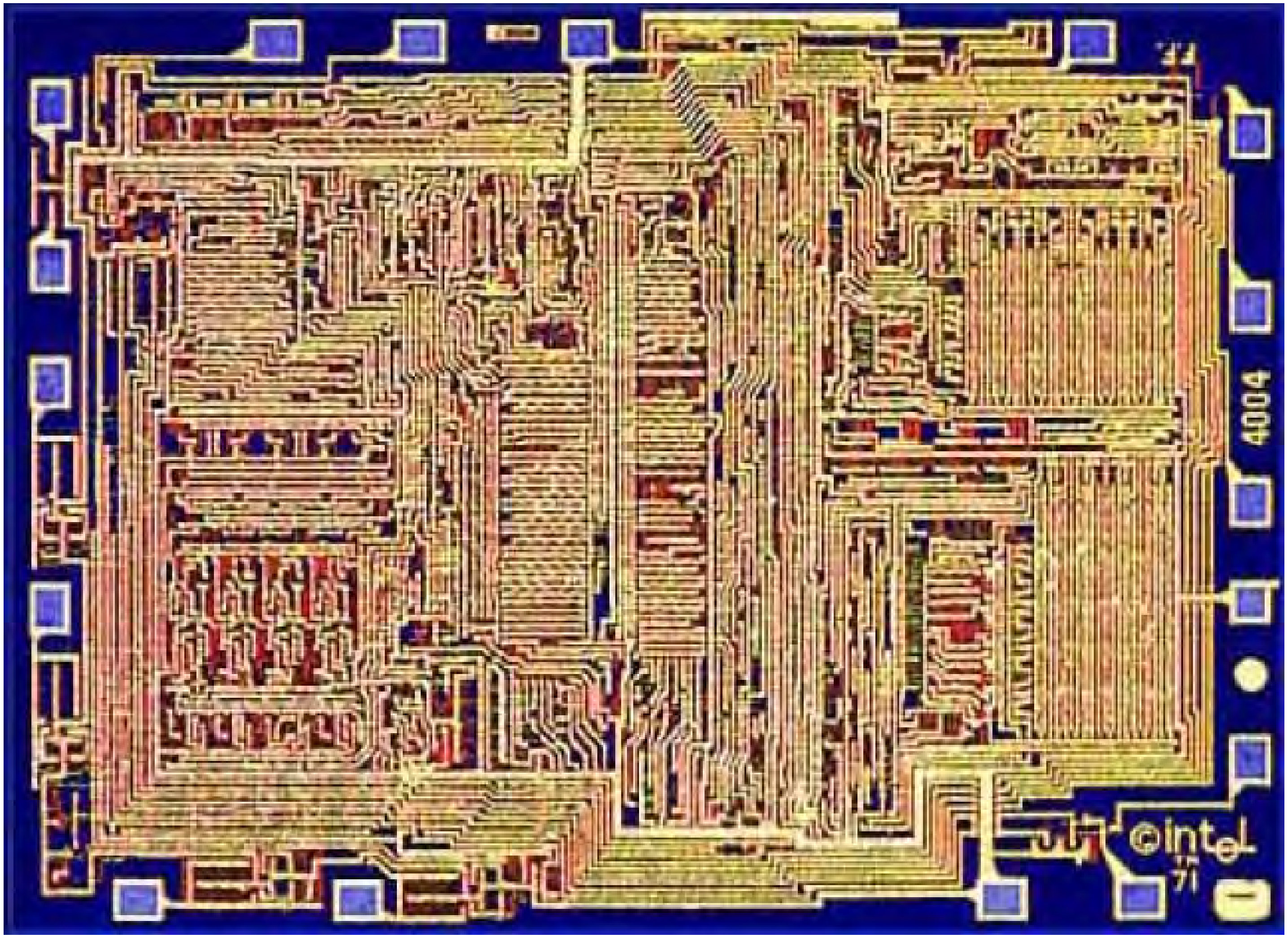
First 1,024 Bit Memory Chip -- 1970



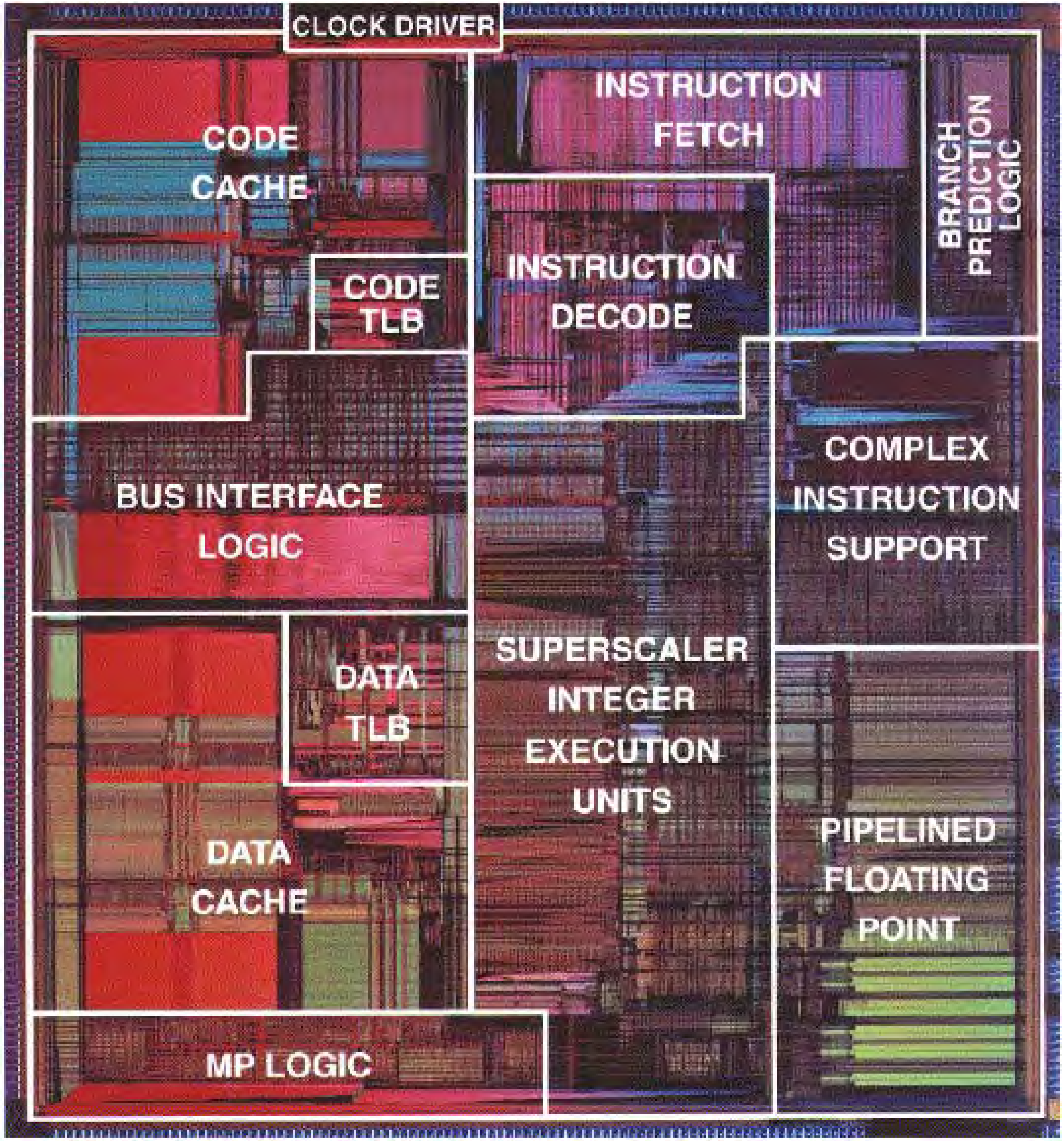
Intel Corporation DRAM

- 1970's processes usually had only nMOS transistors
  - *Inexpensive, but consume power while idle.*
- 1980s-present: CMOS processes for low idle power

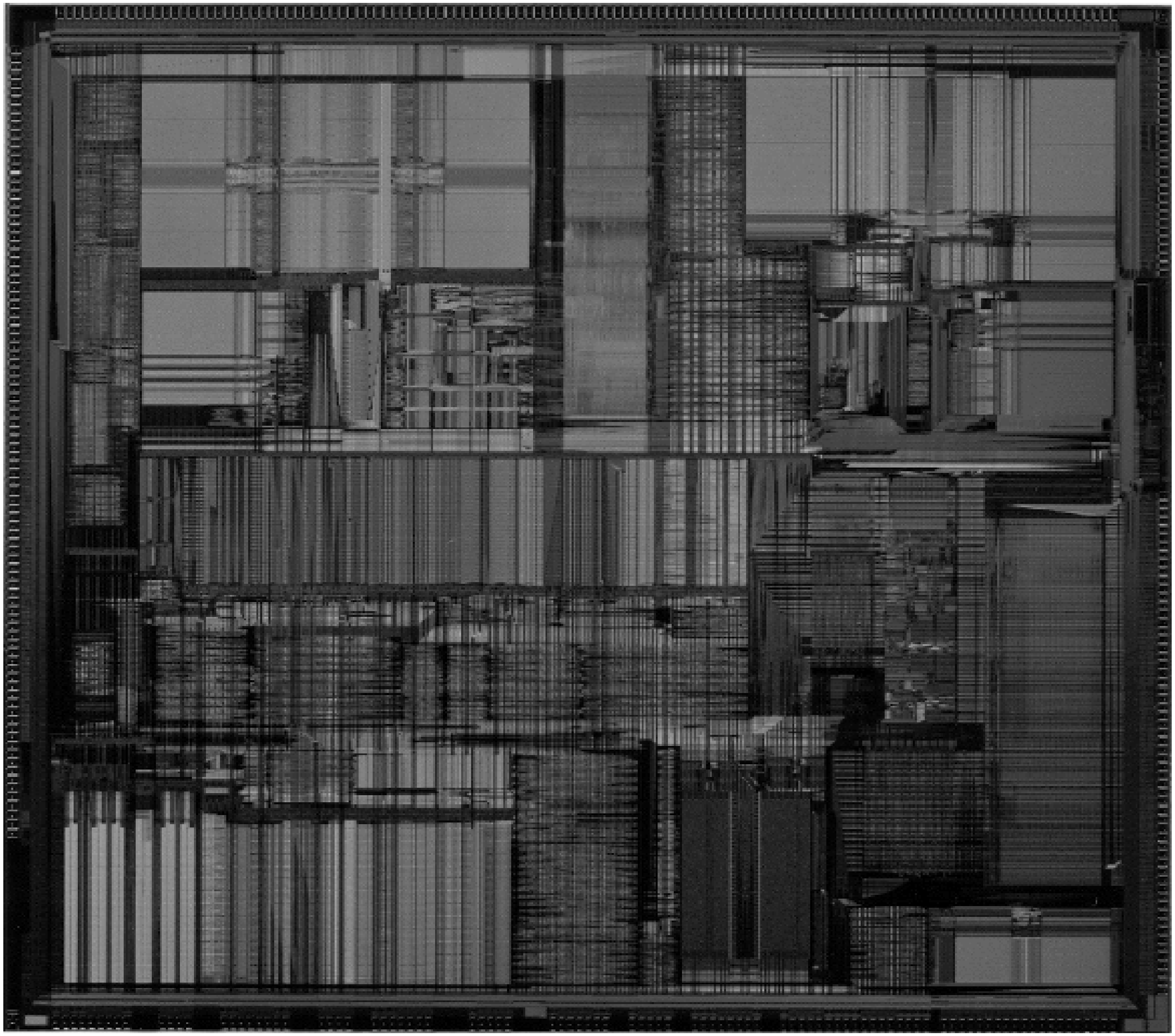
Intel 4004 : 2.3K Transistors (1971)



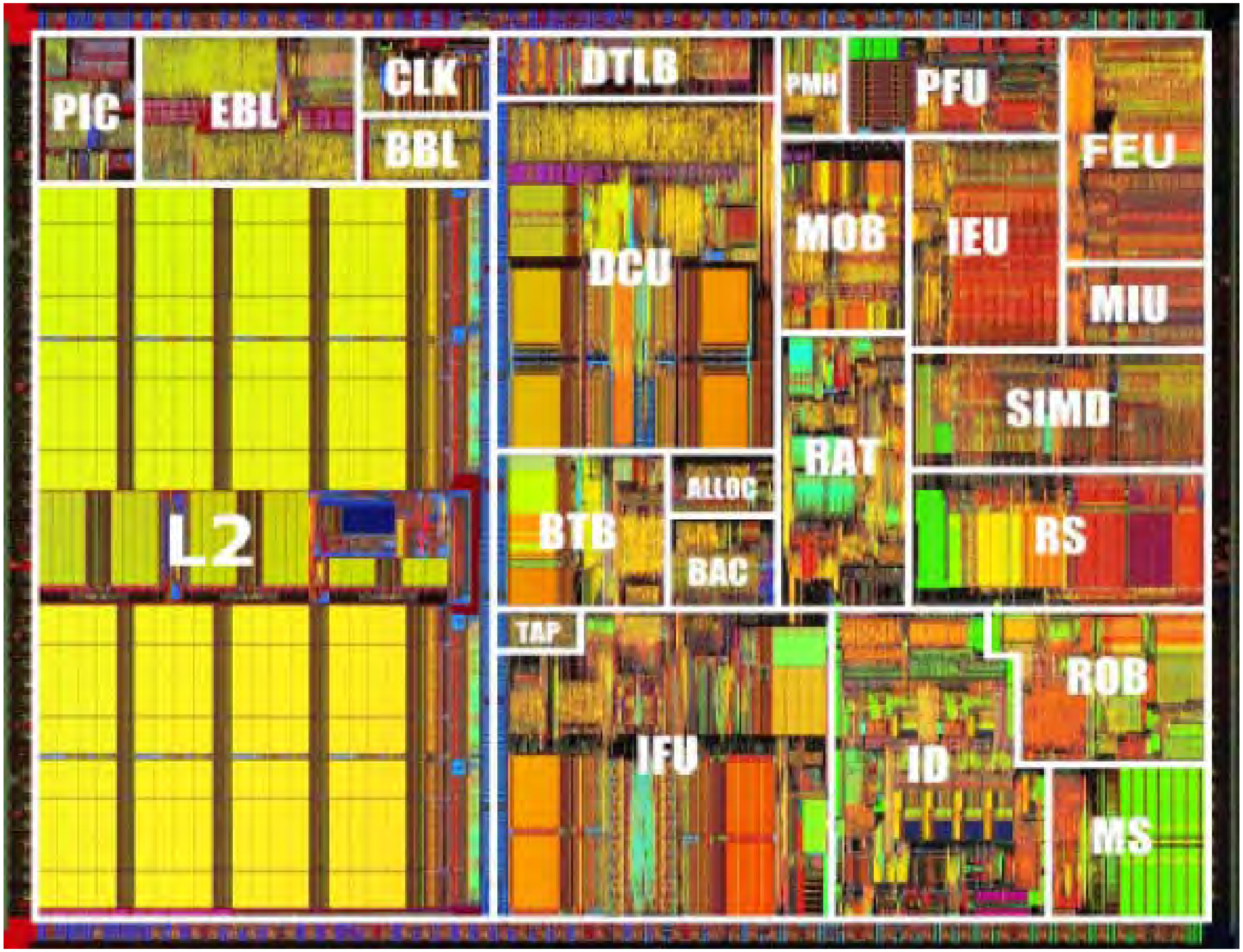
Pentium : 3.1M Transistors (1993)



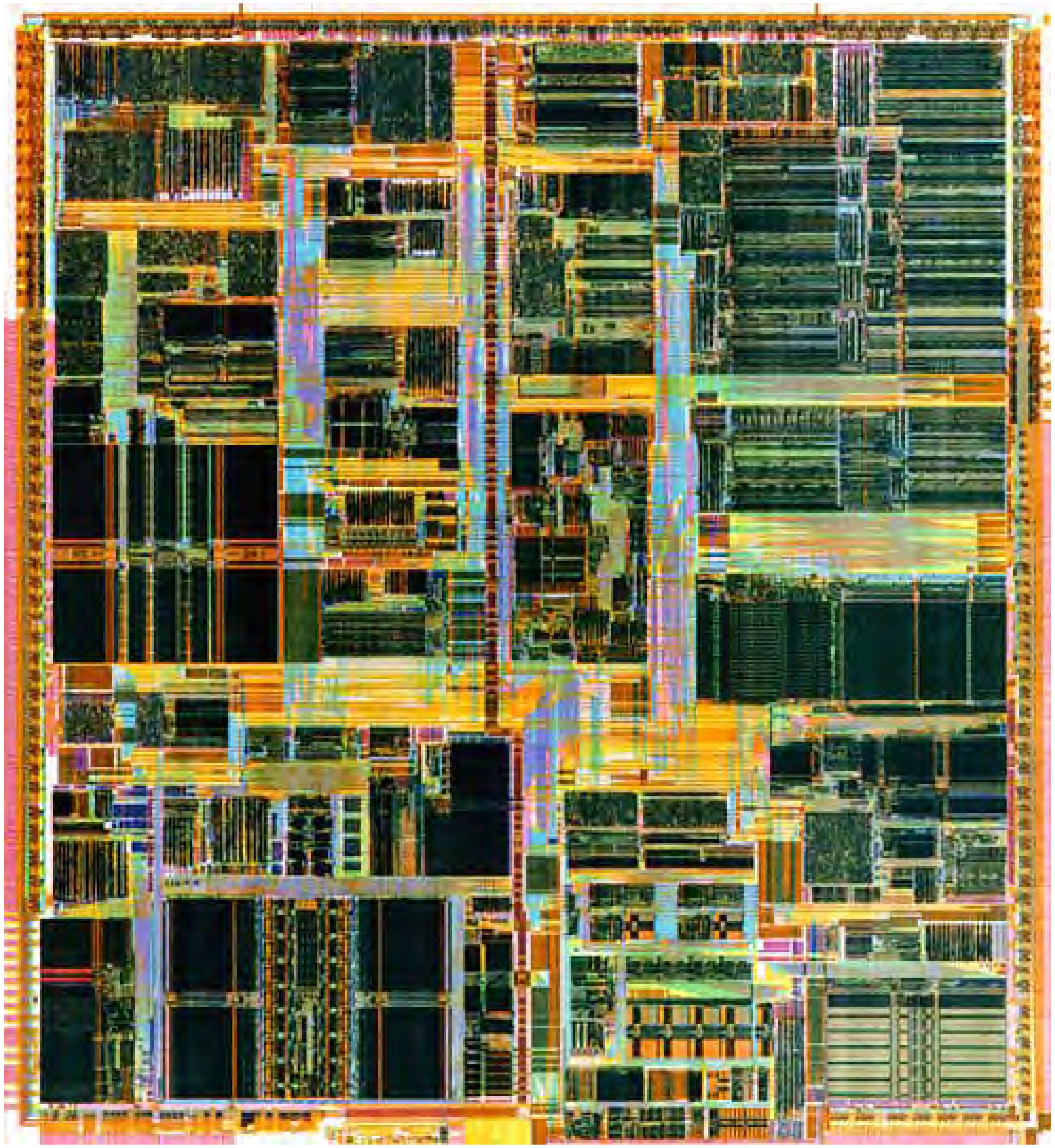
Pentium II : 7.5M Transistors (1997)



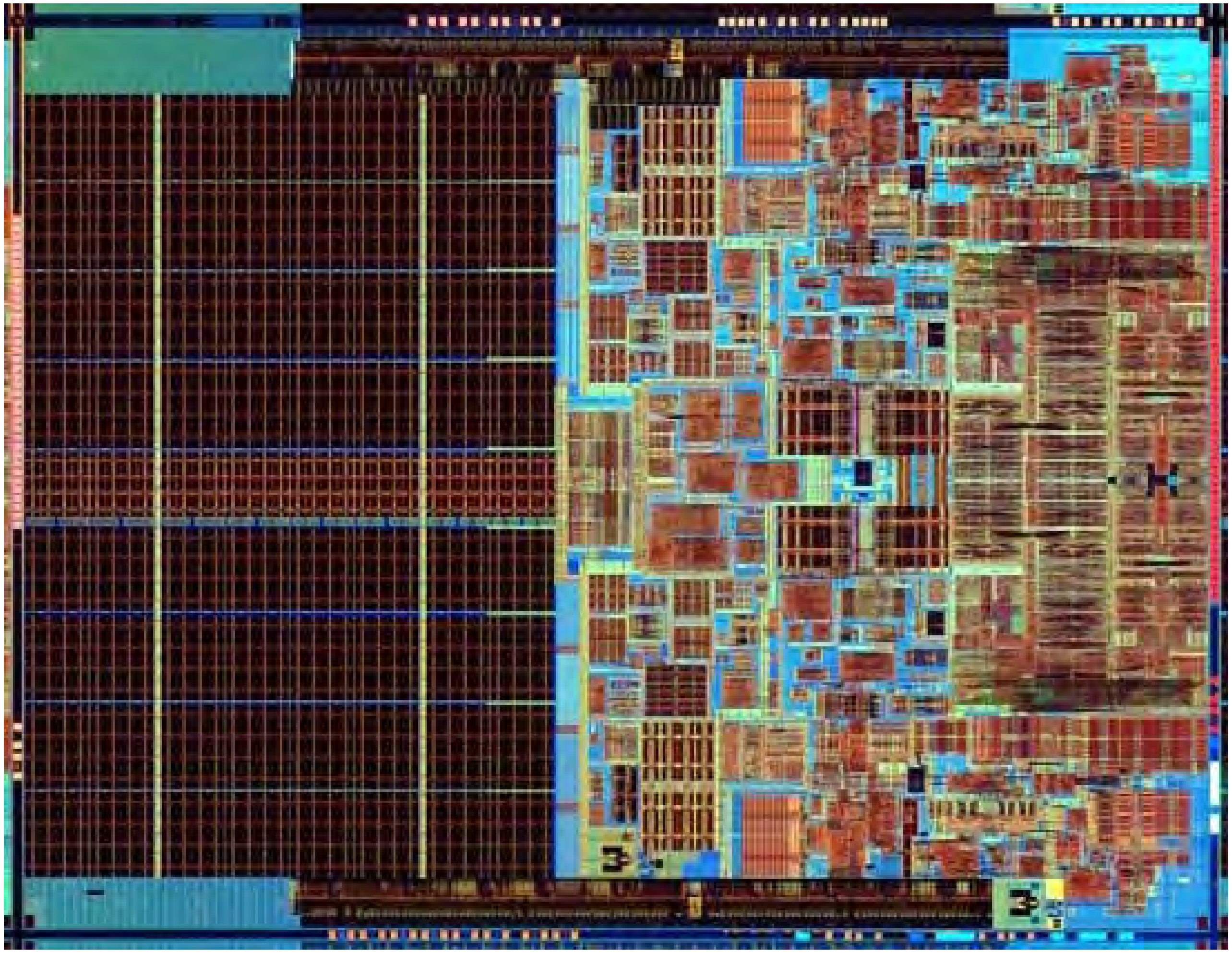
Pentium III : 28.1M Transistors (1999)



Pentium IV : 52M Transistors (2001)

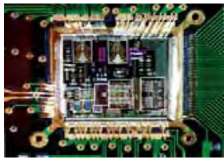


Core 2 Duo: 291M Transistors (2006)



Core 2 Duo T5000/T7000 series mobile processors, called Penryn uses 800M of 45 nanometer devices (2007).

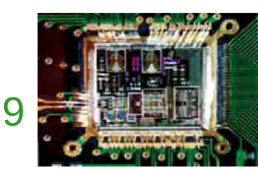
Circuit Design Flow



Integrated Circuits Categories

There are many different types of ICs as listed below.

IC Categories	Functions
Analog ICs	Amplifiers
	Filters
Digital ICs	Boolean Gates
	Encoders/Decoders
	Multiplexers / Demultiplexers
	Flip-flops
	Counters
	Shift Registers
Hybrid ICs	Mixed Signal Processors
Interface ICs	Analog-Digital Converters
	Digital-Analog Converters



Levels of Integration (Chip Complexity)

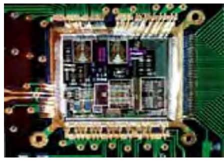
Categorized by the number of gates contained in the chip.

IC Complexity	Number of Gates	Functional Complexity	Examples
SSI	<10	Basic gates	Inverters, AND gates, OR gates, NAND gates, NOR gates
MSI	10-100	Basic gates	Exclusive OR/NOR
		Sub-modules	Adders, subtractors, encoders, decoders, multiplexers, demultiplexers, counters, flip-flops
LSI	100-1000s	Functional modules	Shift registers, stacks
VLSI	1000s-100,000	Major building blocks	Microprocessors, memories
ULSI	>100,000	Complete systems	Single chip computers, digital signal processors
WSI	>10,000,000	Distributed systems	Microprocessor systems

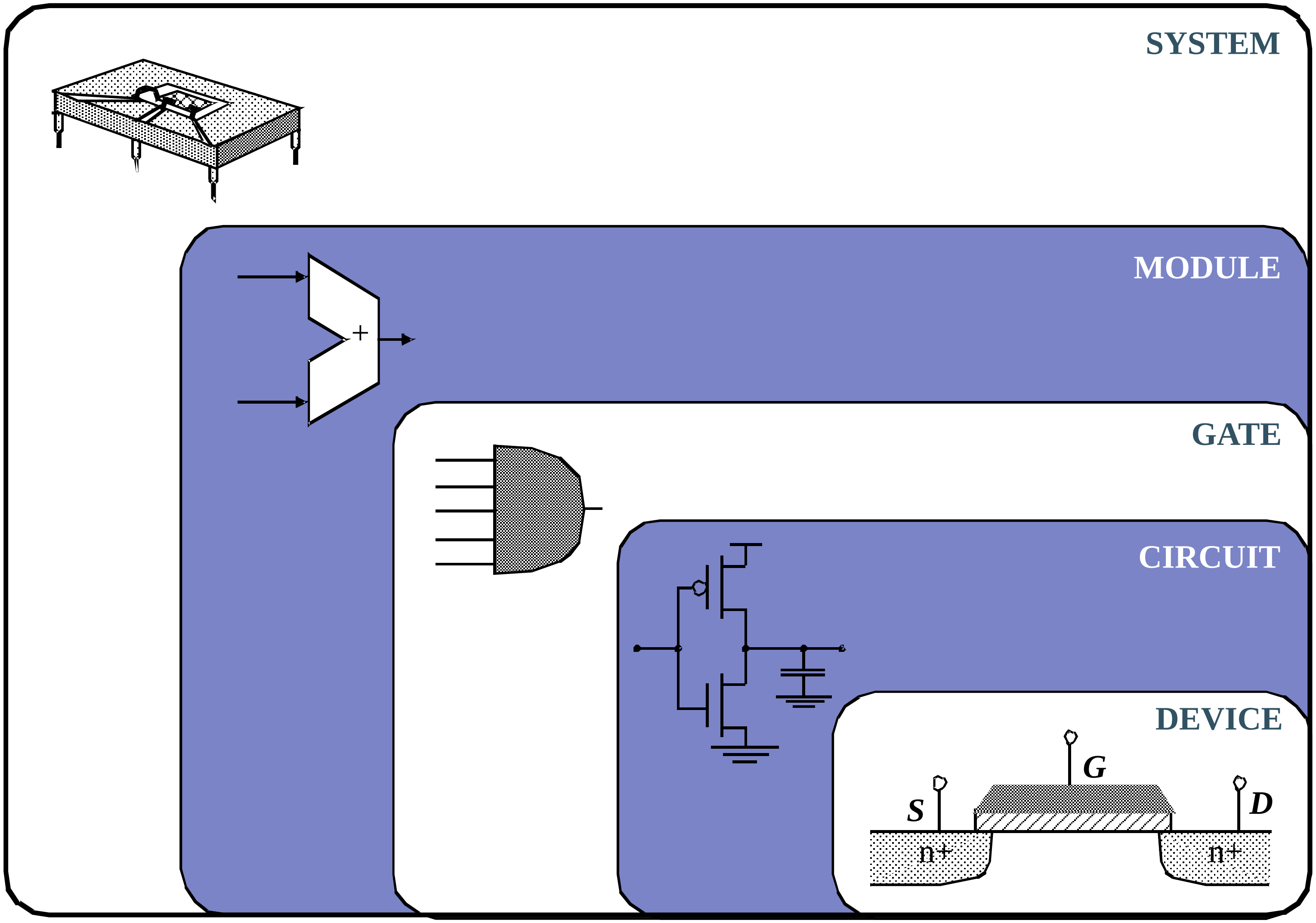
Digital Logic Families

- Various circuit technology used to implement an IC at lower level of abstraction.
- The circuit technology is referred to as a digital logic family.

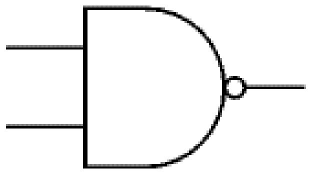
RTL - Resistor-transistor Logic	obsolete
DTL - Diode-transistor logic	obsolete
TTL - Transistor-transistor logic	not much used
ECL - Emitter-coupled logic	high-speed ICs
MOS - Metal-oxide semiconductor	high-component density
CMOS - Complementary Metal-oxide semiconductor	widely used, low-power high-performance and high-packing density IC
BiCMOS - Bipolar Complementary Metal-oxide semiconductor	high current and high-speed
GaAs - Gallium-Arsenide	very high speed circuits



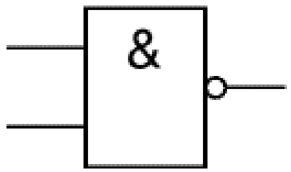
Design Abstraction Levels



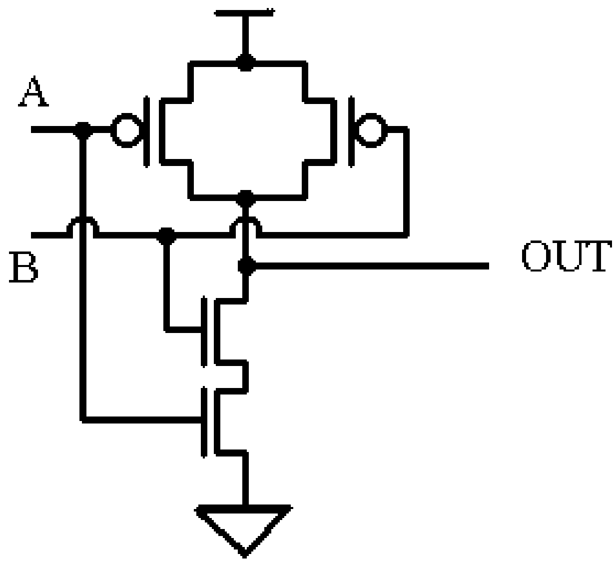
Digital Circuits : Logic to Device



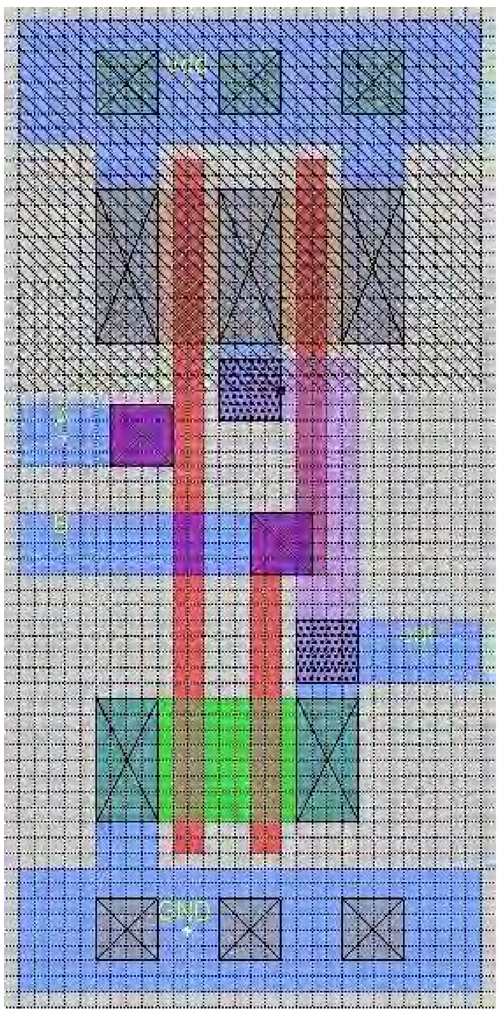
(NAND Gate)



(IEC Symbol)

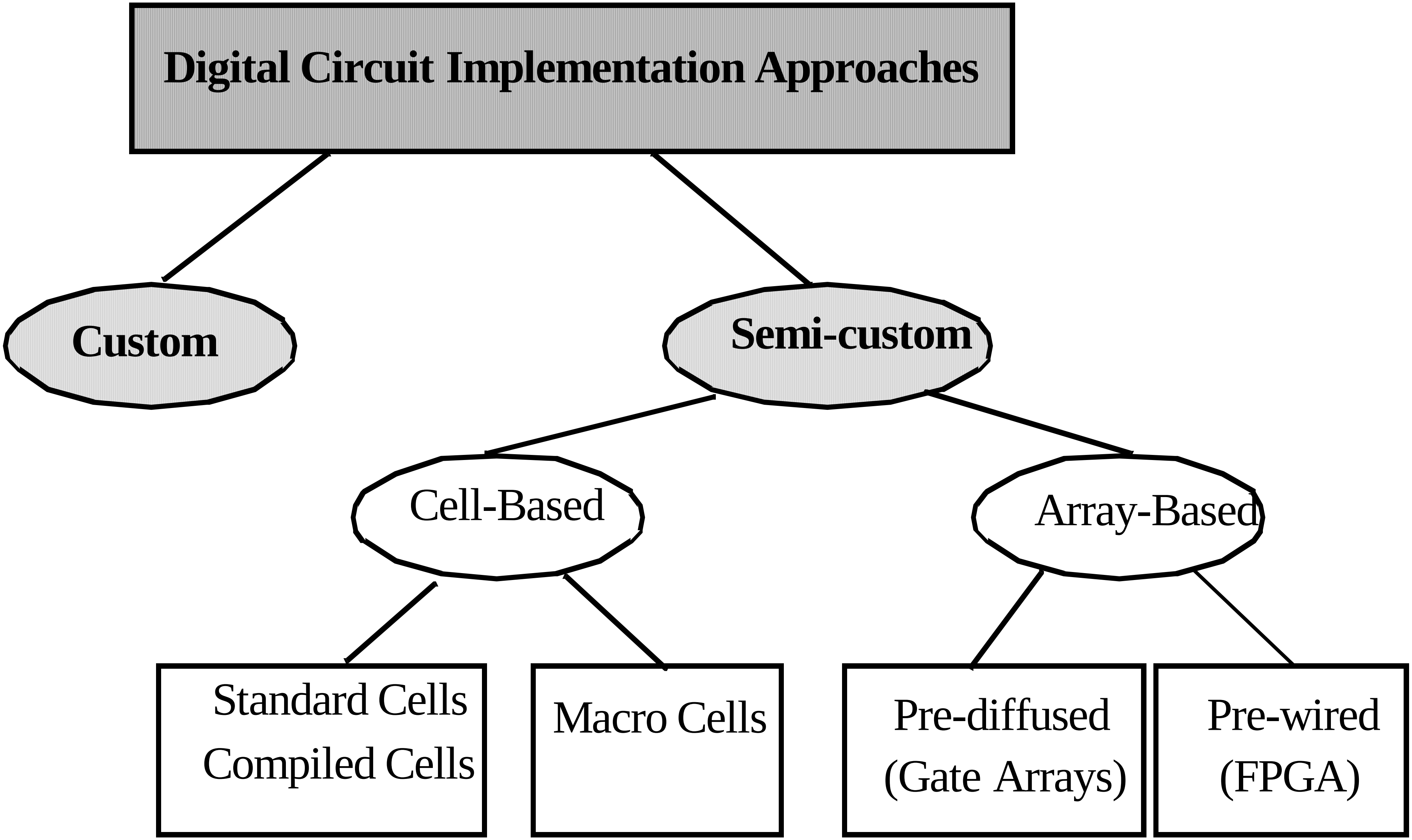


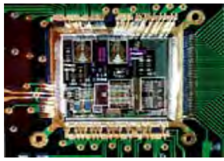
(Transistor Diagram)



(Layout Diagram)

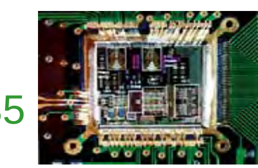
Implementation Approaches for Digital ICs



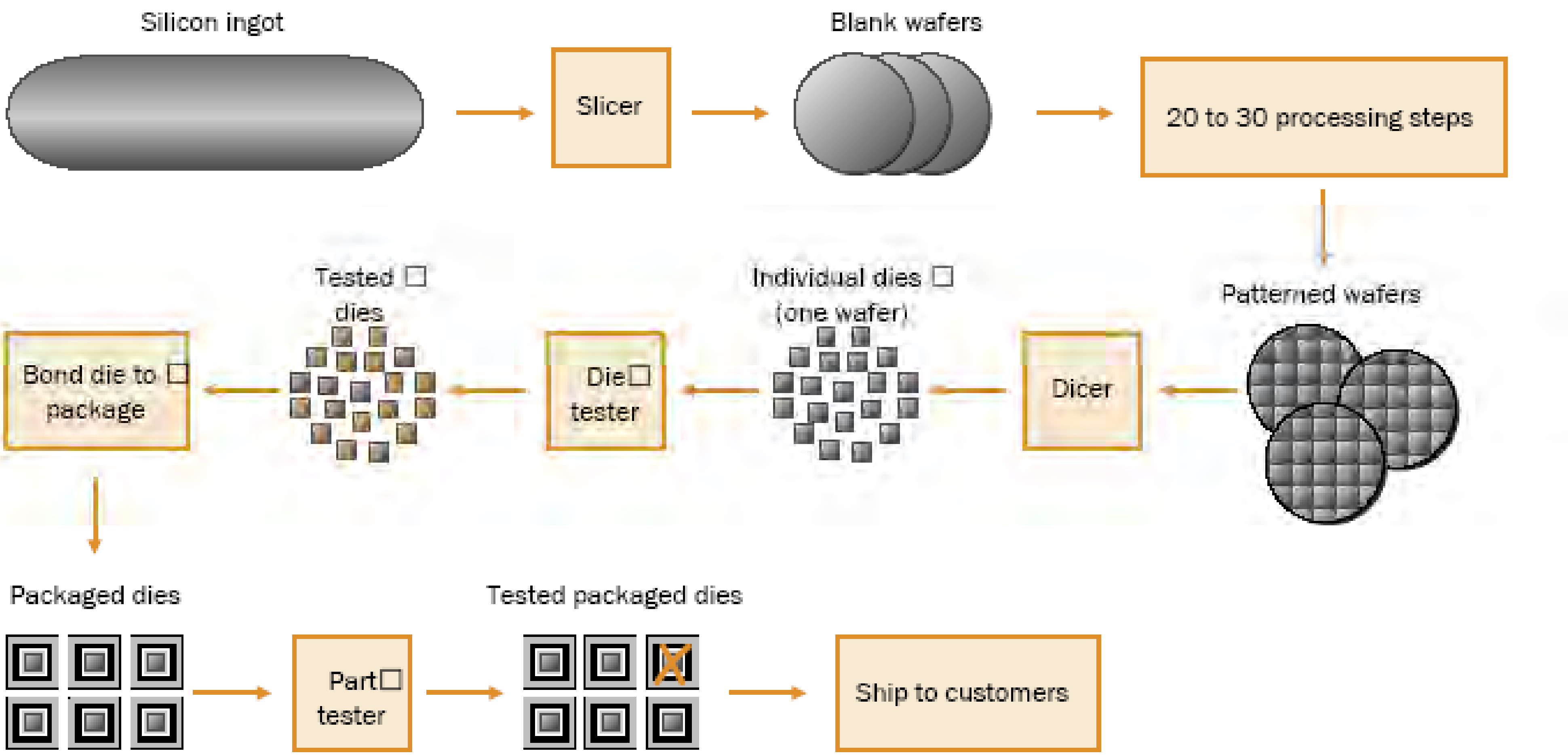


Implementation Approaches for Digital ICs

- Full-custom: all logic cells are customized. A general purpose microprocessor is designed this way.
- Semi-custom: all of the logic cells are from predesigned cell libraries (reduces the manufacture lead time of the IC)
- Standard-cell based IC uses predesigned logic cells such as AND gates, OR gates, MUXs, FFs,.., etc.
- Macrocells (also called megacells) are larger predesigned cells, such as microcontrollers, even microprocessors, etc.
- Gate-Array, Sea-of-Gates or prediffused arrays contains array of transistors or gates which can be connected by wires to implement the chip.
- Programmable-Logic-Array (PLA) is an example of fuse-based FPGA design. (NOTE: Fuse-based, nonvolatile and volatile are three types of FPGAs)



Digital IC Fabrication Flow



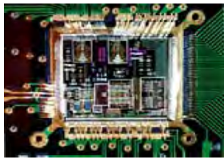
Technology Growth and Moore's Law

Different Attributes of an IC or chip

We will briefly discuss the VLSI technological growth based on these attributes.

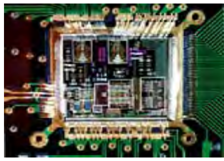
- Transistor count of a chip
- Operating frequency of a chip
- Power consumption of a chip
- Power density in a chip
- Size of a device used in chip

NOTE: Chip is informal name for IC.

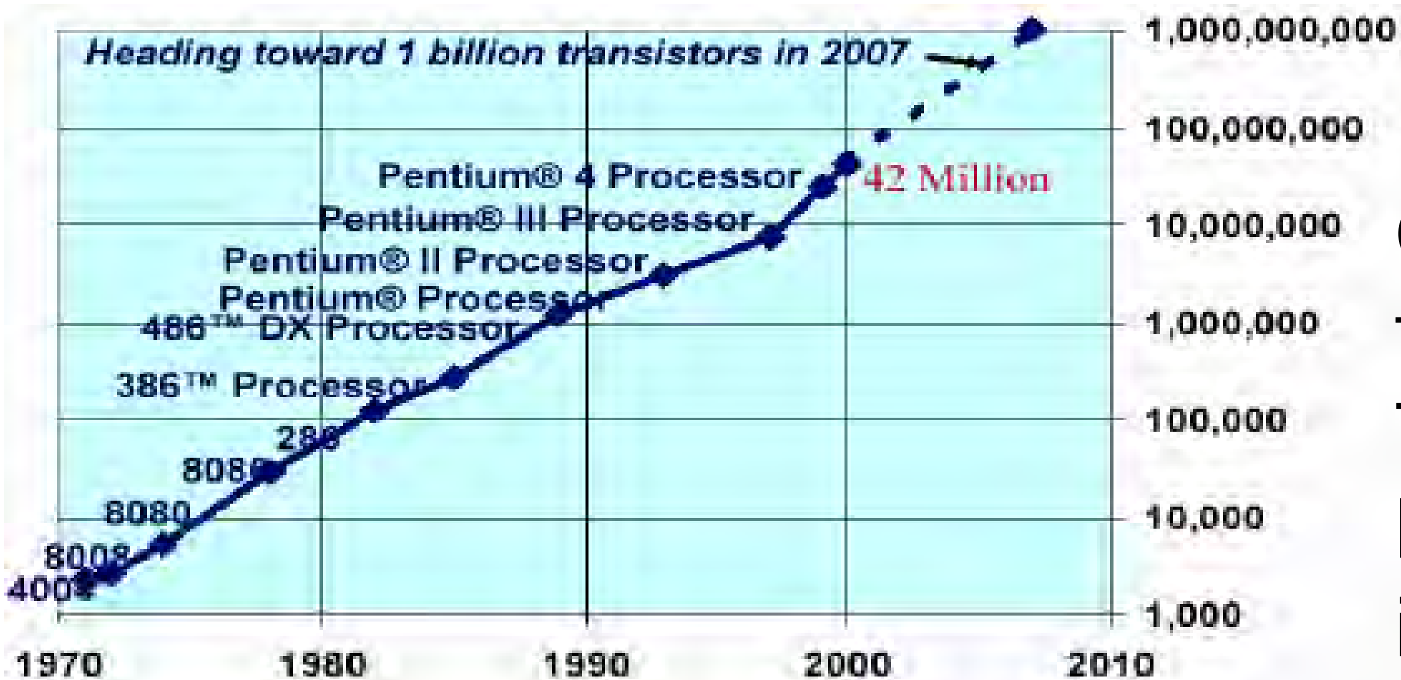


Moore's Law

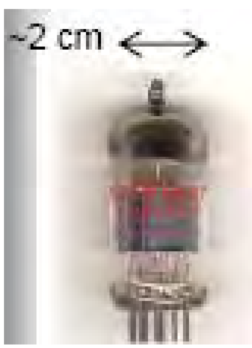
- 1965: Gordon Moore plotted transistor on each chip
  - Transistor counts have doubled every 26 months
- Many other factors grow exponentially
  - clock frequency
  - processor performance



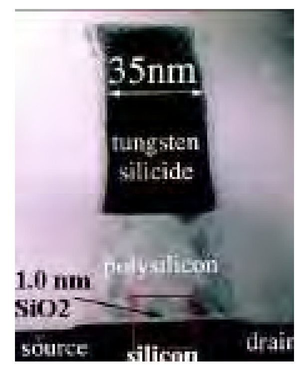
VLSI Trend



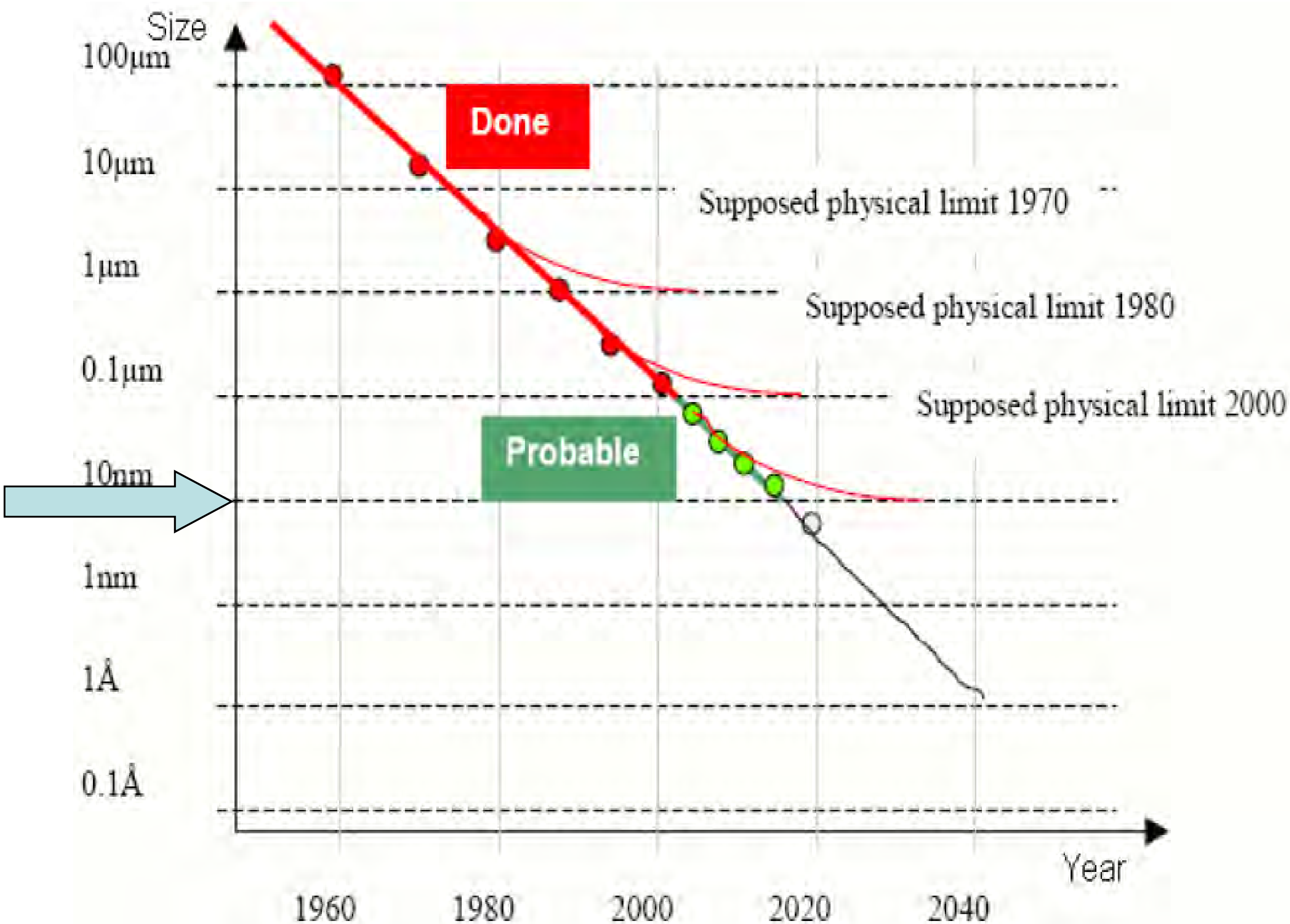
Power, Operating frequency, and Throughput have increased.



VLSI technology is the fastest growing technology in human history.

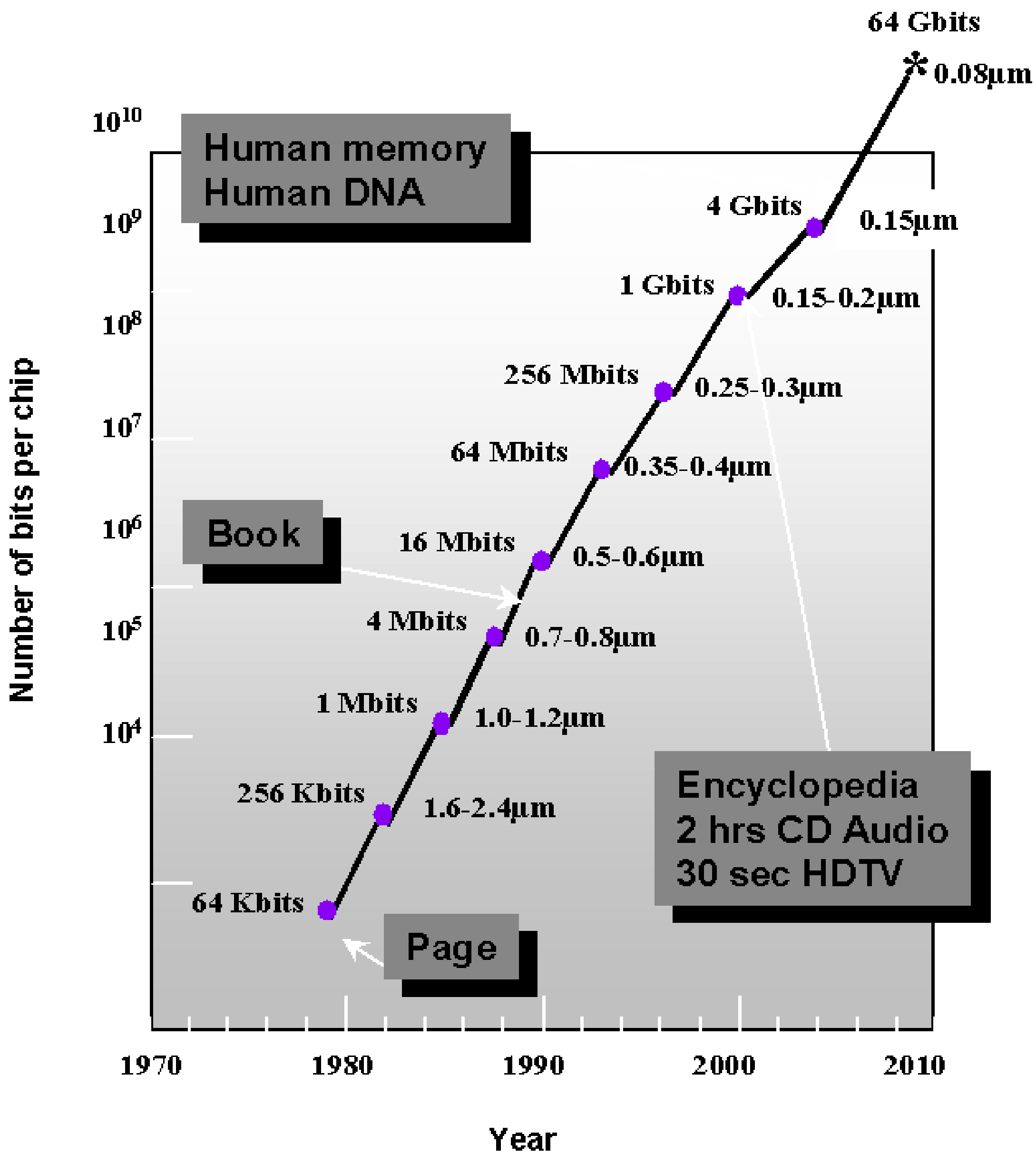


Technology Scaling Trend



Source: Bendhia 2003

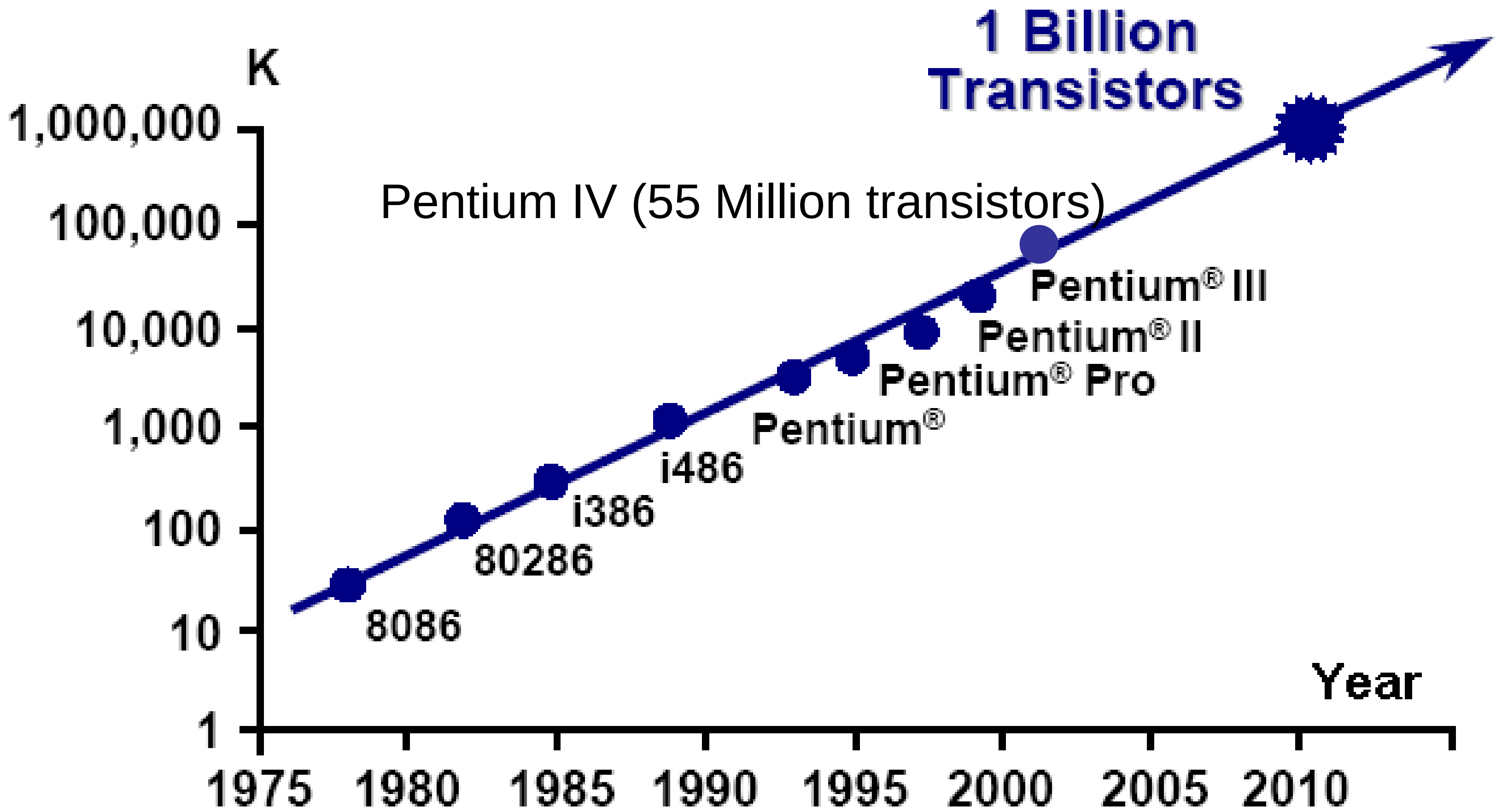
Evolution in Complexity



Why Scaling?

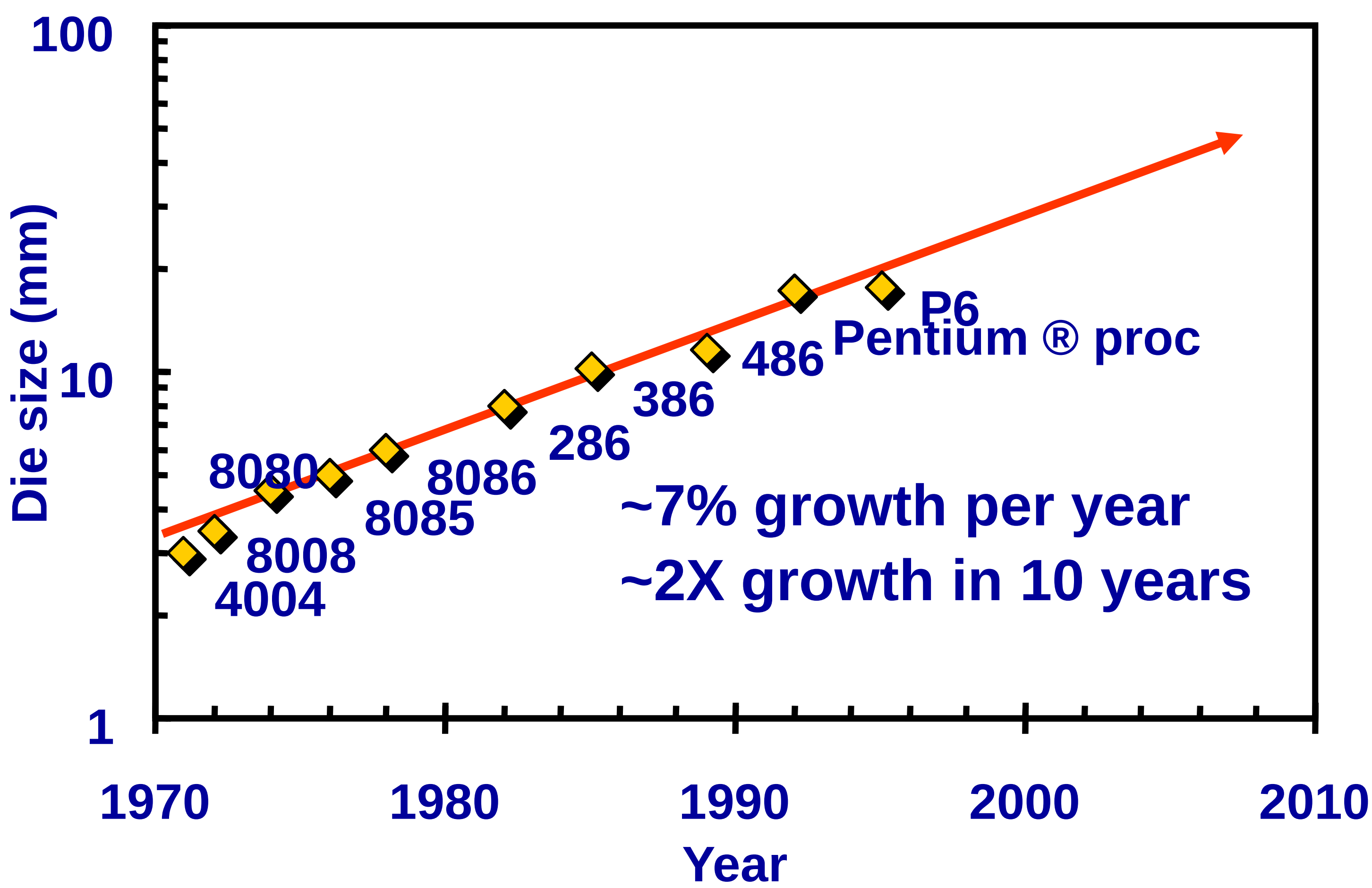
- Technology shrinks by 0.7/generation
- With every generation can integrate 2x more functions per chip; chip cost does not increase significantly
- Cost of a function decreases by 2x
- But …
  - How to design chips with more and more functions?
  - Design engineering population does not double every two years…
- Hence, a need for more efficient design methods
  - Exploit different levels of abstraction

Increase in Transistor Count



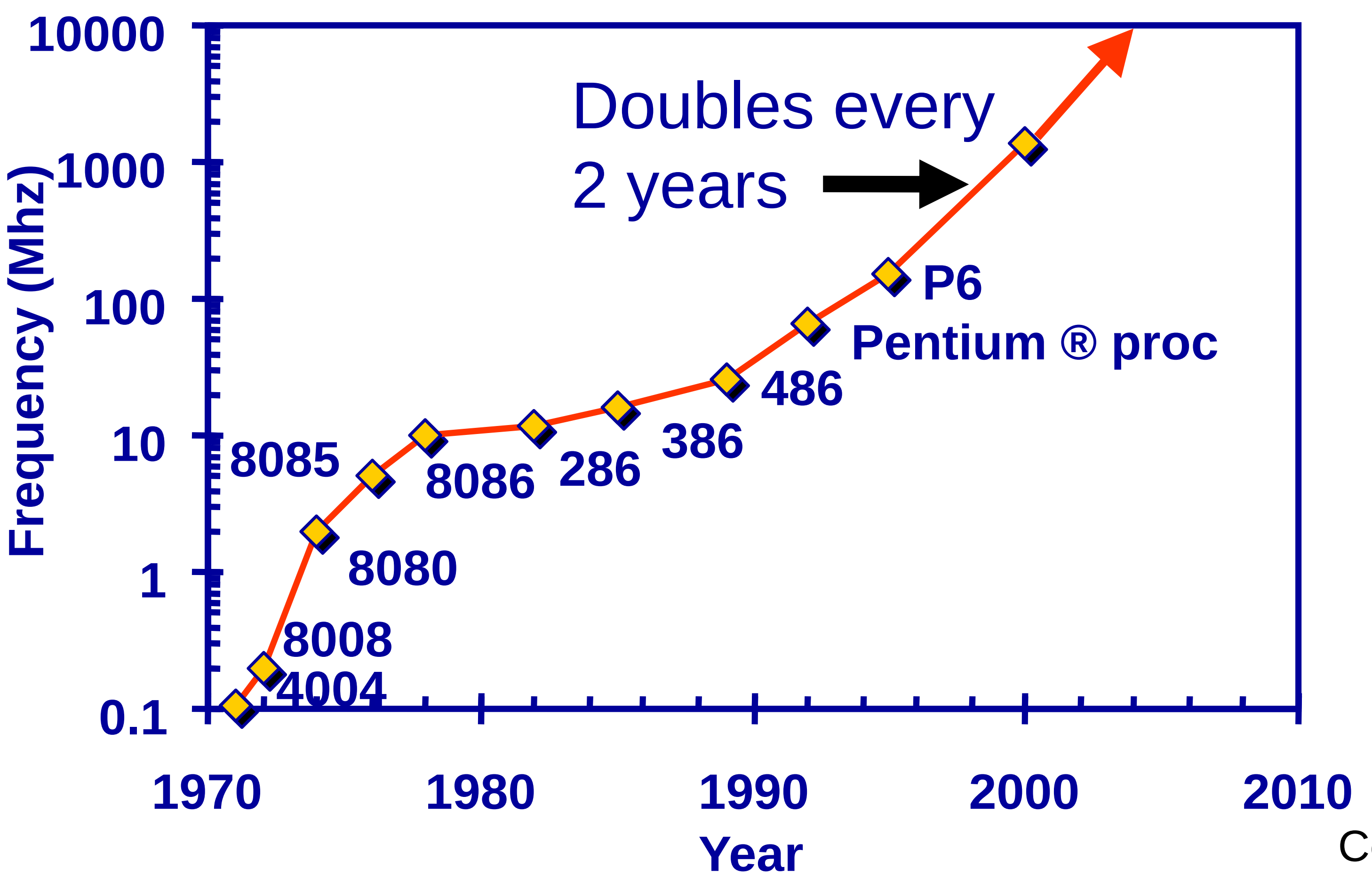
Transistors on Lead Microprocessors double every 2 years

Die Size Growth



Die size grows by 14% to satisfy Moore's Law

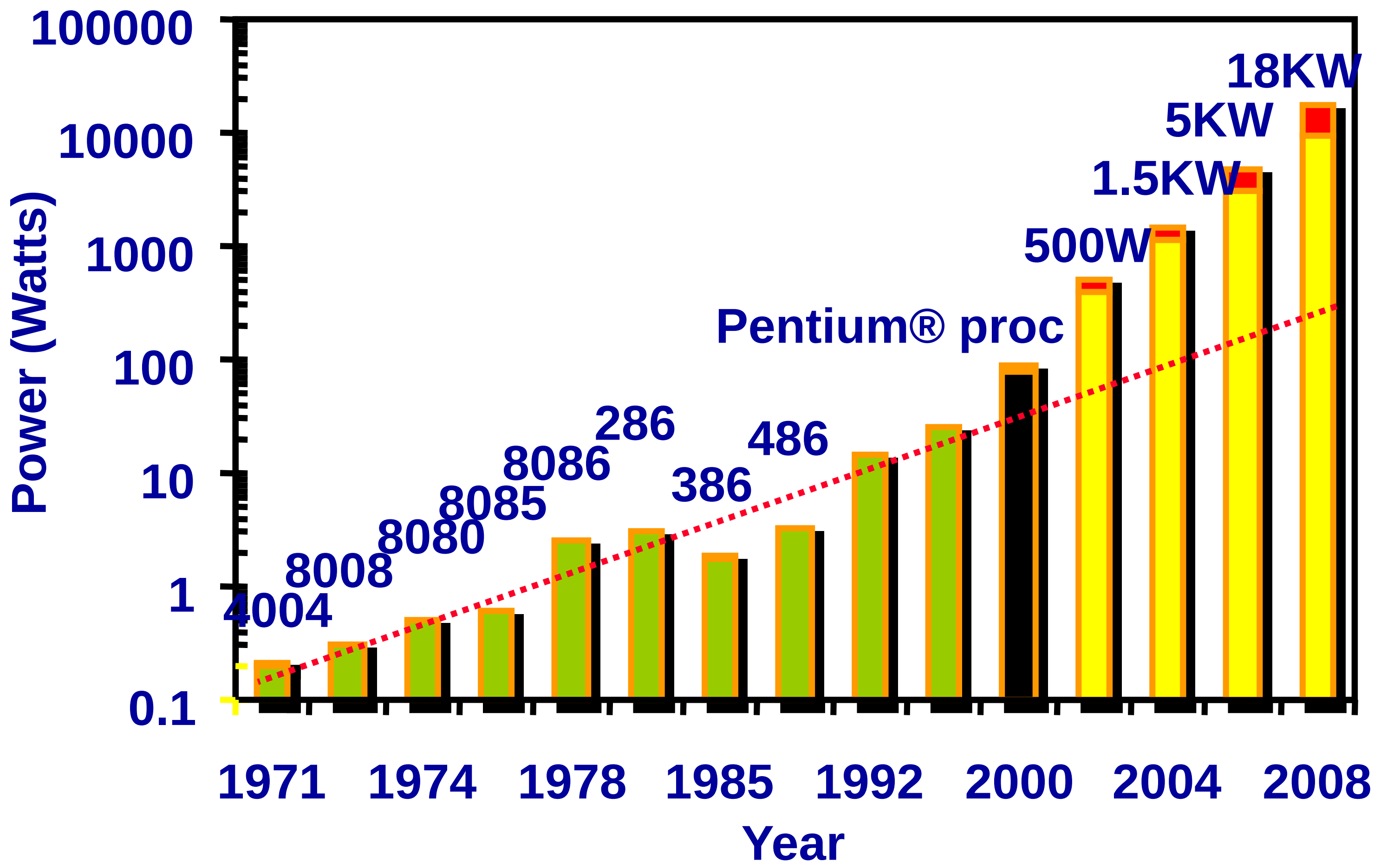
Increase in Operating Frequency



Courtesy, Intel

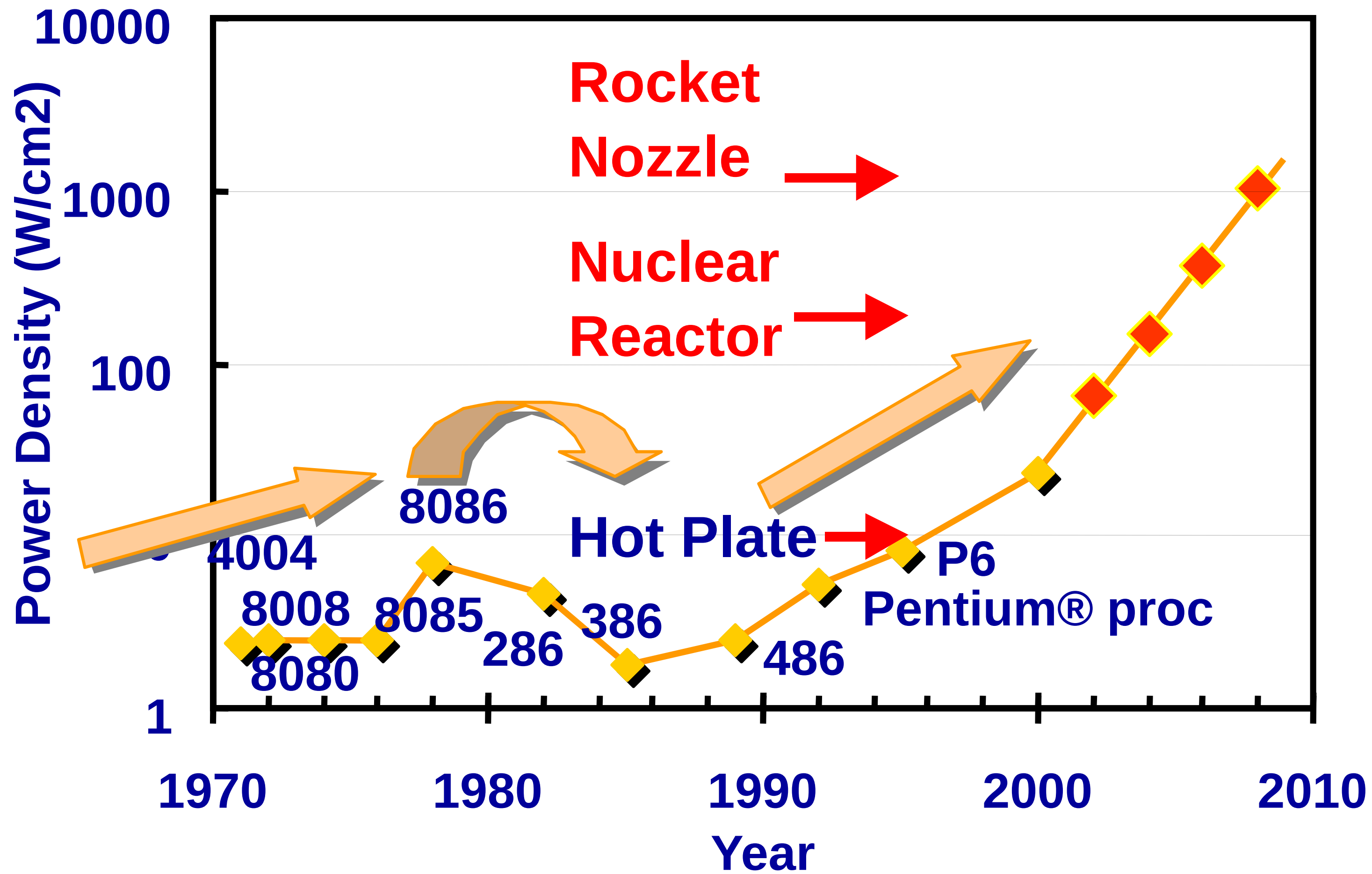
Lead Microprocessors frequency doubles every 2 years

Power will be a major problem



Power delivery and dissipation will be prohibitive

Power density



Power density too high to keep junctions at low temp

Challenges in Digital Design

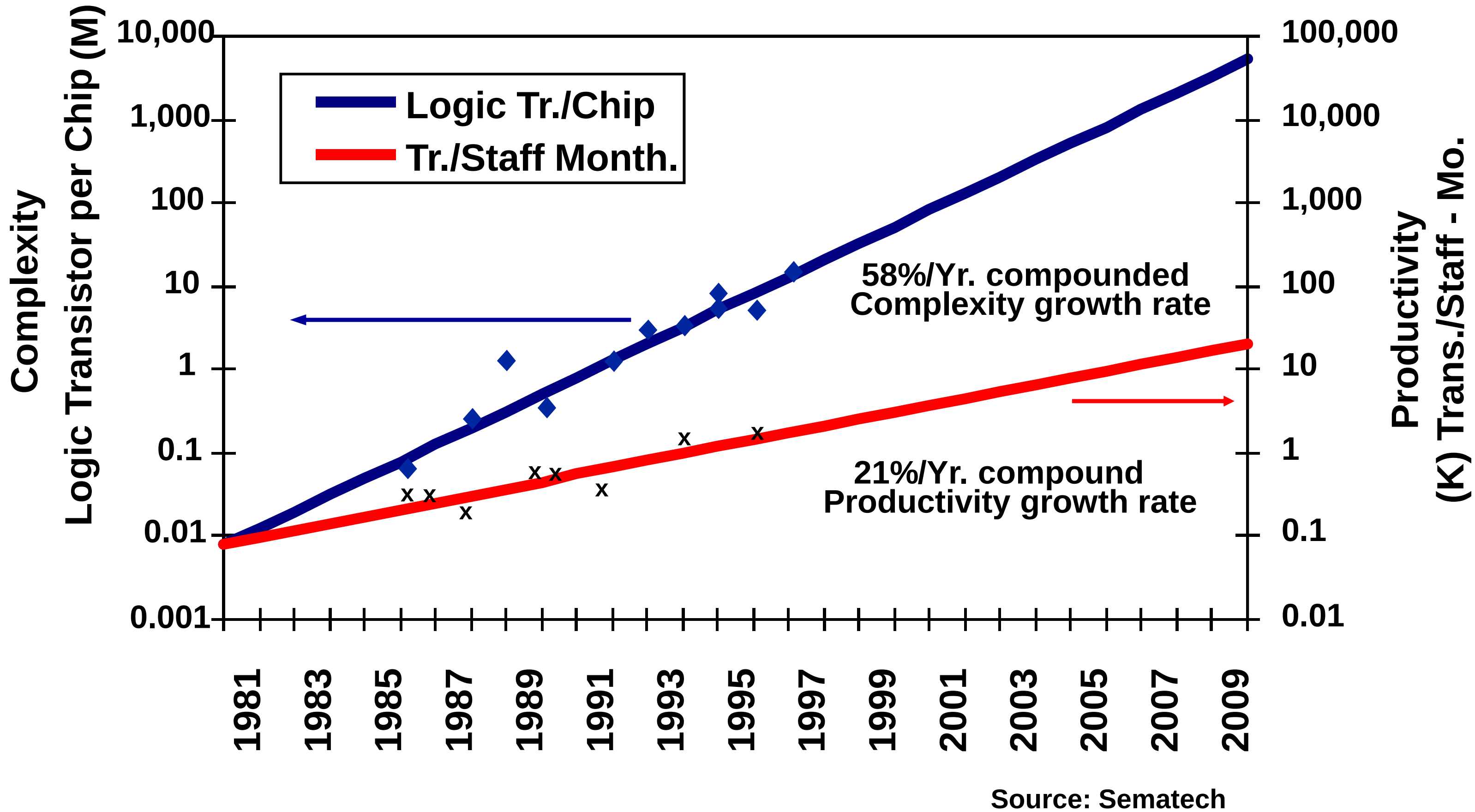
"Microscopic Problems"
- Ultra-high speed design
- Interconnect
- Noise, Crosstalk
- Reliability, Manufacturability
- Power Dissipation
- Clock distribution.

"Macroscopic Issues"
- Time-to-Market
- Millions of Gates
- High-Level Abstractions
- Reuse & IP: Portability
- Predictability
- etc.

Everything Looks a Little Different

…and There's a Lot of Them!

Productivity Trends



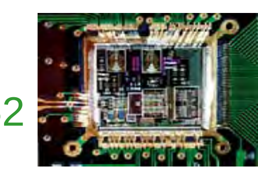
Complexity outpaces design productivity

Courtesy, ITRS Roadmap

Circuit Design Metrics

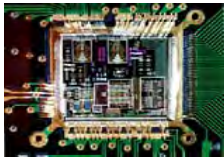
Design Metrics

- How to evaluate performance of a digital circuit (gate, block, …)?
  - Cost
  - Reliability
  - Scalability
  - Speed (delay, operating frequency)
  - Power dissipation
  - Energy to perform a function

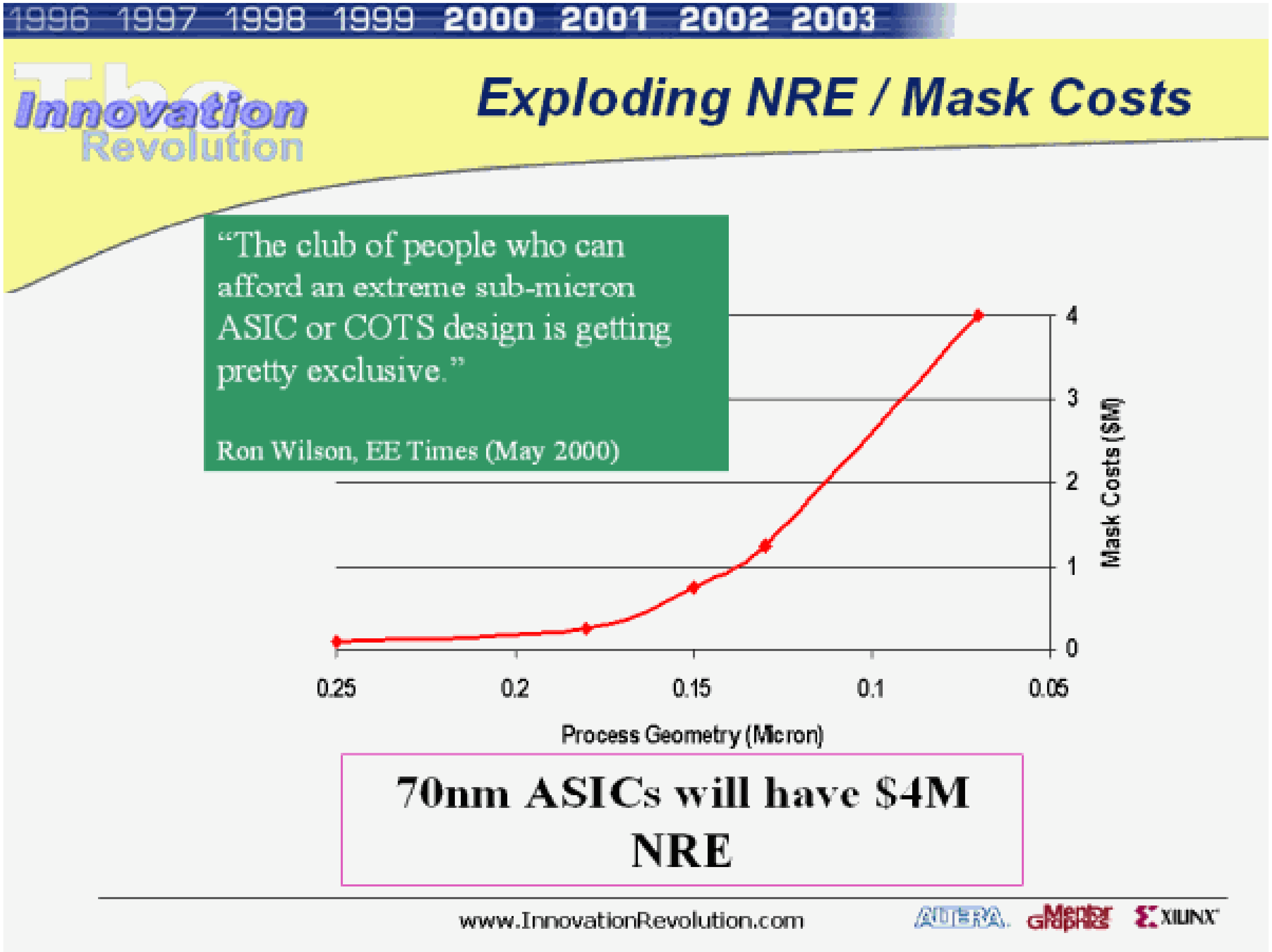


Cost of Integrated Circuits

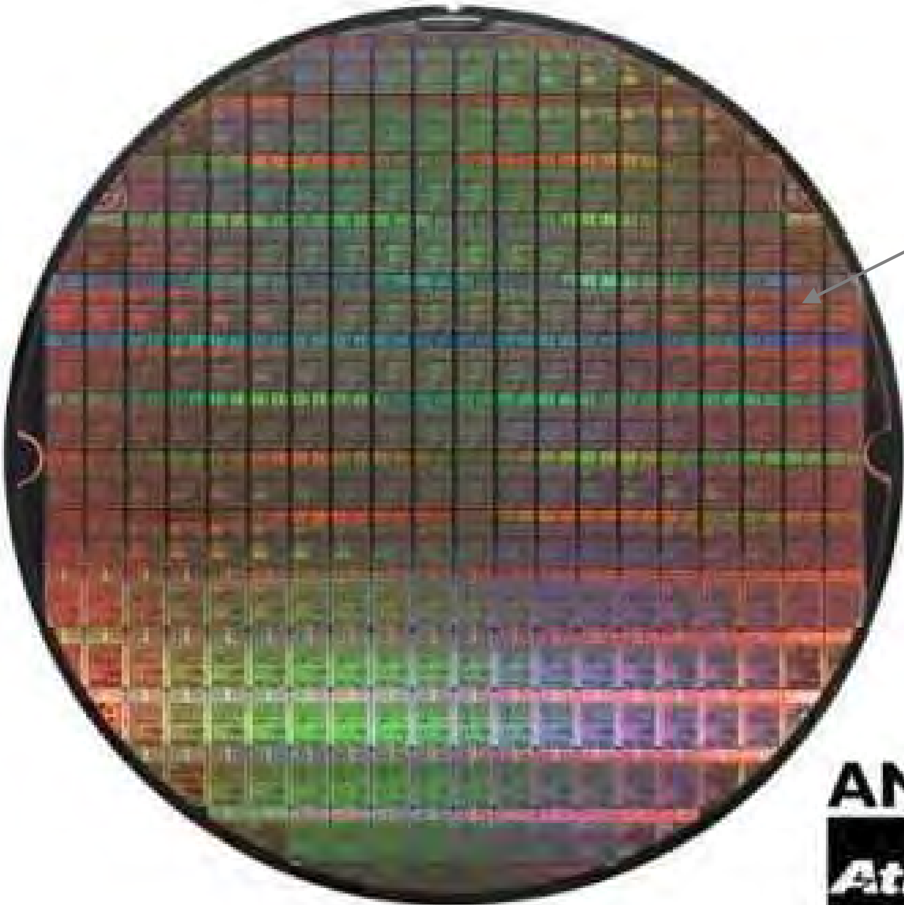
- NRE (non-recurrent engineering) costs
  - design time and effort, mask generation
  - one-time cost factor
- Recurrent costs
  - silicon processing, packaging, test
  - proportional to volume
  - proportional to chip area



NRE Cost is Increasing



Die Cost

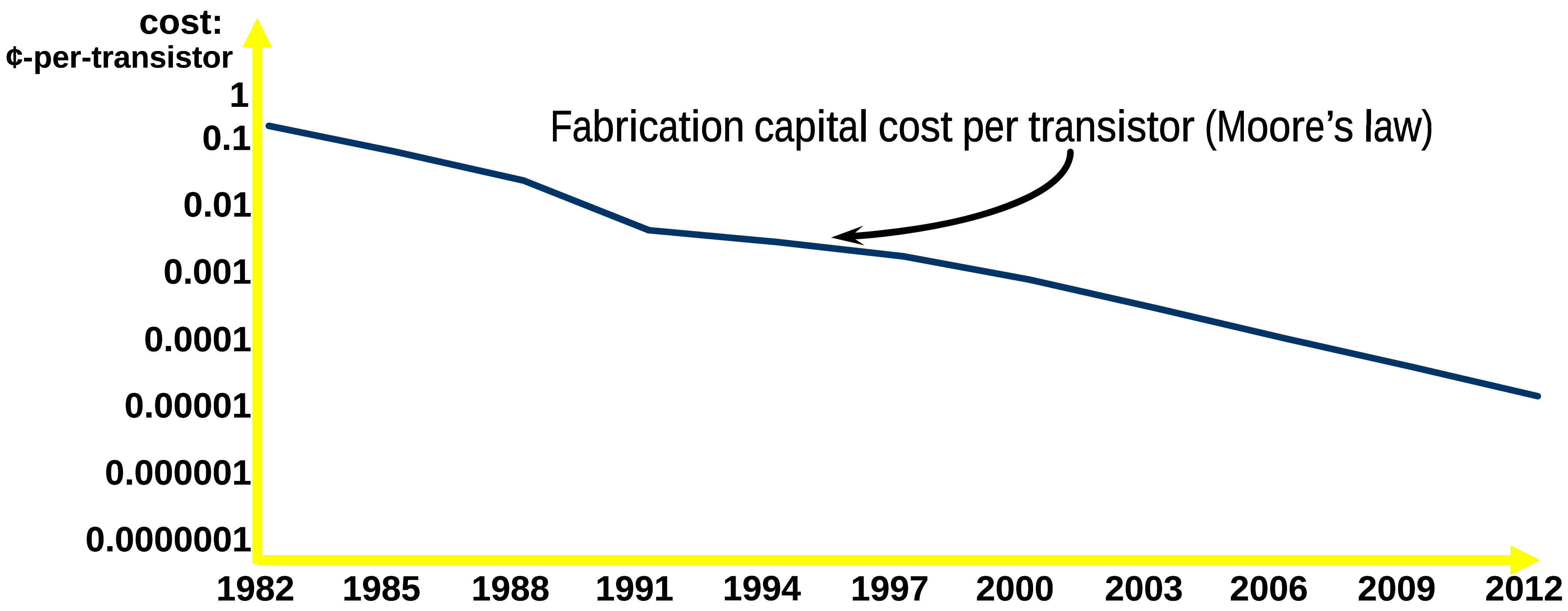


Single die

Wafer

Going up to 12” (30cm)

Cost per Transistor

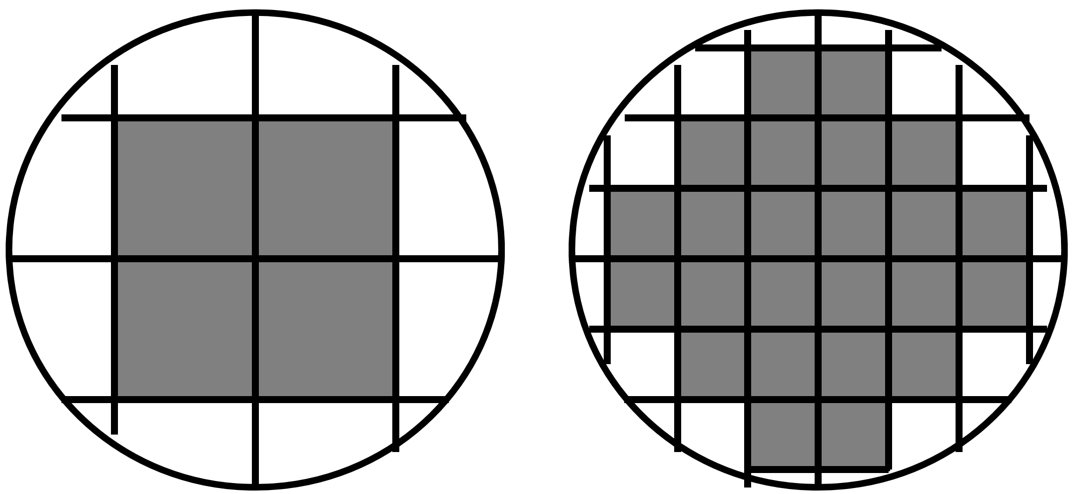


Yield

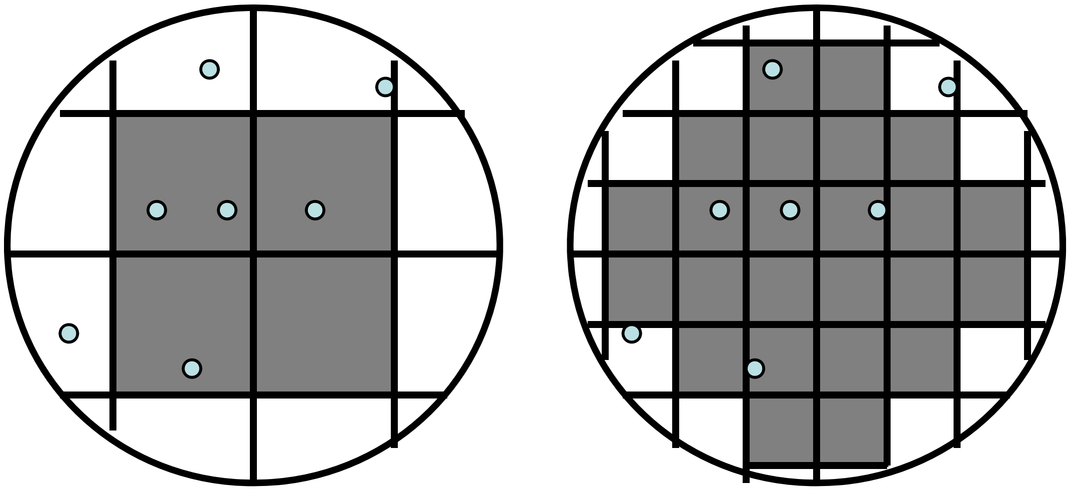
$$Y = \frac{\text{No. of good chips per wafer}}{\text{Total number of chips per wafer}} \times 100\%$$

$$\text{Die cost} = \frac{\text{Wafer cost}}{\text{Dies per wafer} \times \text{Die yield}}$$

$$\text{Dies per wafer} = \frac{\pi \times (\text{wafer diameter}/2)^2}{\text{die area}} - \frac{\pi \times \text{wafer diameter}}{\sqrt{2 \times \text{die area}}}$$



Defects



$$\text{die yield} = \left(1 + \frac{\text{defects per unit area} \times \text{die area}}{\alpha}\right)^{-\alpha}$$

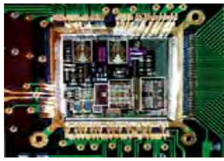
α is approximately 3

$$\text{die cost} = f\,(\text{die area})^4$$

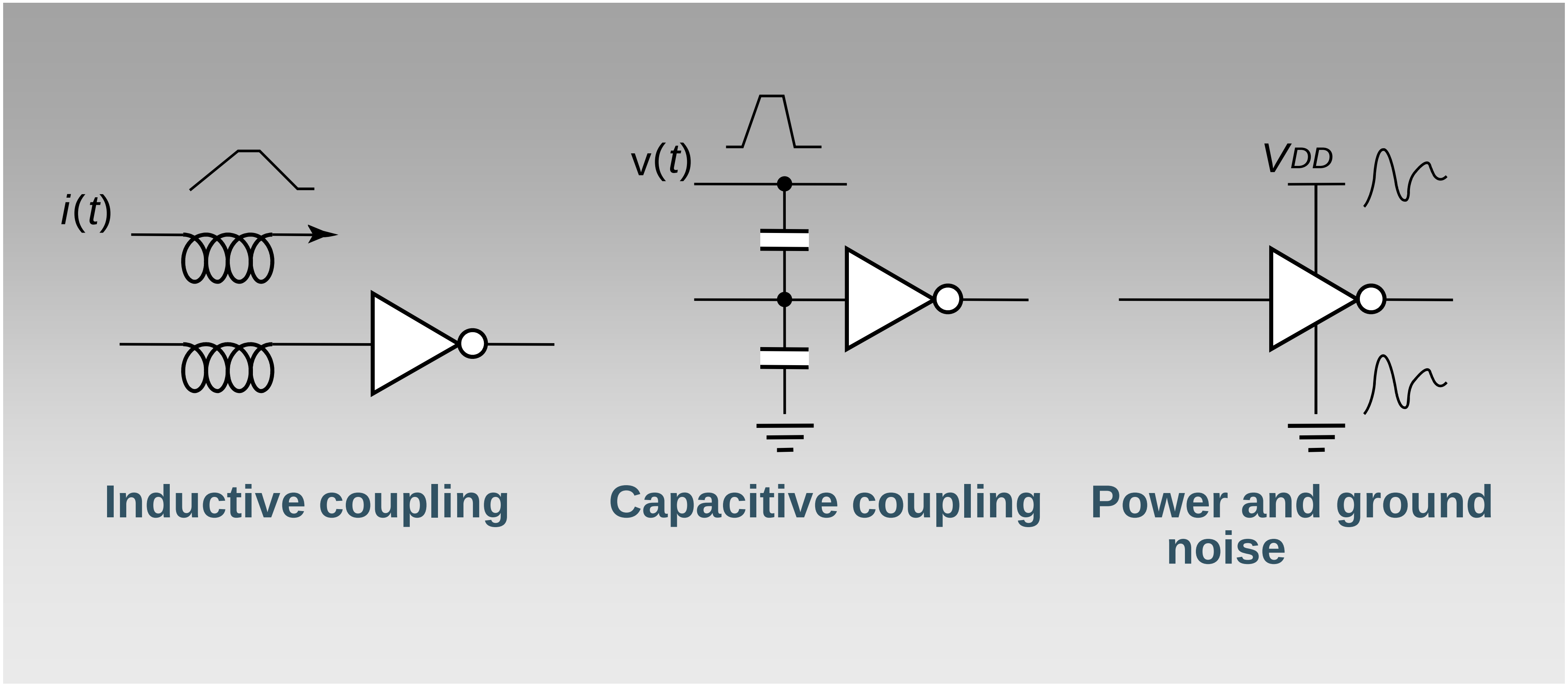
NOTE: Solve Example 1.3 , page-18 of Rabaey text book.

Some Examples (1994)

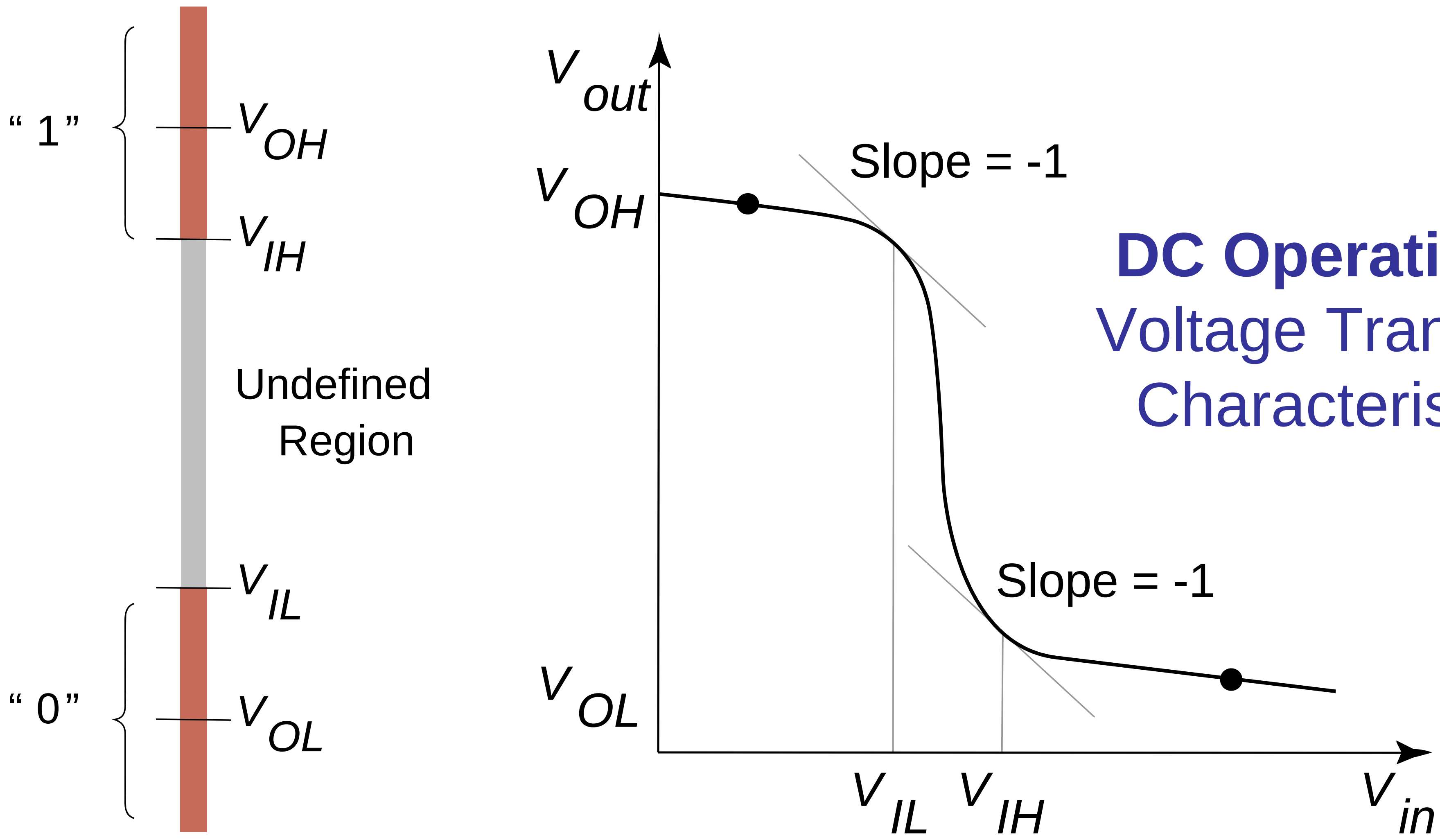
Chip	Metal layers	Line width	Wafer cost	Def./ cm^2	Area mm^2	Dies/ wafer	Yield	Die cost
386DX	2	0.90	$900	1.0	43	360	71%	$4
486 DX2	3	0.80	$1200	1.0	81	181	54%	$12
Power PC 601	4	0.80	$1700	1.3	121	115	28%	$53
HP PA 7100	3	0.80	$1300	1.0	196	66	27%	$73
DEC Alpha	3	0.70	$1500	1.2	234	53	19%	$149
Super Sparc	3	0.70	$1700	1.6	256	48	13%	$272
Pentium	3	0.80	$1500	1.5	296	40	9%	$417



Reliability—
Noise in Digital Integrated Circuits

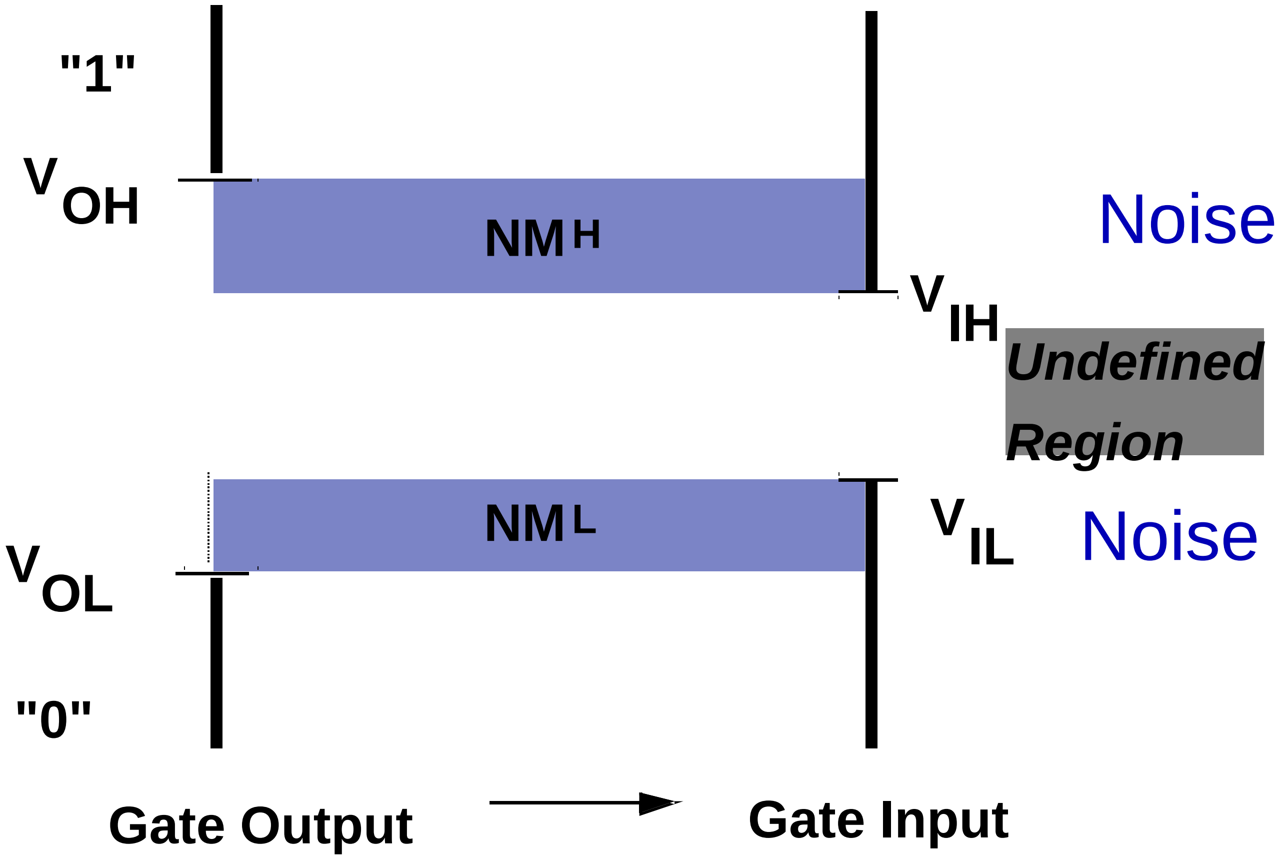


Mapping between analog and digital signals



DC Operation:
Voltage Transfer Characteristic

Definition of Noise Margins

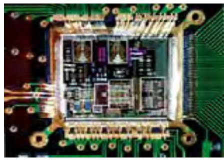


Noise margin high

Noise margin low

Noise Budget

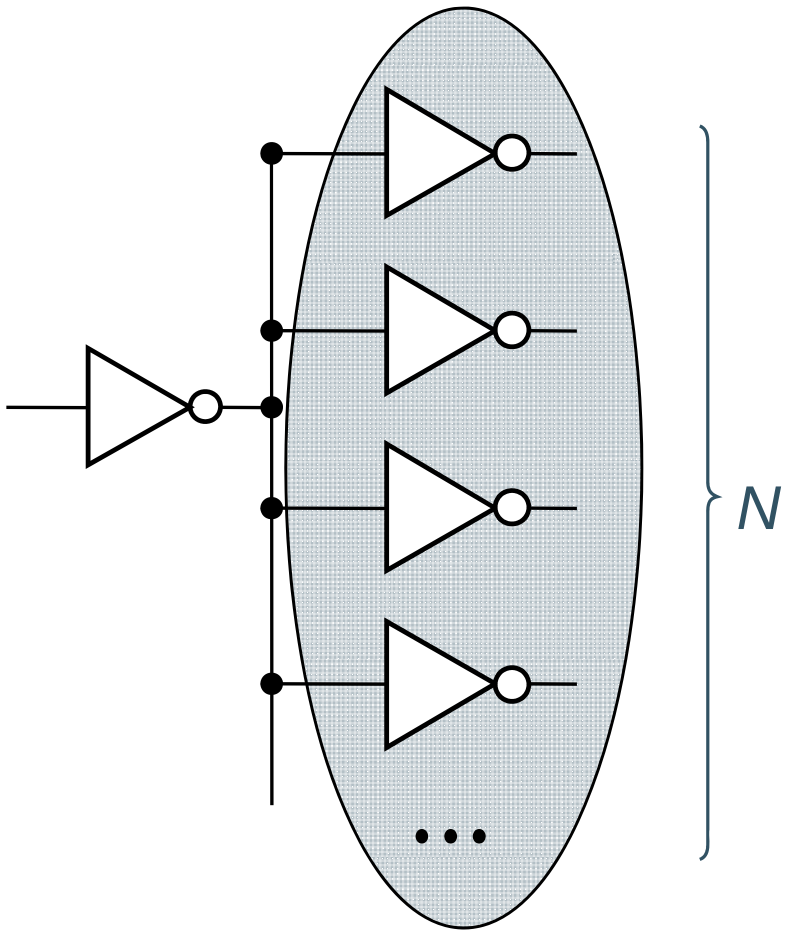
- Allocates gross noise margin to expected sources of noise
- Sources: supply noise, cross talk, interference, offset
- Differentiate between fixed and proportional noise sources

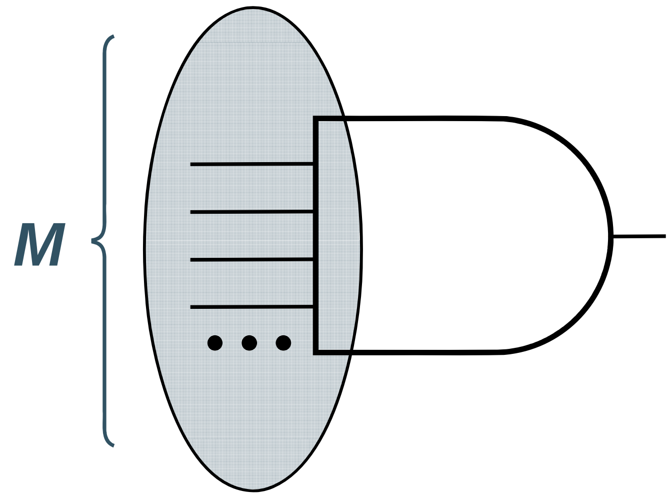


Key Reliability Properties

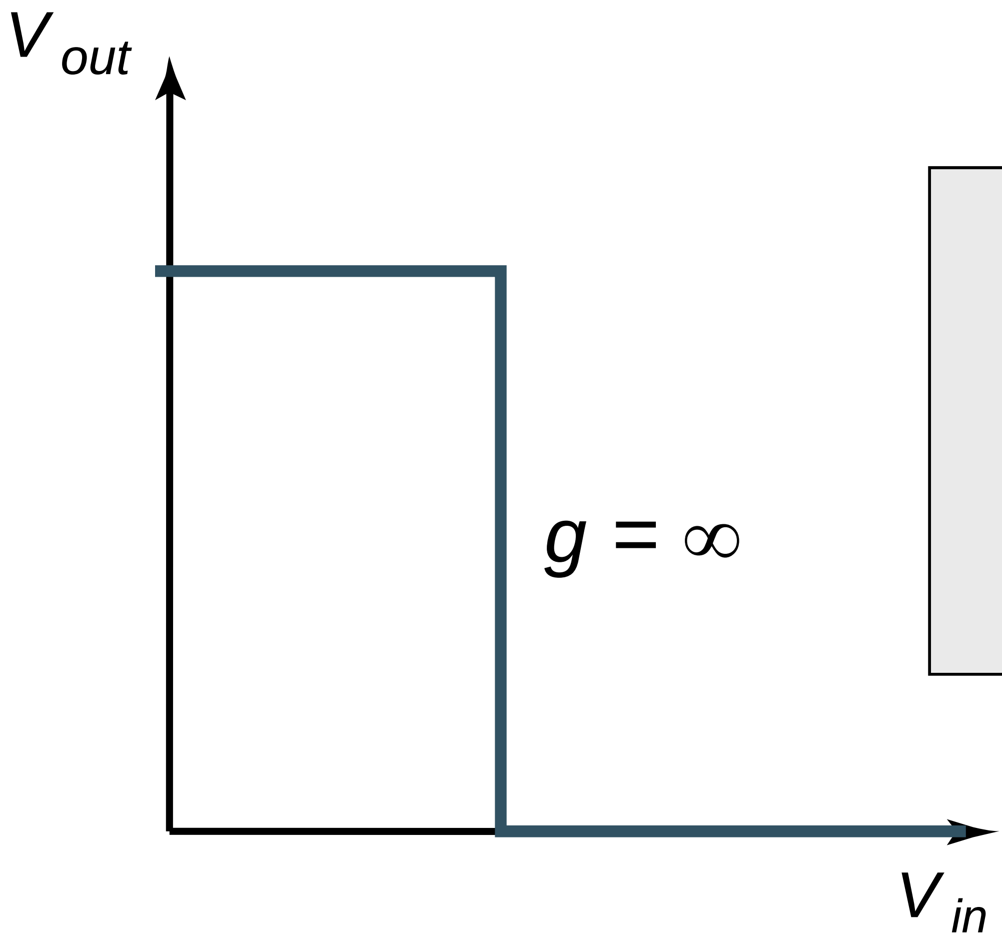
- Absolute noise margin values are deceptive
  - a floating node is more easily disturbed than a node driven by a low impedance (in terms of voltage)
- Noise immunity is the more important metric – the capability to suppress noise sources
- Key metrics: Noise transfer functions, Output impedance of the driver and input impedance of the receiver;

Fan-in and Fan-out





The Ideal Gate



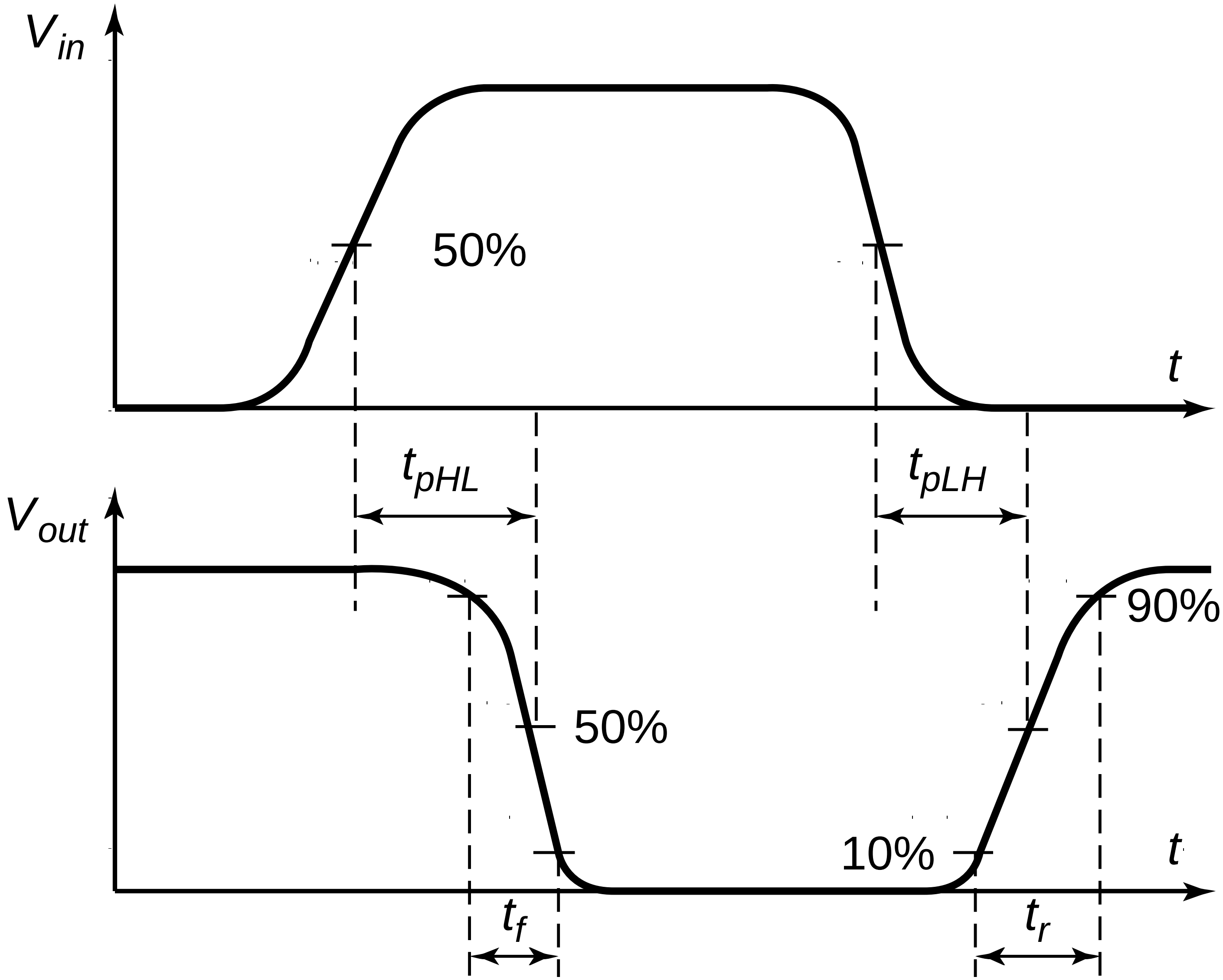
$R_i = \infty$

$R_o = 0$

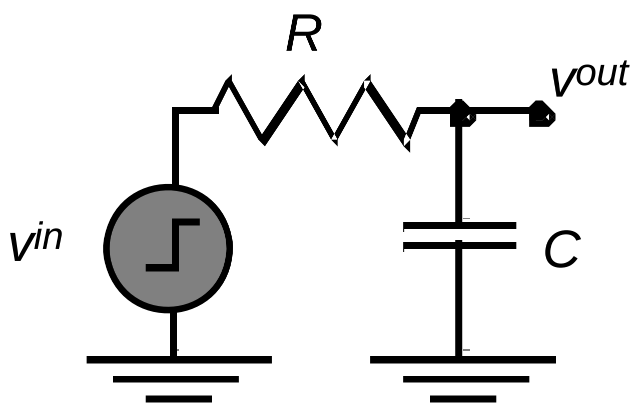
$\text{Fanout} = \infty$

$NM_H = NM_L = V_{DD}/2$

Delay Definitions



A First-Order RC Network



$$v_{out}(t) = (1 - e^{-t/\tau})\, V$$

$t_p = \ln(2)\, \tau = 0.69\, RC$

Important model – matches delay of inverter

Power Dissipation

Instantaneous power:

$$p(t) = v(t)i(t) = V_{supply}i(t)$$

Peak power:

$$P_{peak} = V_{supply}i_{peak}$$

Average power:

$$P_{ave} = \frac{1}{T}\int_t^{t+T} p(t)dt = \frac{V_{supply}}{T}\int_t^{t+T} i_{supply}(t)dt$$

Energy and Energy-Delay

Power-Delay Product (PDP) =

E = Energy per operation = $P_{av} \times t_p$

Energy-Delay Product (EDP) =

quality metric of gate = $E \times t_p$

Summary

- Digital integrated circuits have come a long way and still have quite some potential left for the coming decades
- Some interesting challenges ahead
  - Getting a clear perspective on the challenges and potential solutions is the purpose of this book
- Understanding the design metrics that govern digital design is crucial
  - Cost, reliability, speed, power and energy dissipation