

# Lecture 2: Overview

## CSCE 5730

## Digital CMOS VLSI Design

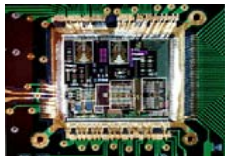
**Instructor:** Saraju P. Mohanty, Ph. D.

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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

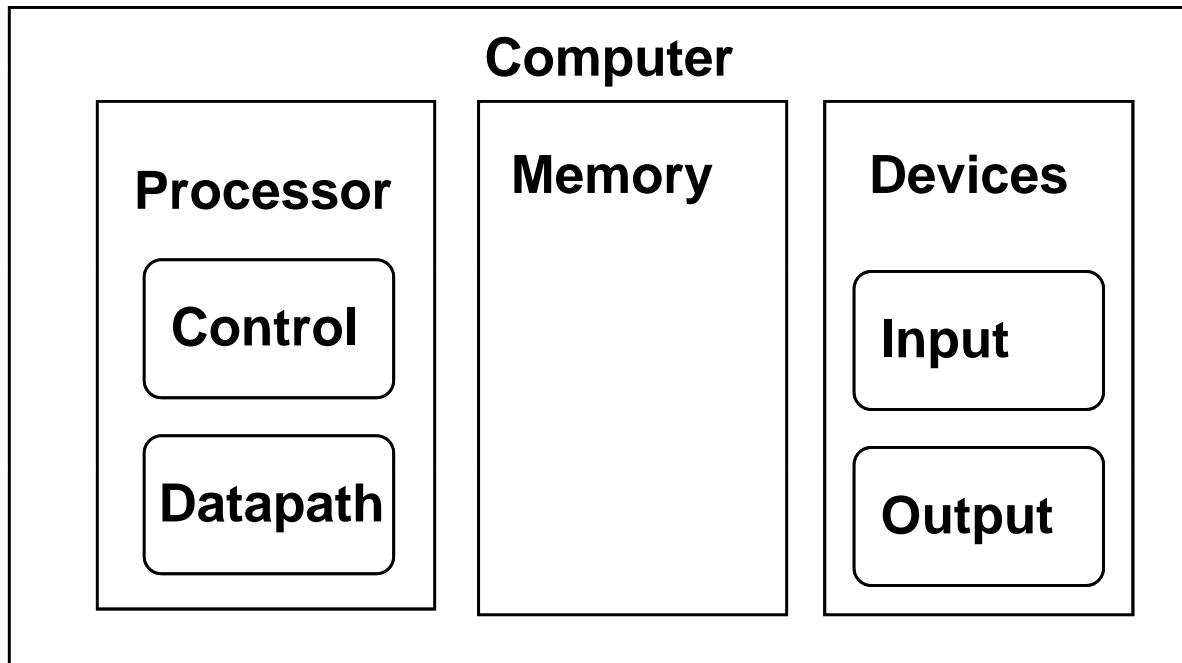


# Different Types and Forms of Computer

- 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



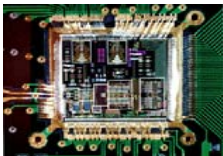
# What is a microprocessor ?

- **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).



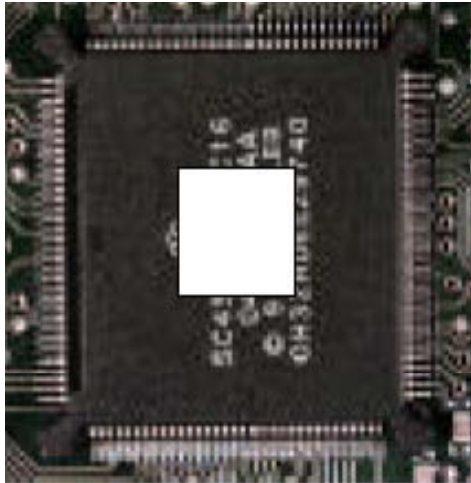
# What is an Integrated Circuit ?

- 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.

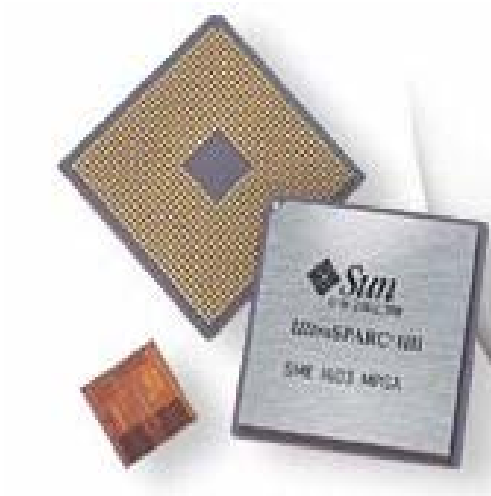




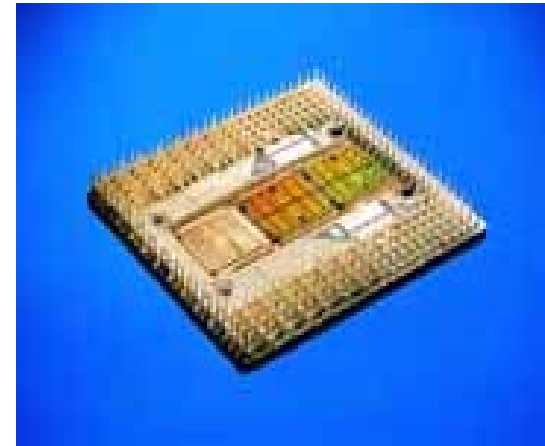
# How does a microprocessor look?



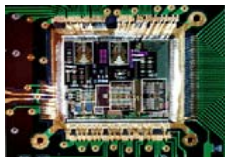
(1) ASIC



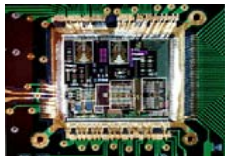
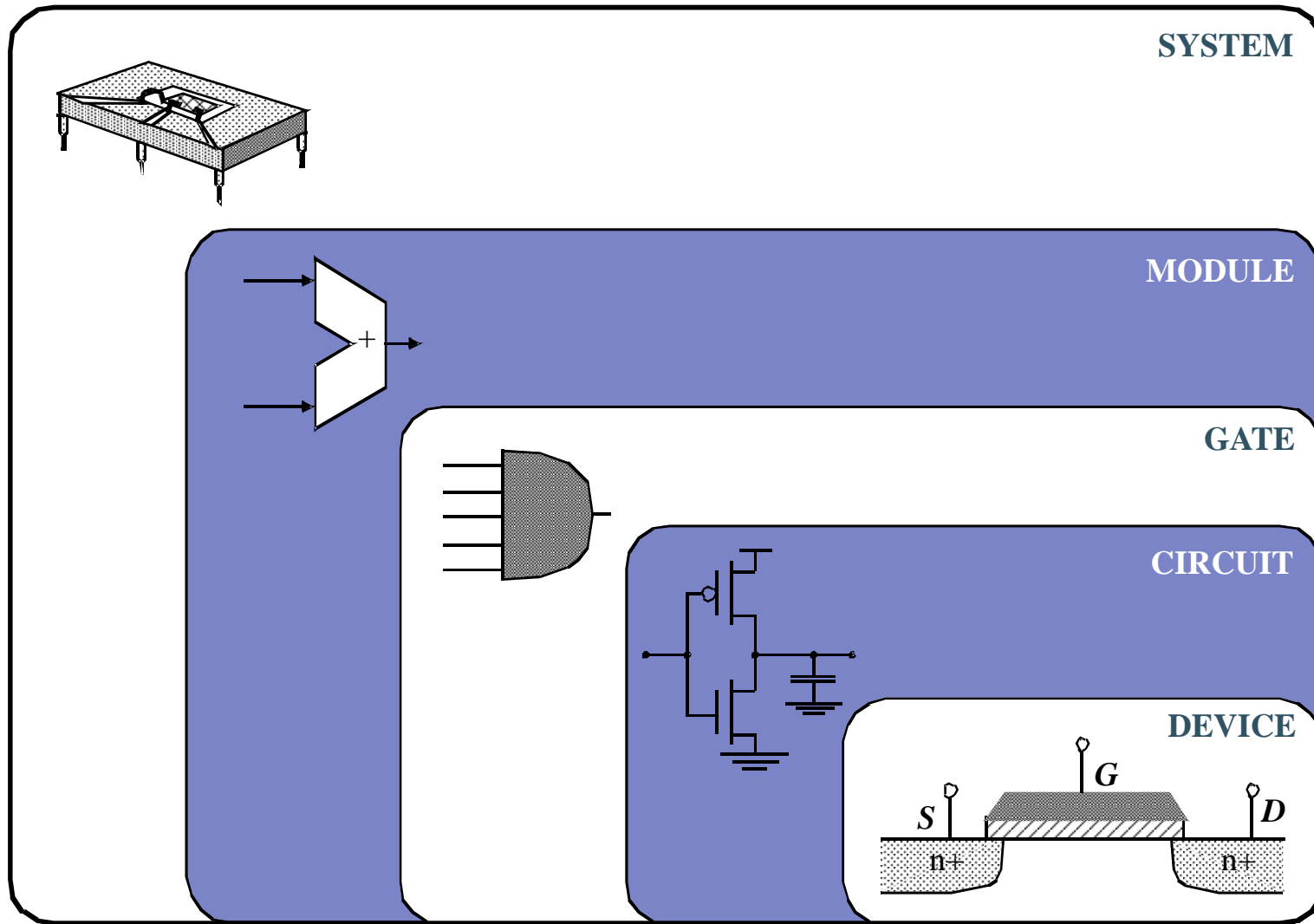
(2) Sun UltraSparc



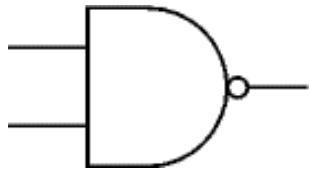
(3) PentiumPro



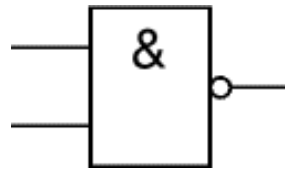
# Design Abstraction Levels



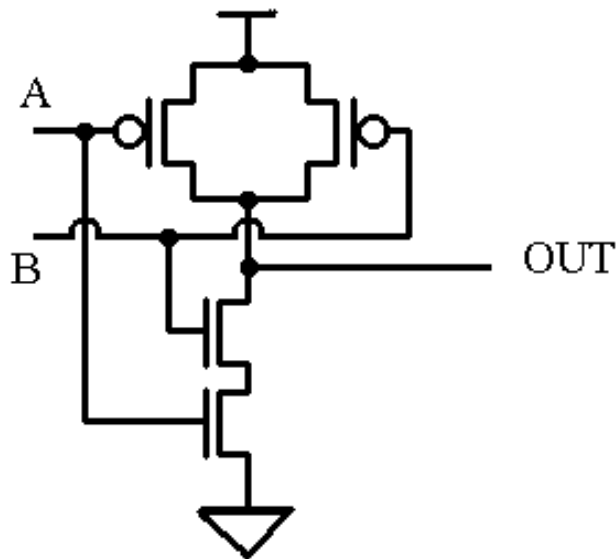
# Digital Circuits : Logic to Device



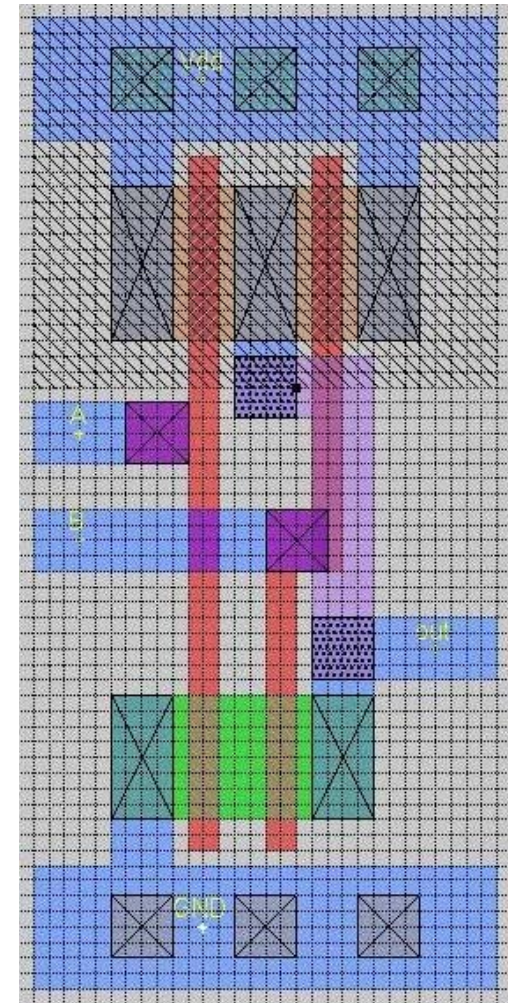
**(NAND Gate)**



**(IEC Symbol)**



**(Transistor Diagram)**



**(Layout Diagram)**

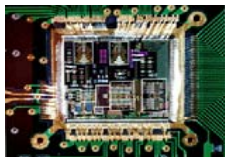


# Historical Development



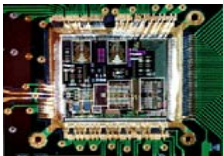
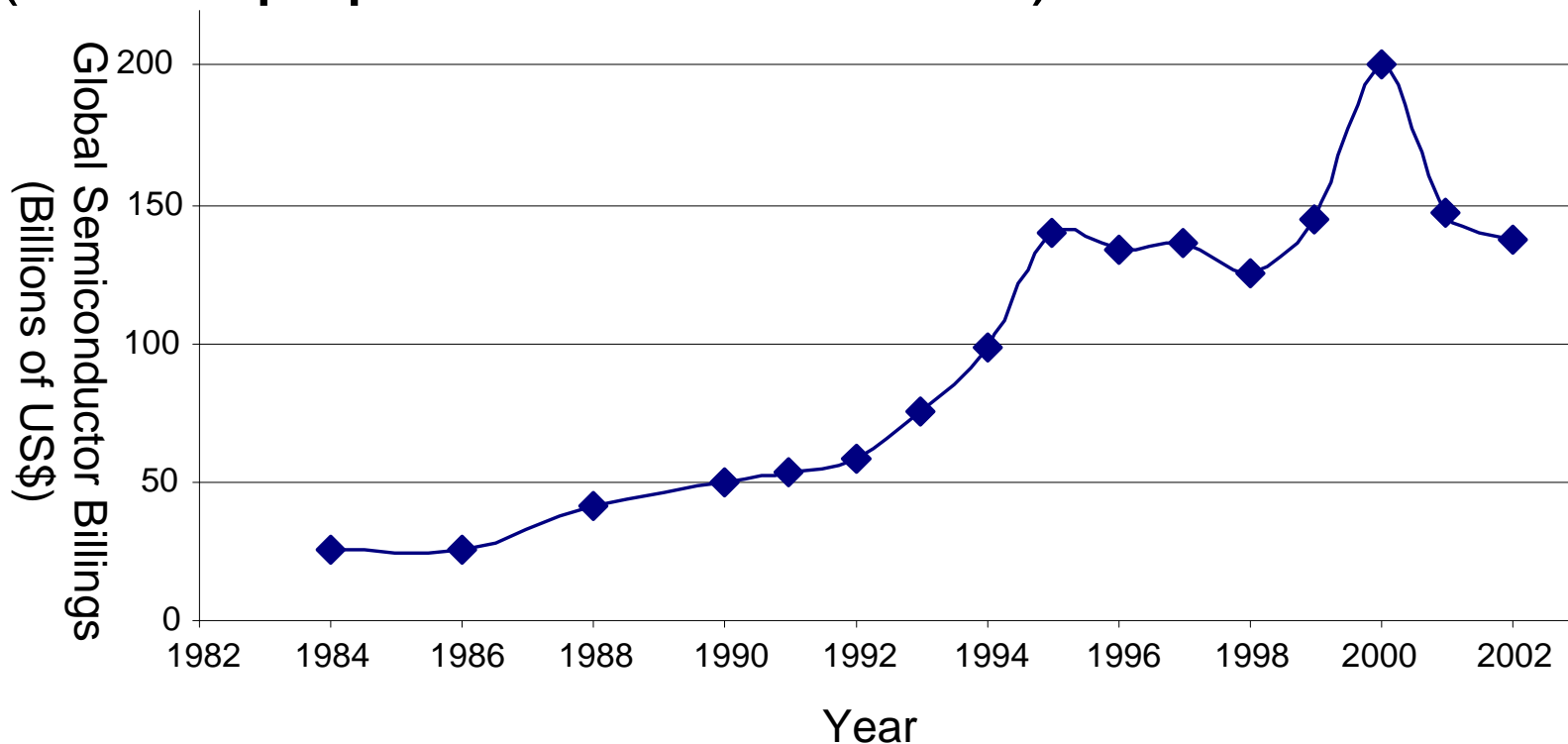
# VLSI Technology: Highest Growth in History

- 1958: First integrated circuit
  - Flip-flop using two transistors
  - Built by Jack Kilby at Texas Instruments
- 2003
  - Intel Pentium 4  $\mu$ processor (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



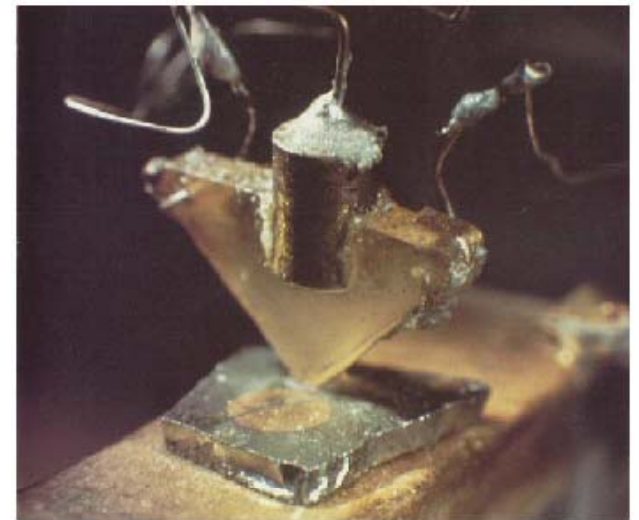
# VLSI Industry : Annual Sales

- $10^{18}$  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<sup>th</sup> century  
Large, expensive, power-hungry, unreliable
- 1947: first point contact transistor
  - John Bardeen and Walter Brattain at Bell Labs
  - Earned Nobel prize in 1956





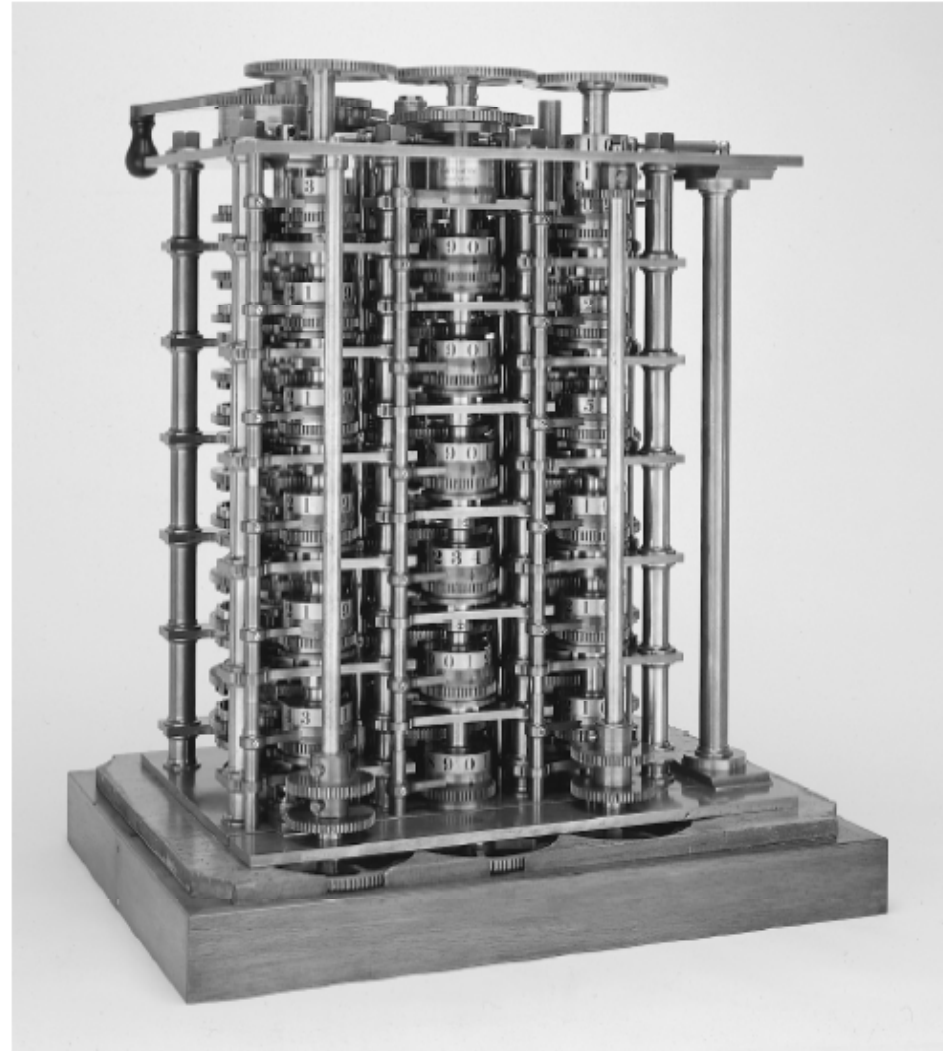
# Transistor Types

- 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

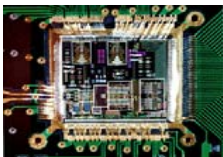
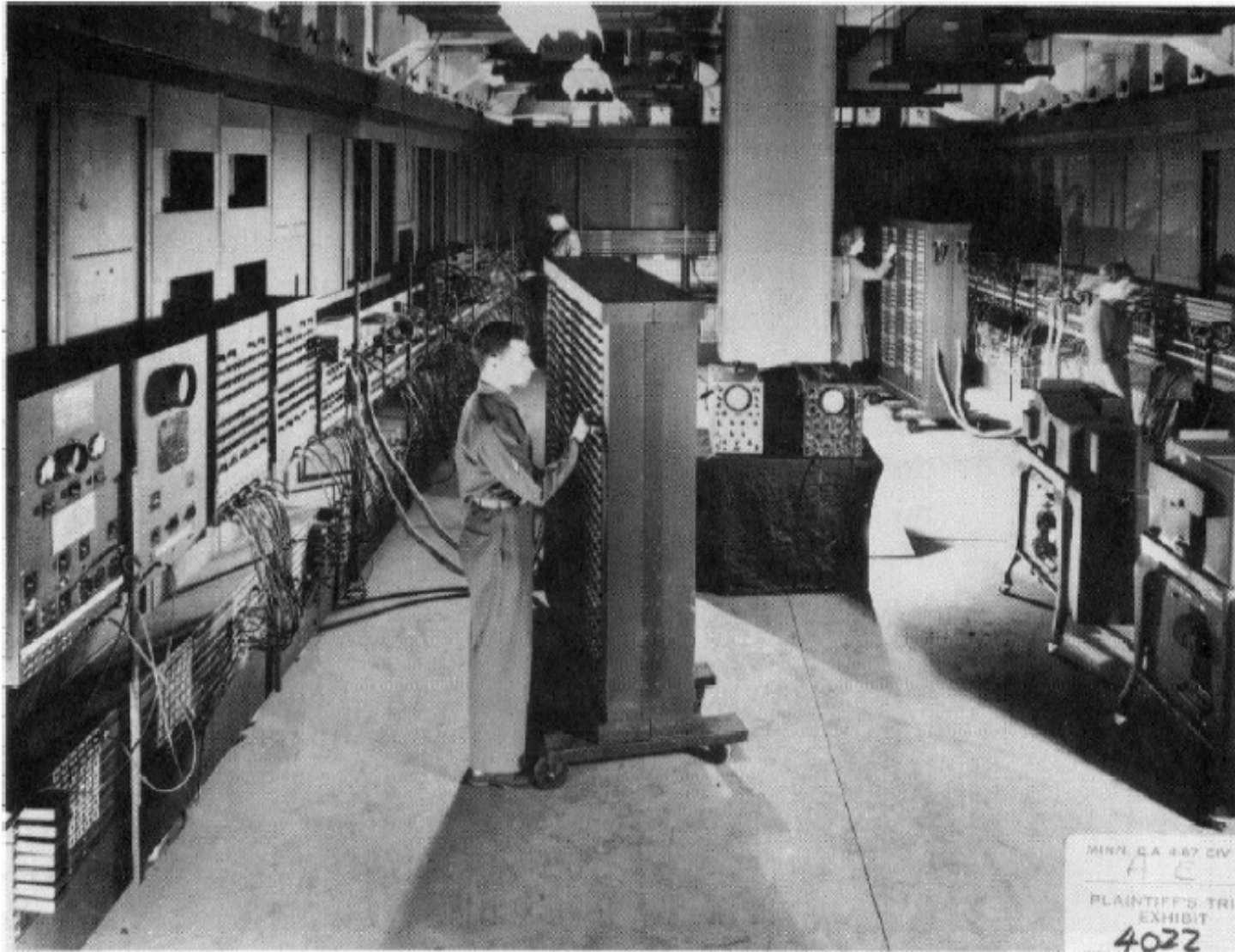




# The Babbage Difference Machine in 1832

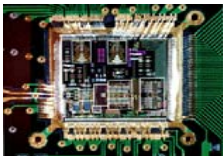
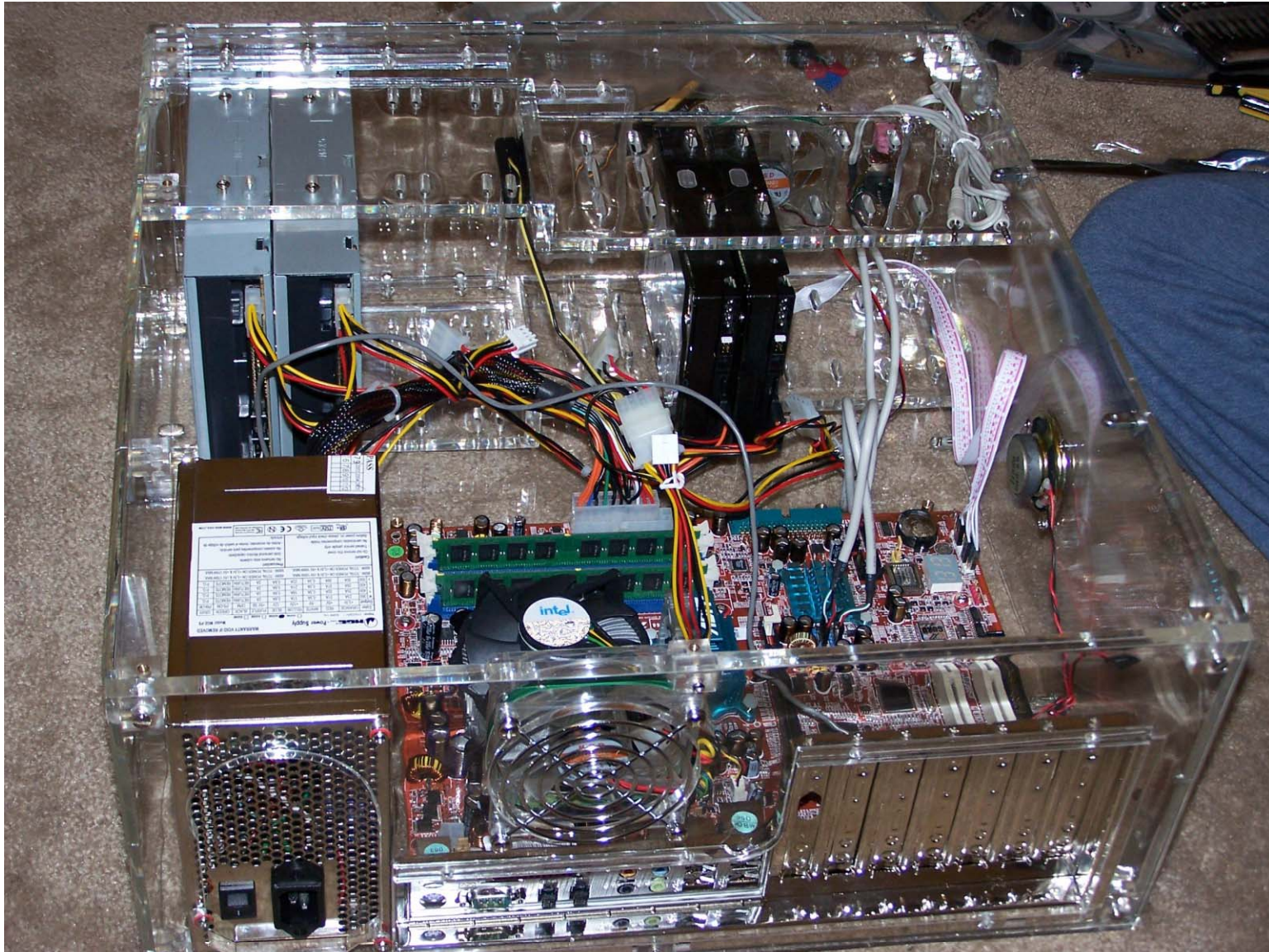


# The First Electronic Computer in 1946 (ENIAC)



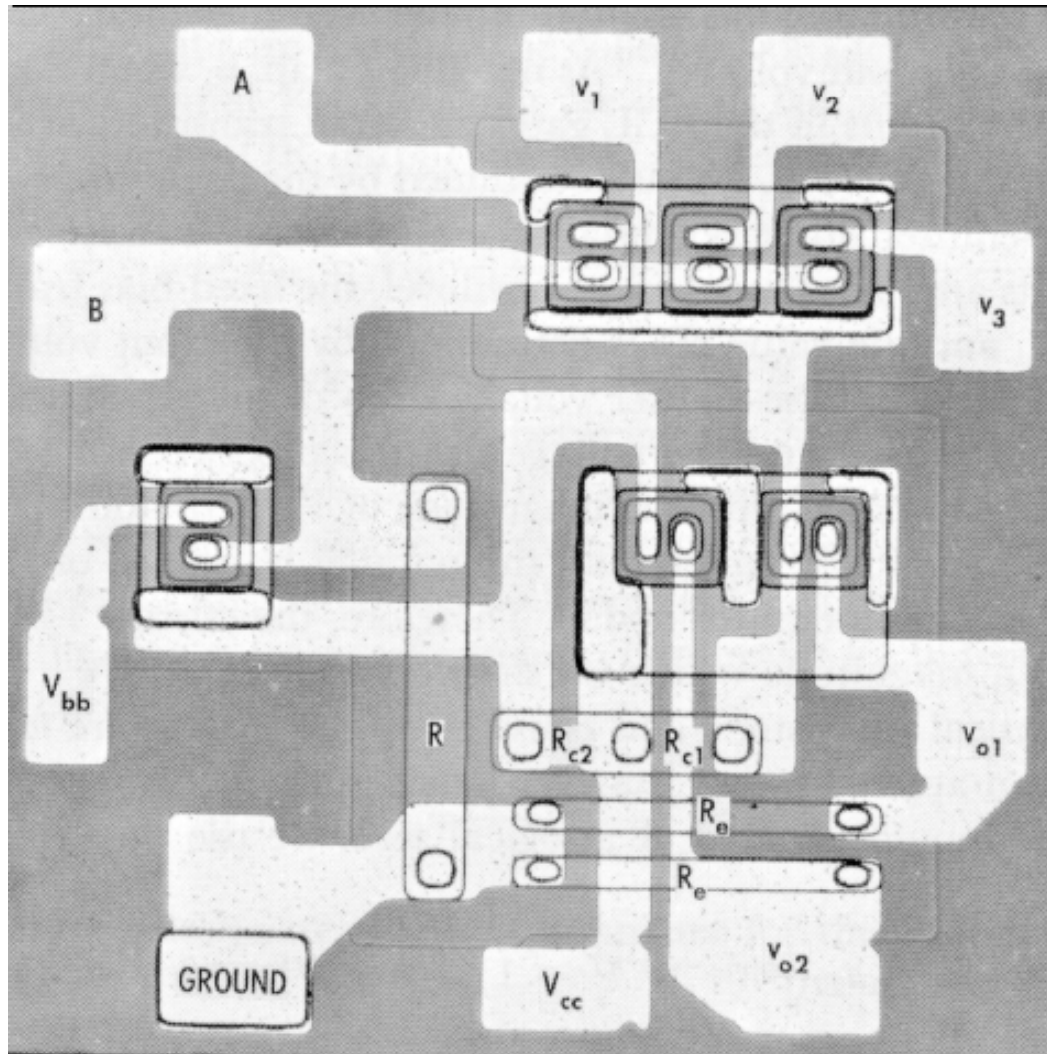


# How a Home PC Looks Today??





# The First Integrated Circuits

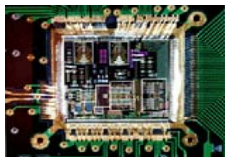
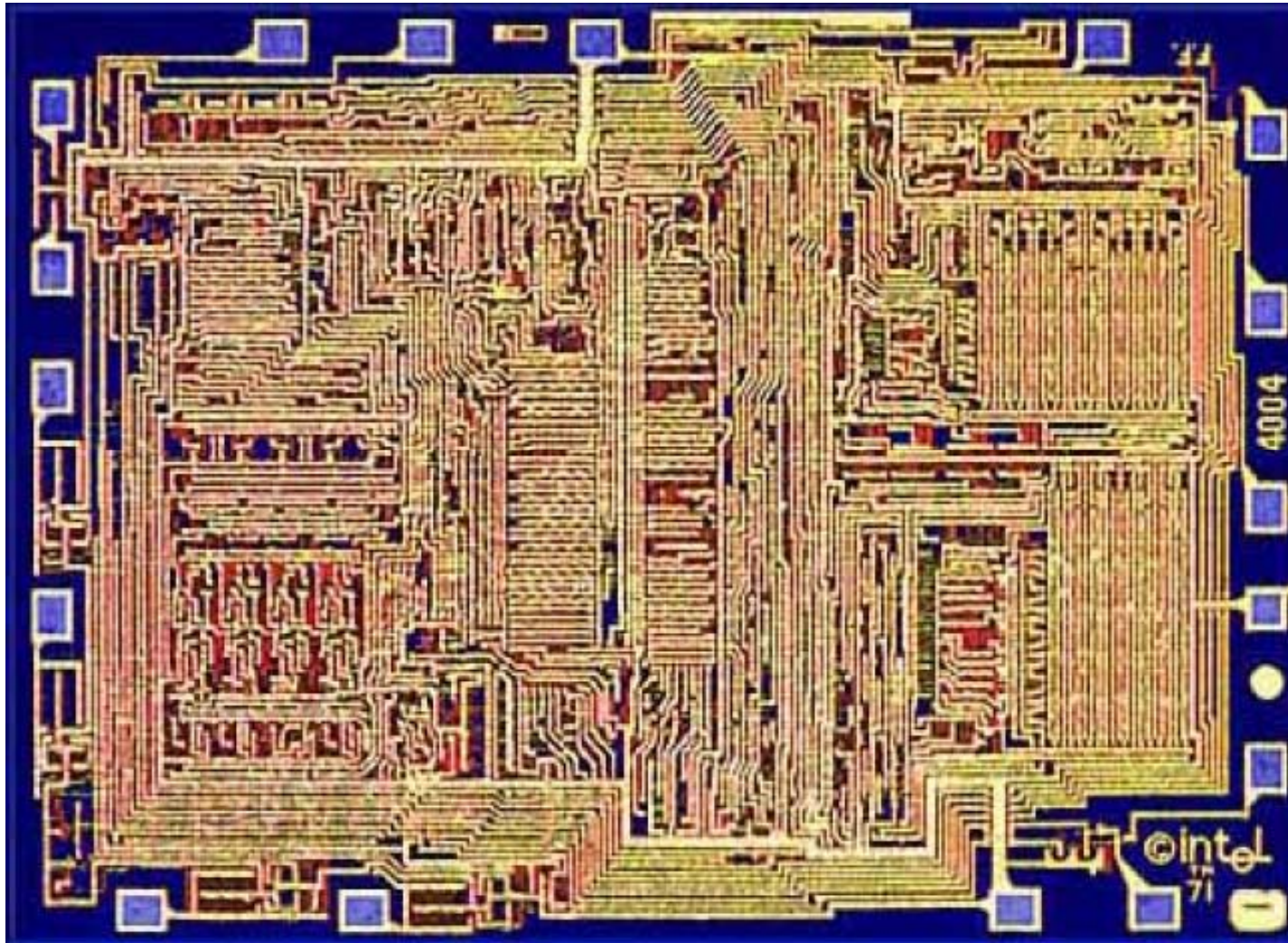


*Bipolar logic  
1960's*

ECL 3-input Gate  
Motorola 1966

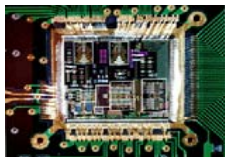
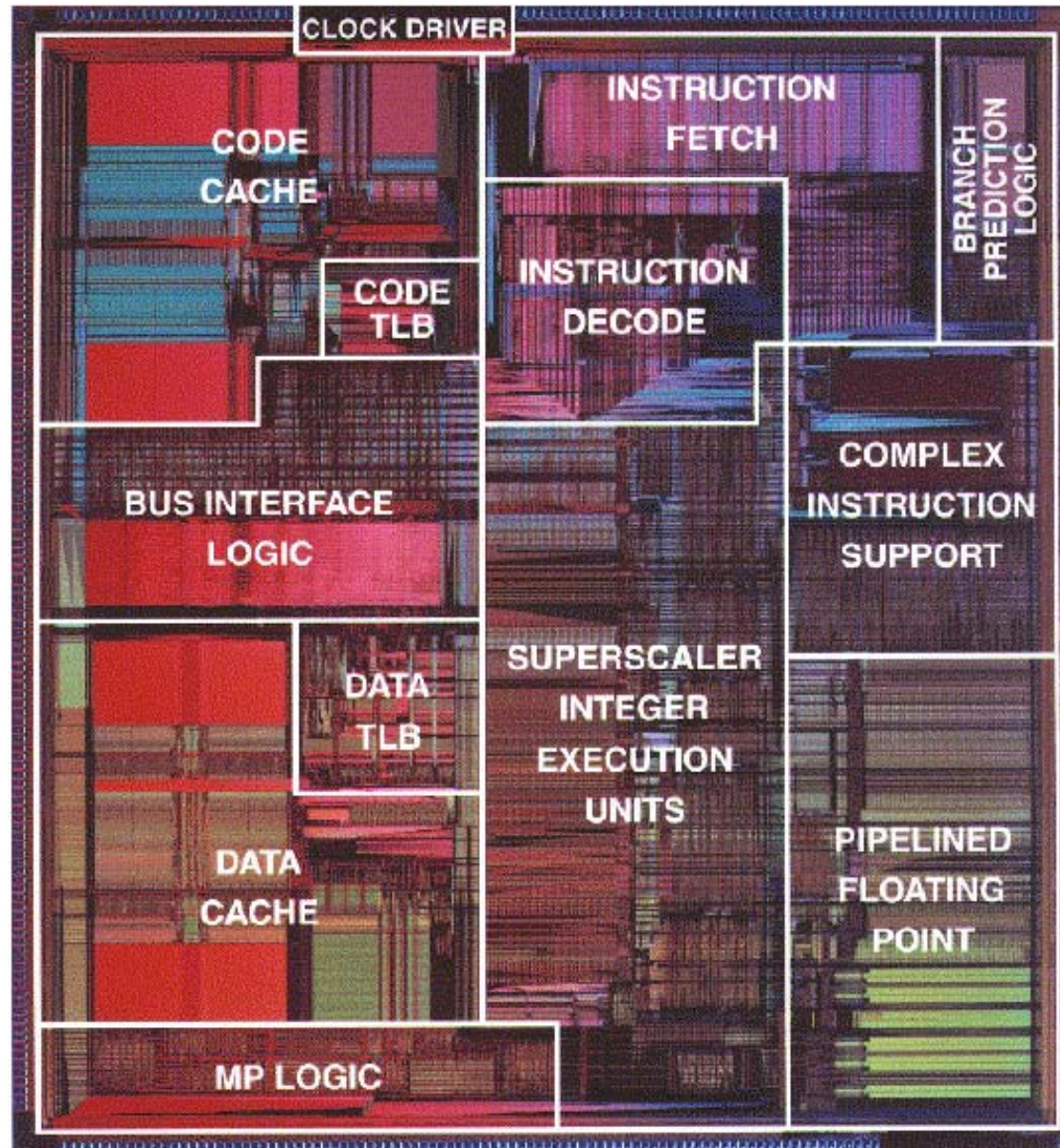


# Intel 4004 : 2.3K Transistors (1971)

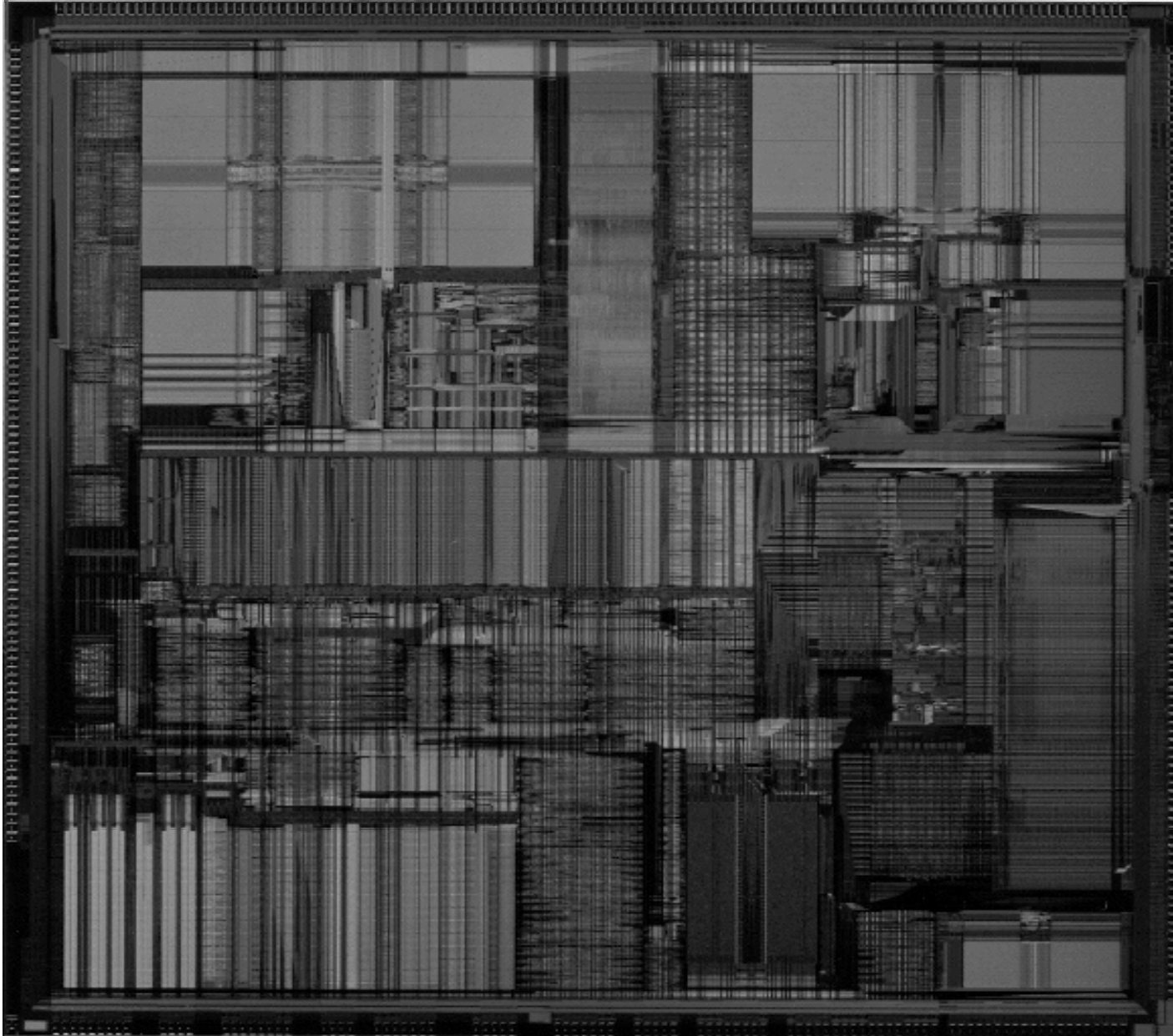




# Pentium : 3.1M Transistors (1993)

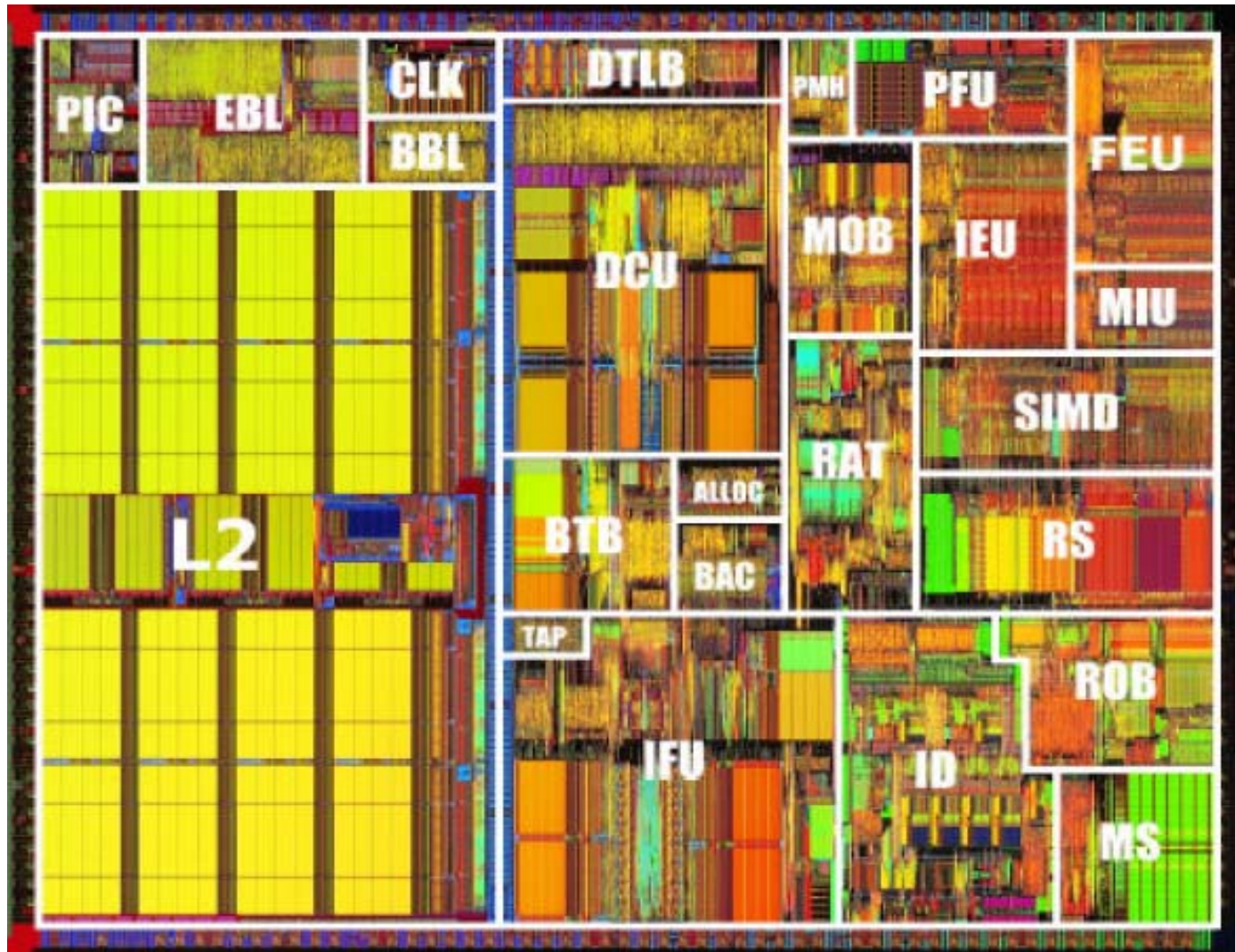


# Pentium II : 7.5M Transistors (1997)



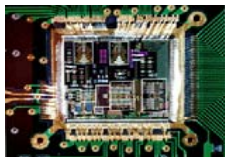
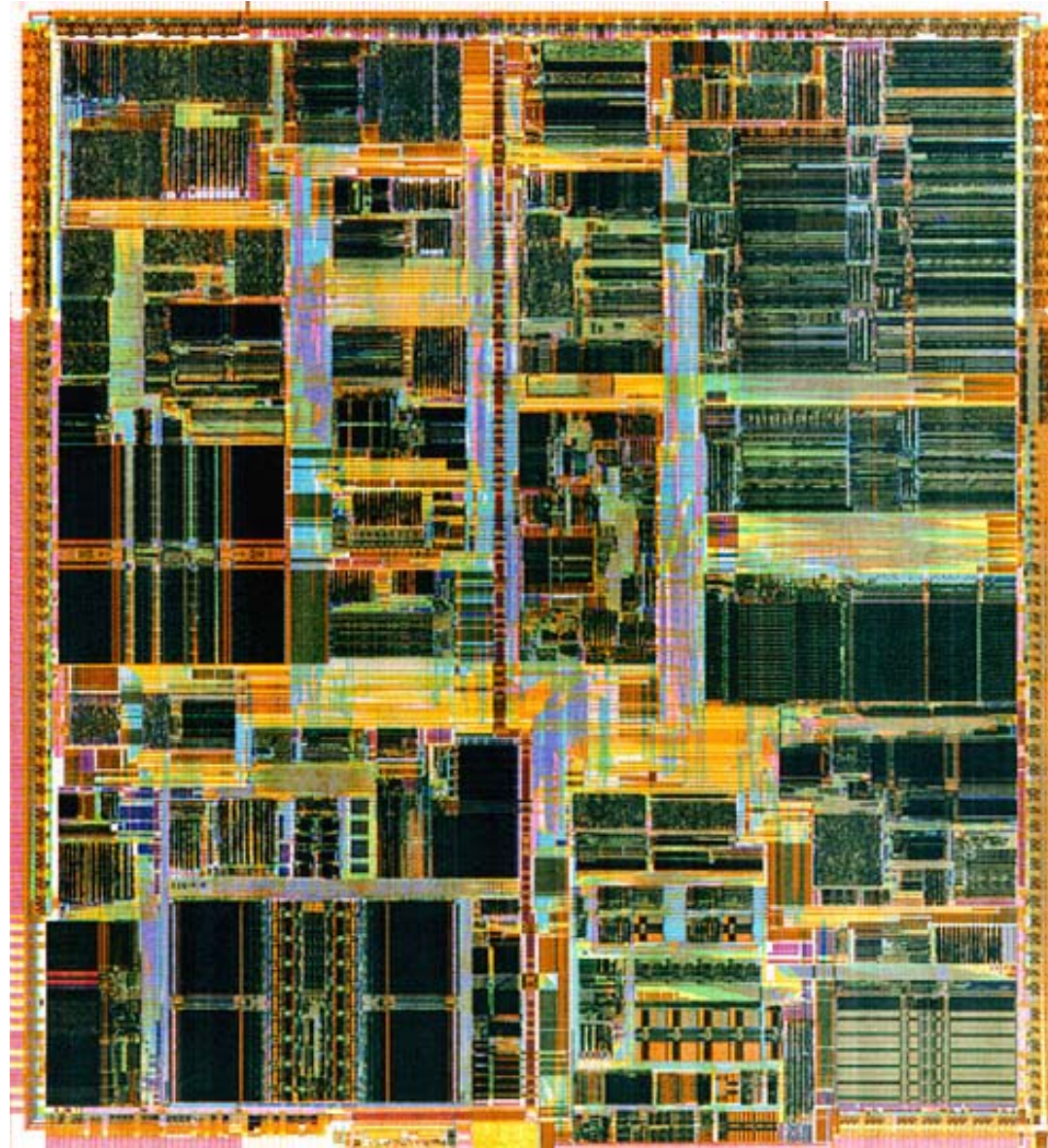


# Pentium III : 28.1M Transistors (1999)





# Pentium IV : 52M Transistors (2001)



# 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.

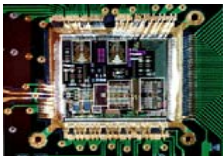
- Transistor count of a chip
- Operating frequency of a chip
- Power consumption of a chip
- Power density in a chip
- Size of a device used in chip

**NOTE:** Chip is informal name for IC.

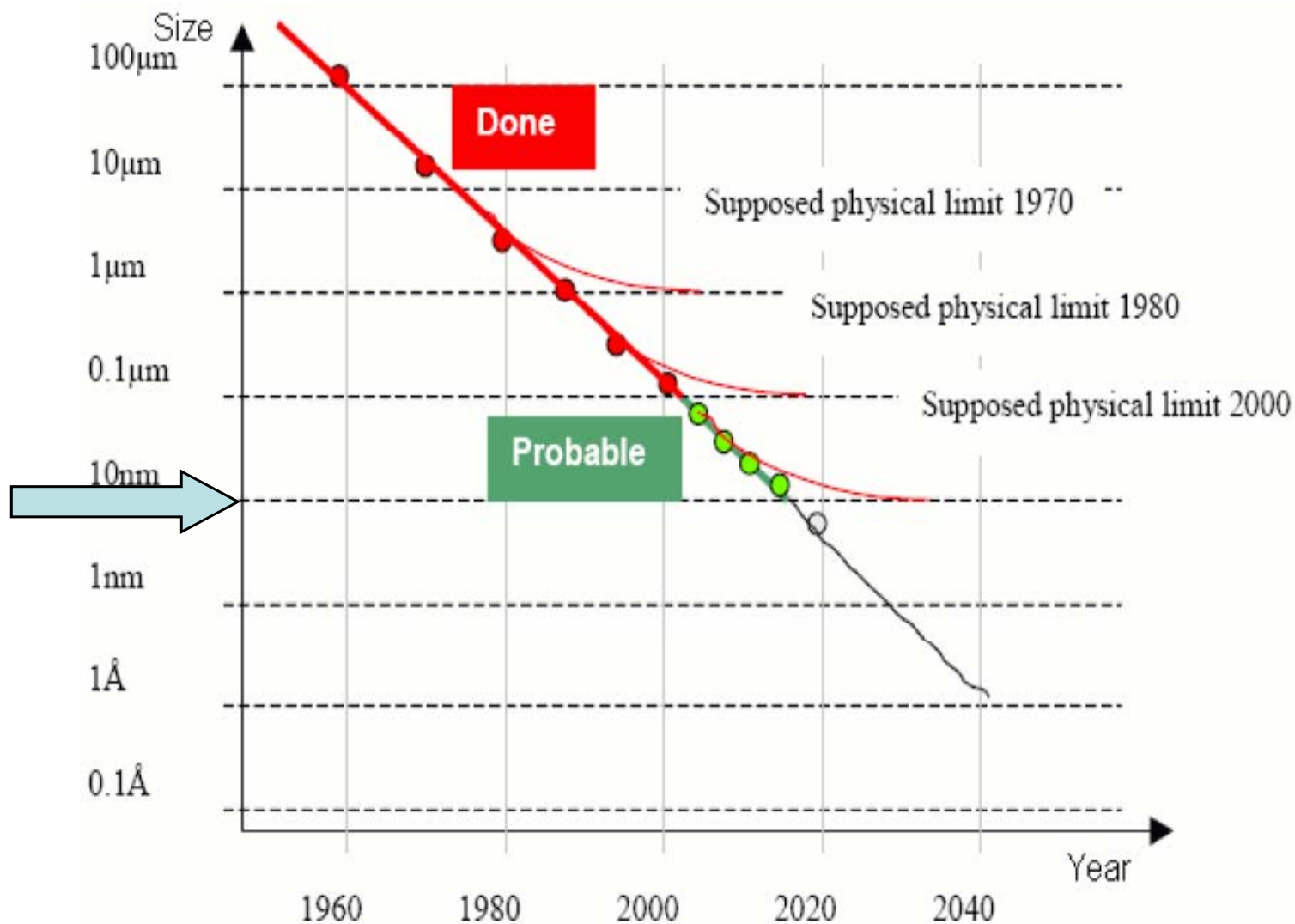


# Moore's Law

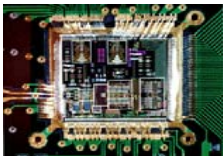
- 1965: Gordon Moore plotted transistor on each chip
  - Transistor counts have doubled every 26 months
- Many other factors grow exponentially
  - clock frequency
  - processor performance



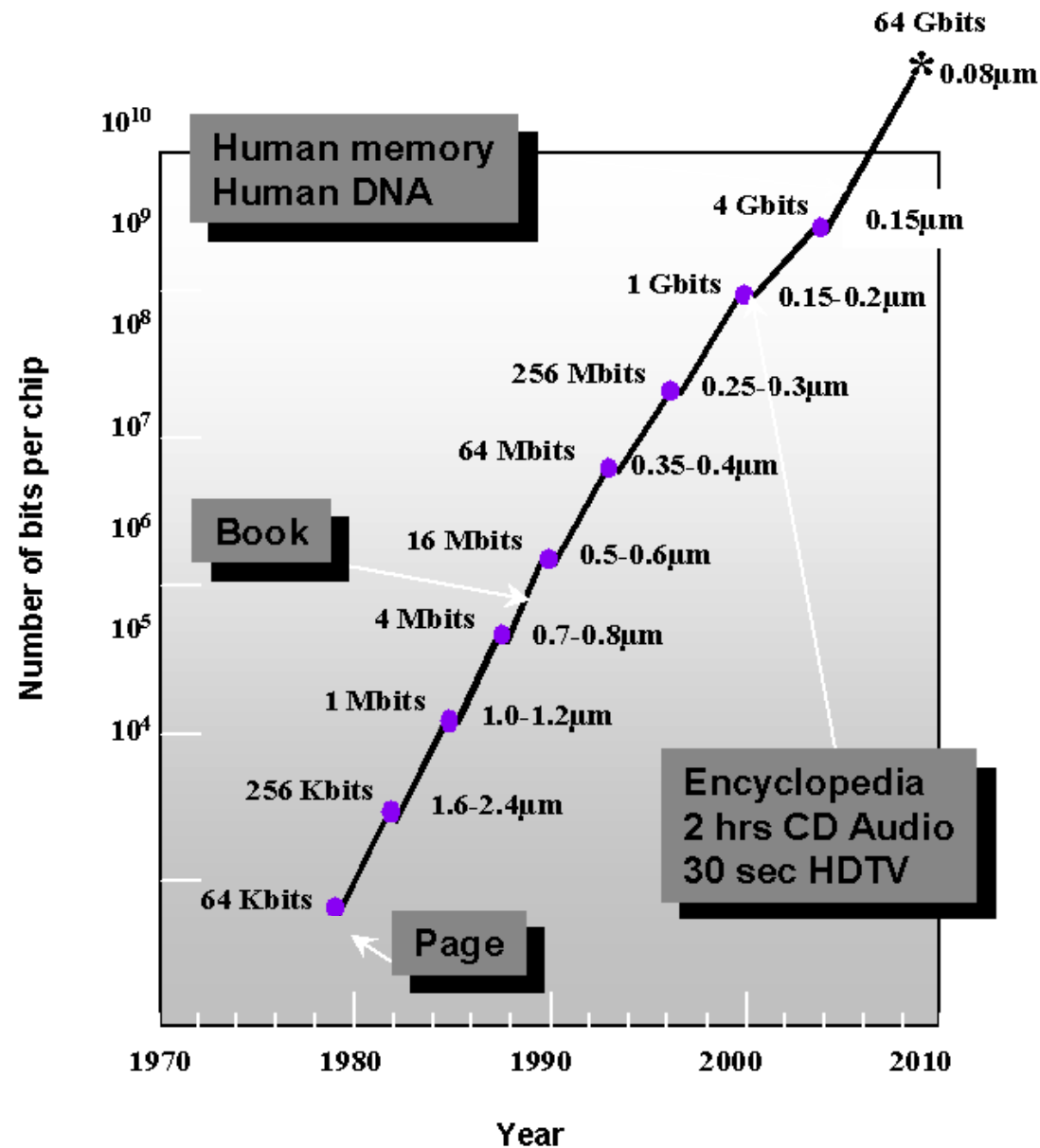
# Technology Scaling Trend



Source: Bendhia 2003



# Evolution in Complexity



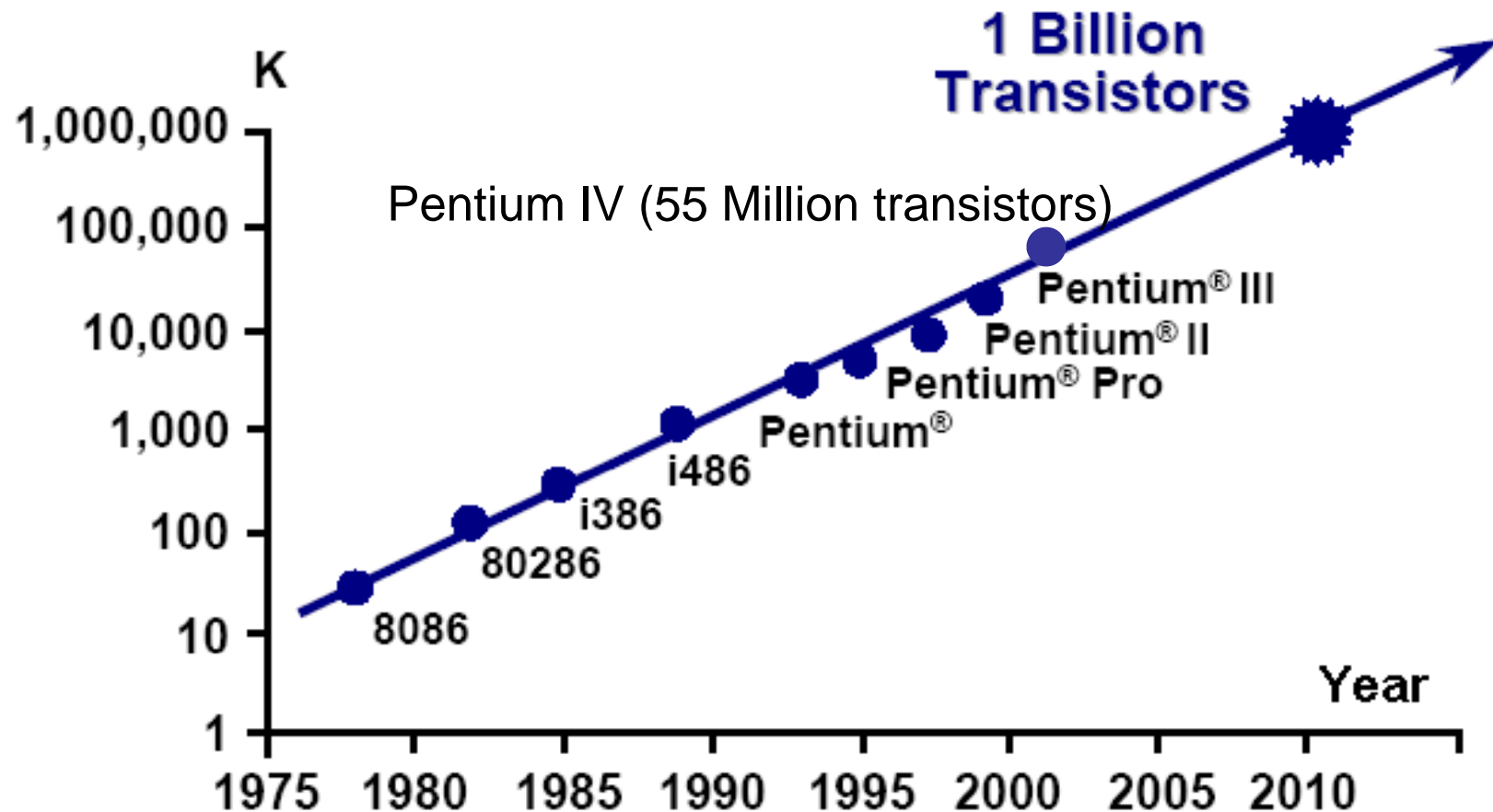


# Why Scaling?

- 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

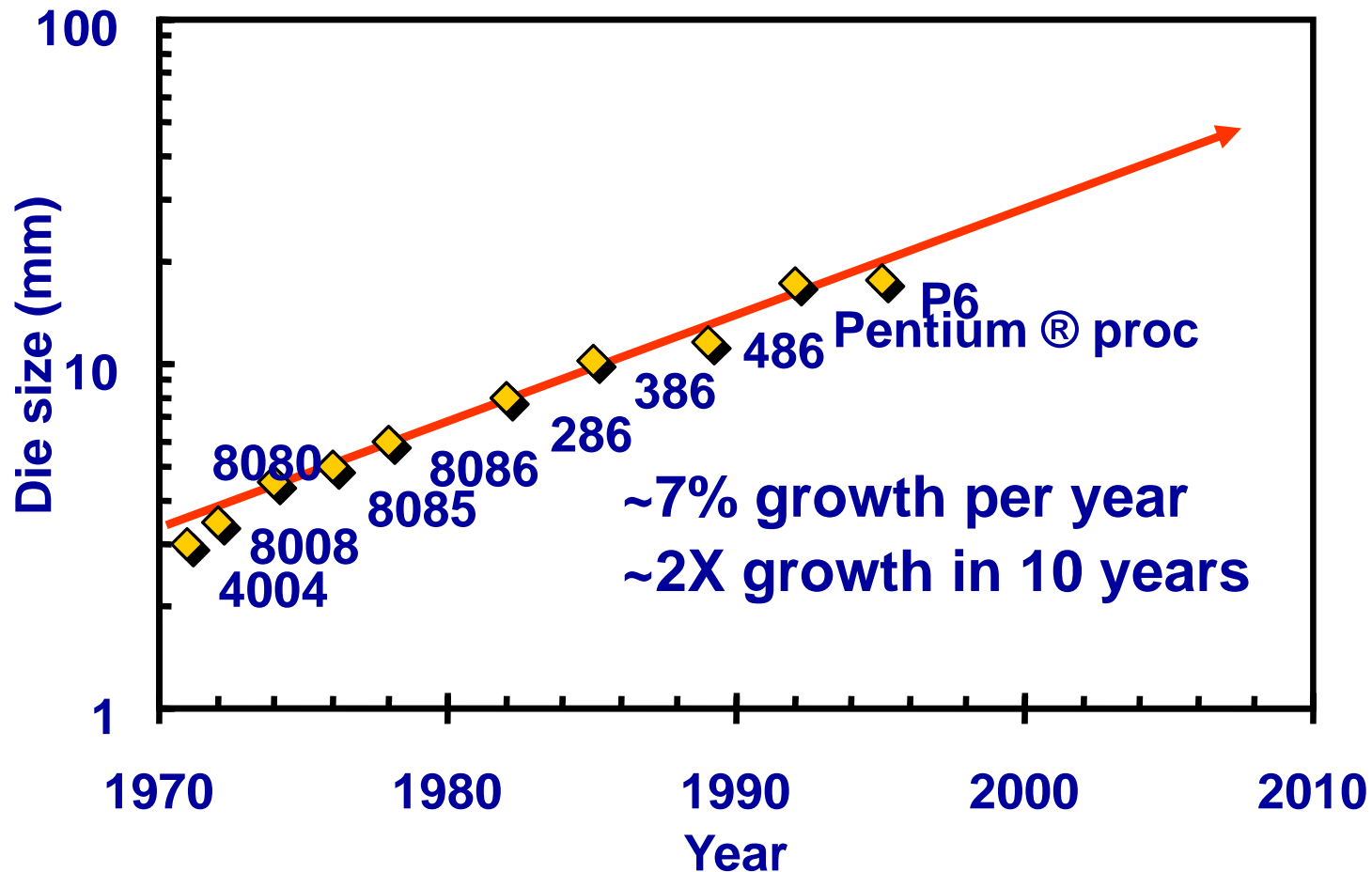


**Transistors on Lead Microprocessors double every 2 years**





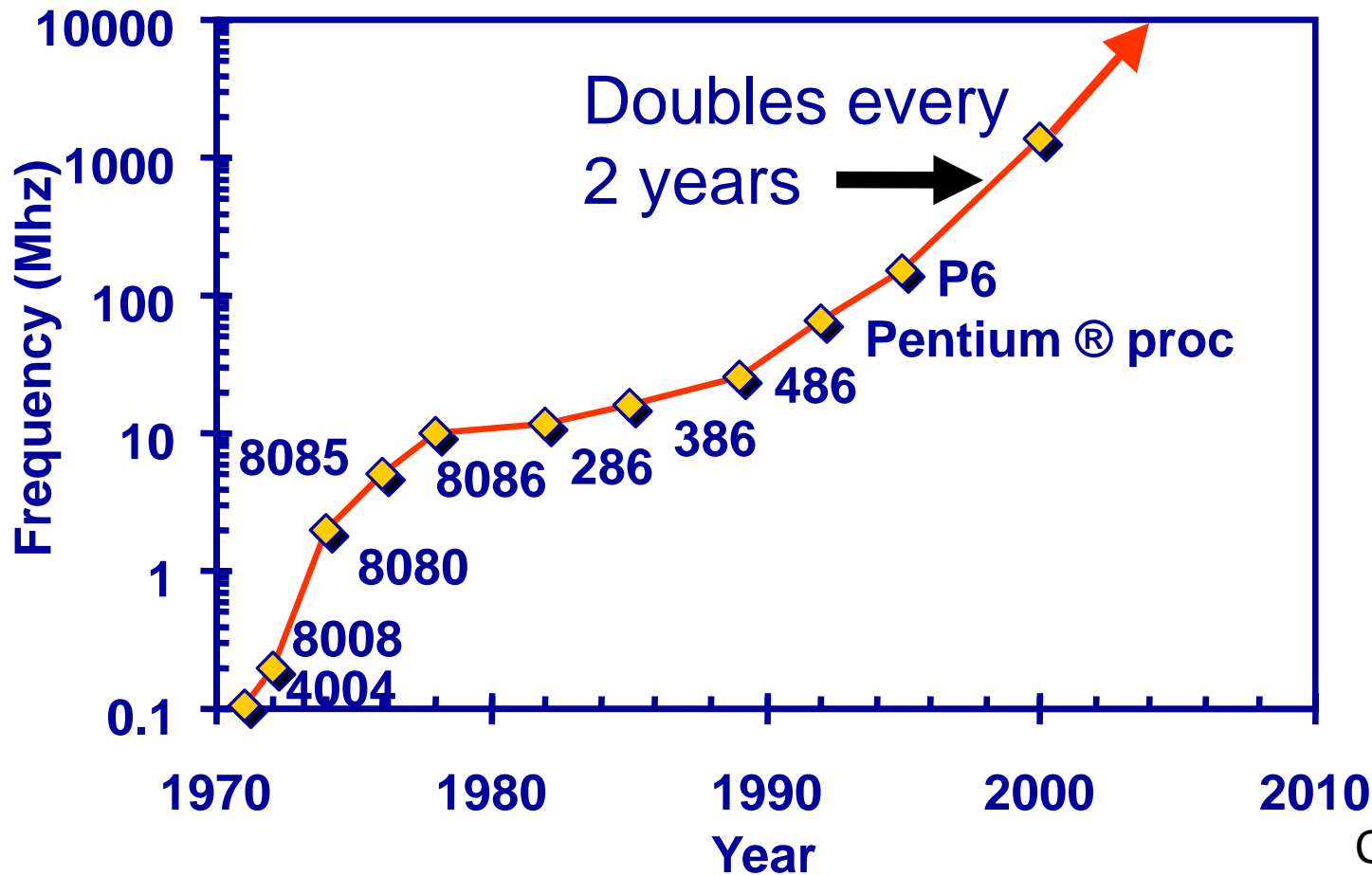
# Die Size Growth



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



# Increase in Operating Frequency

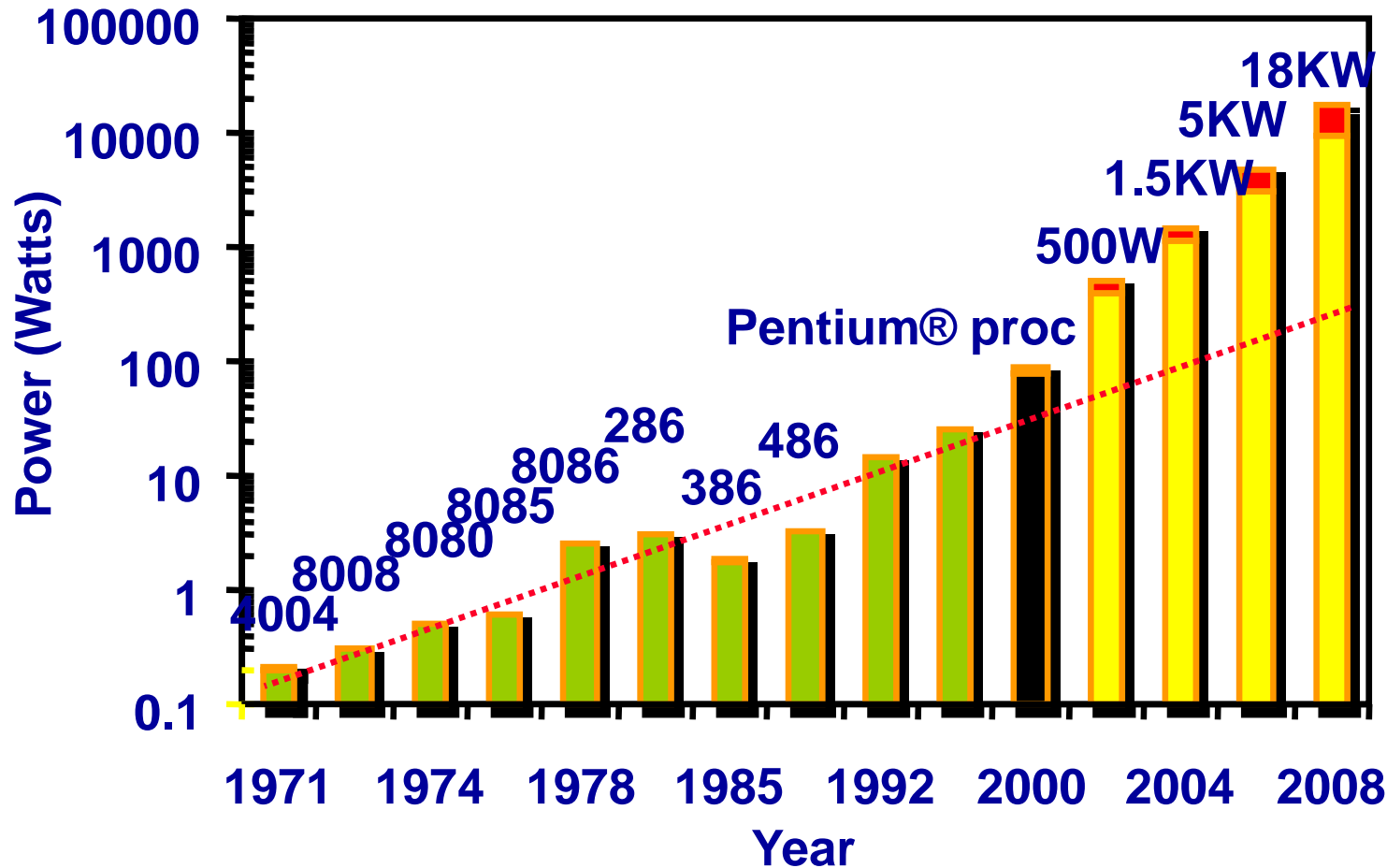


Courtesy, Intel

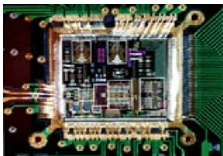
**Lead Microprocessors frequency doubles every 2 years**



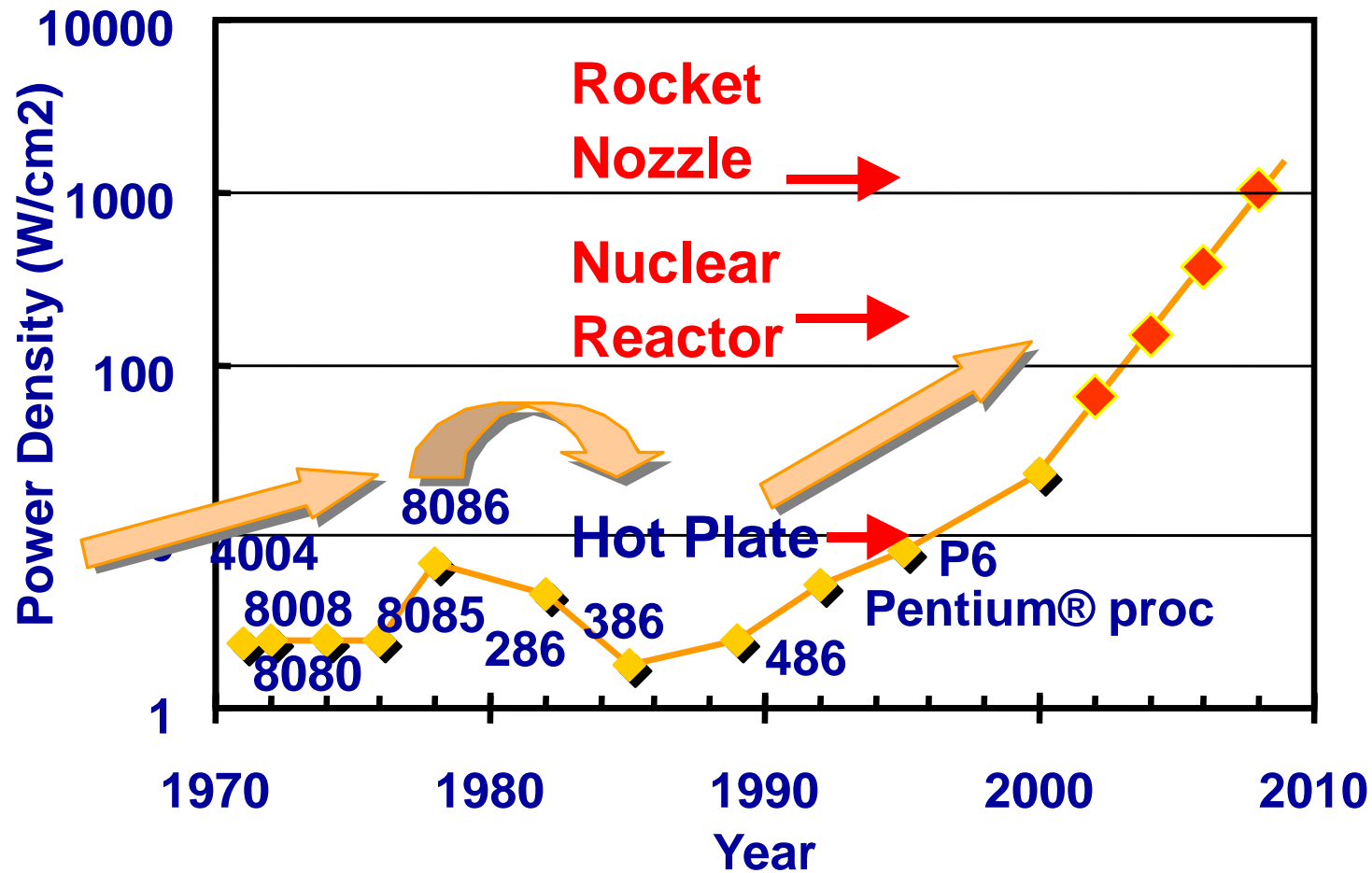
# Power will be a major problem



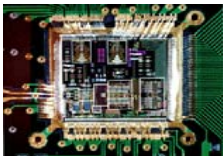
Power delivery and dissipation will be prohibitive



# 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”

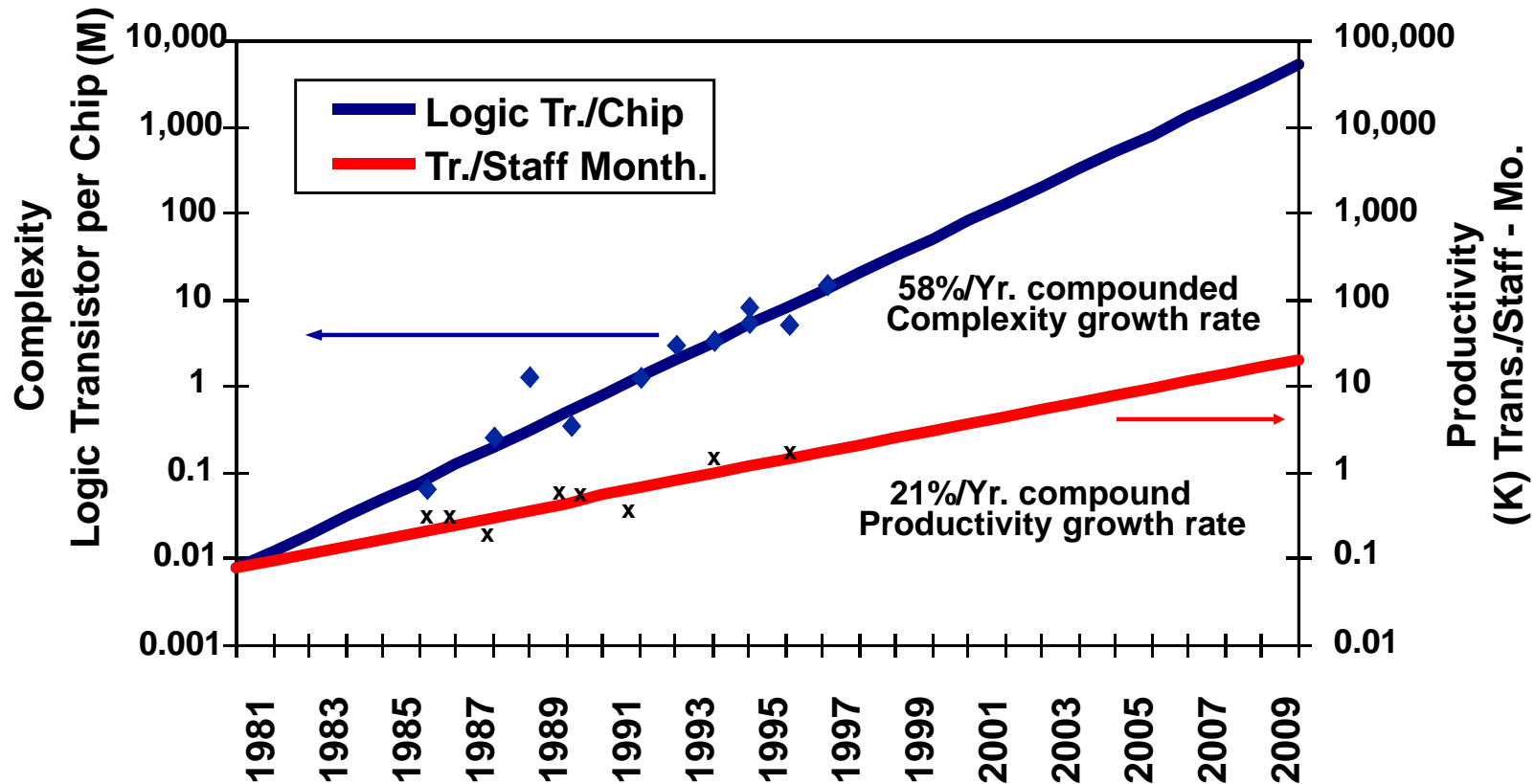
- Time-to-Market
- Millions of Gates
- High-Level Abstractions
- Reuse & IP: Portability
- Predictability
- etc.

Everything Looks a Little Different

...and There's a Lot of Them!



# Productivity Trends



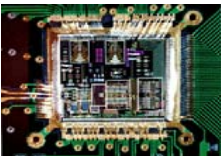
Source: Sematech

**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



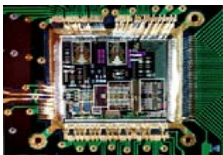
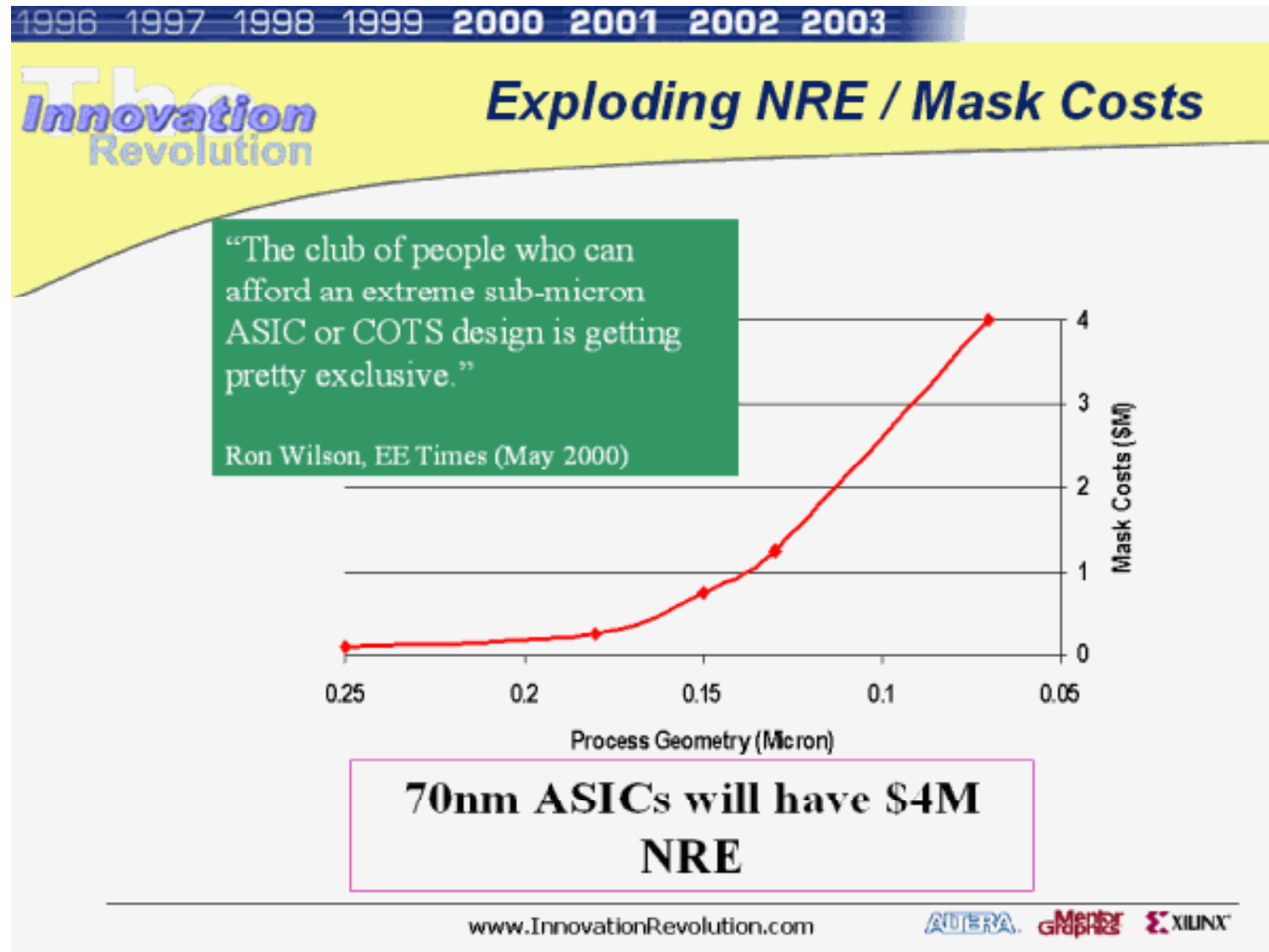


# Cost of Integrated Circuits

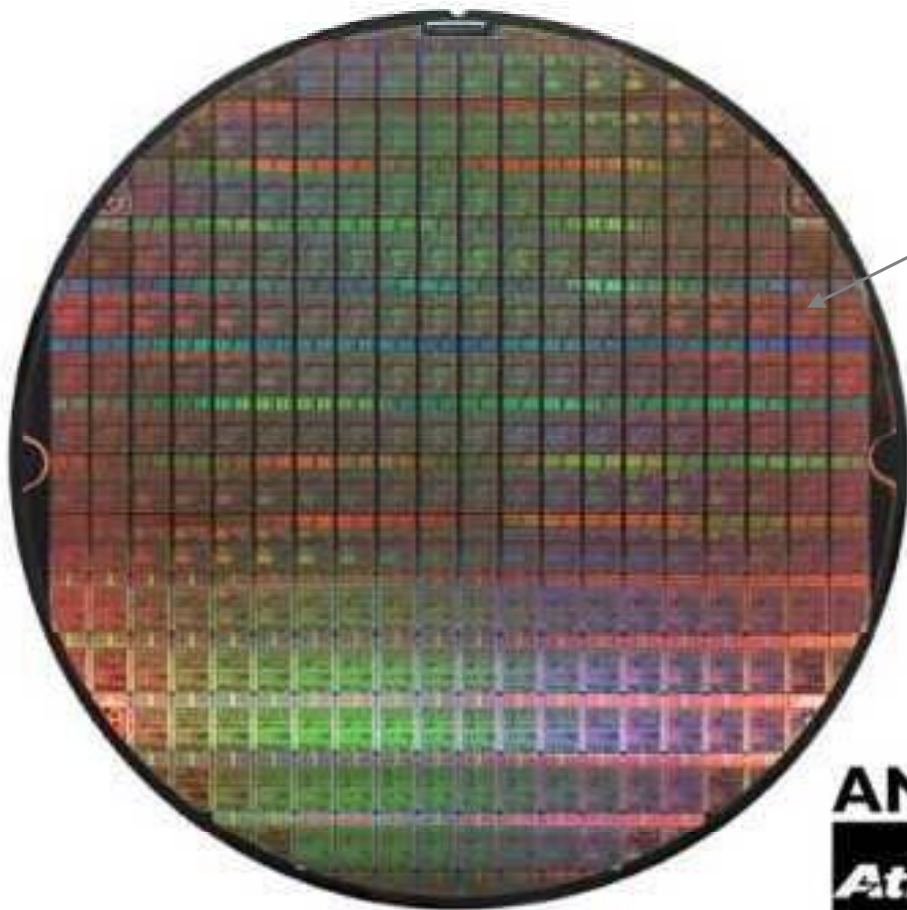
- NRE (non-recurrent engineering) costs
  - design time and effort, mask generation
  - one-time cost factor
- Recurrent costs
  - silicon processing, packaging, test
  - proportional to volume
  - proportional to chip area



# NRE Cost is Increasing



# Die Cost



Single die

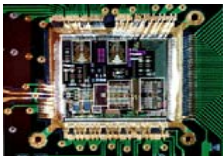
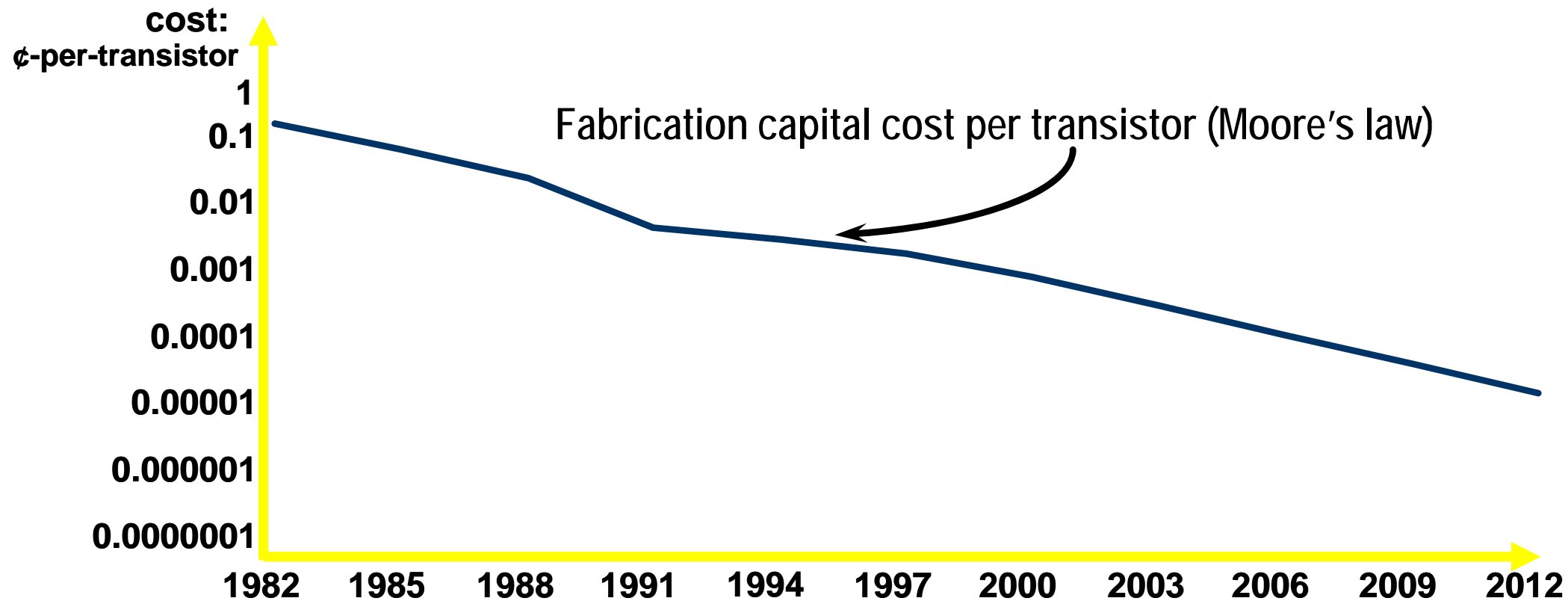
Wafer



Going up to 12" (30cm)



# Cost per Transistor

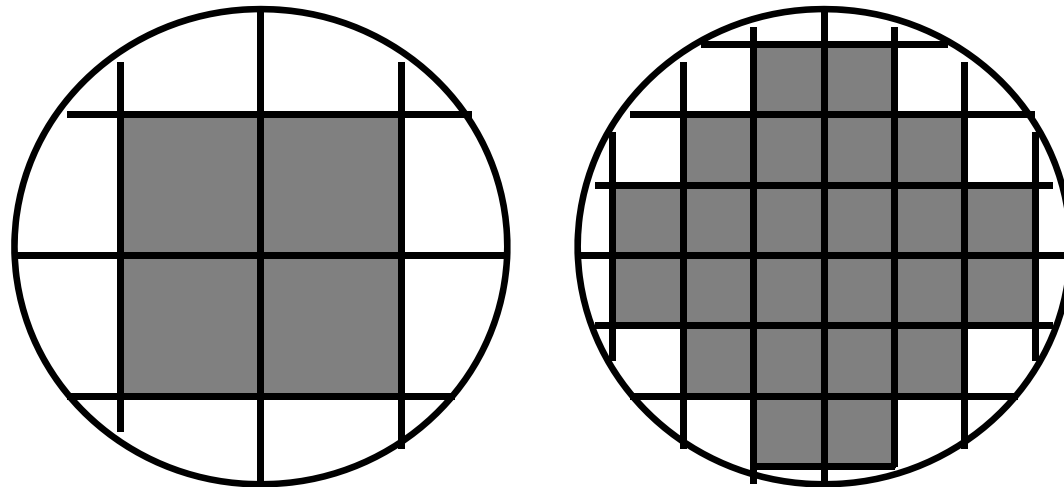


# Yield

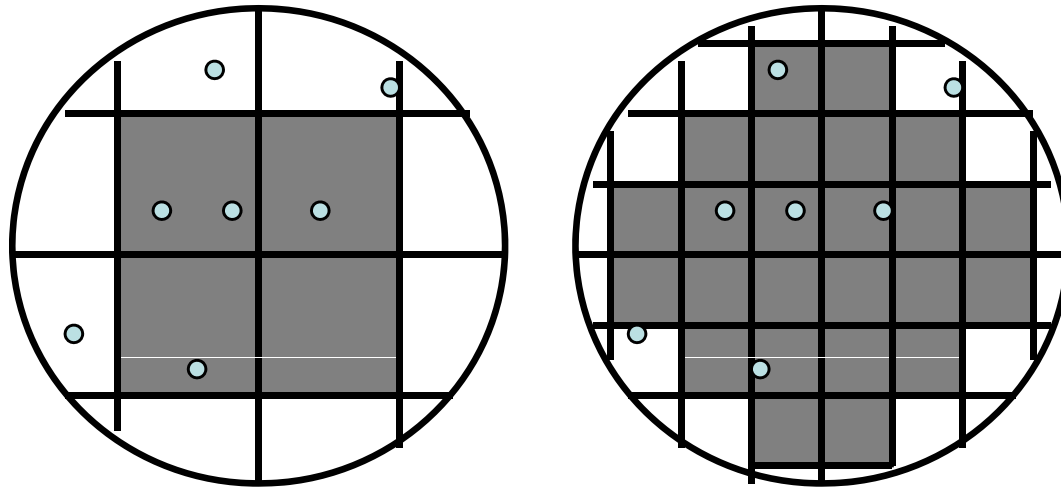
$$Y = \frac{\text{No. of good chips per wafer}}{\text{Total number of chips per wafer}} \times 100\%$$

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

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



# Defects

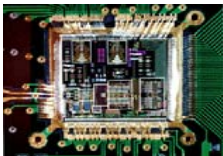


$$\text{die yield} = \left( 1 + \frac{\text{defects per unit area} \times \text{die area}}{\alpha} \right)^{-\alpha}$$

$\alpha$  is approximately 3

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

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

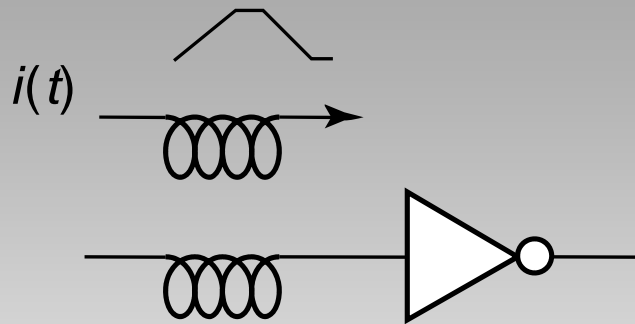


# Some Examples (1994)

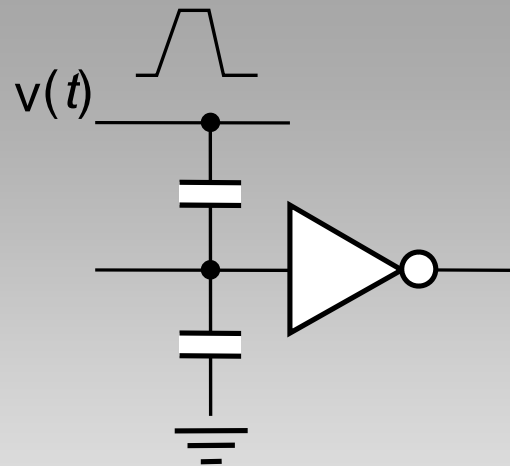
Chip	Metal layers	Line width	Wafer cost	Def./cm <sup>2</sup>	Area mm <sup>2</sup>	Dies/wafer	Yield	Die cost
386DX	2	0.90	\$900	1.0	43	360	71%	\$4
486 DX2	3	0.80	\$1200	1.0	81	181	54%	\$12
Power PC 601	4	0.80	\$1700	1.3	121	115	28%	\$53
HP PA 7100	3	0.80	\$1300	1.0	196	66	27%	\$73
DEC Alpha	3	0.70	\$1500	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



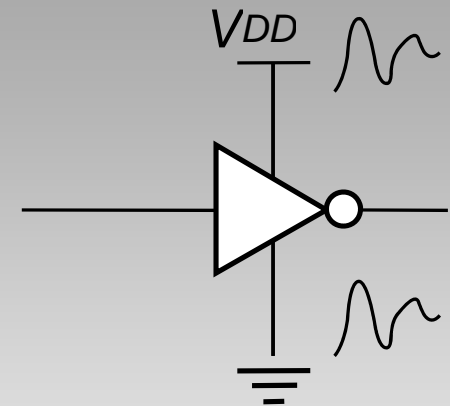
# Reliability— Noise in Digital Integrated Circuits



**Inductive coupling**



**Capacitive coupling**

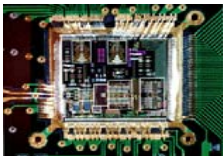
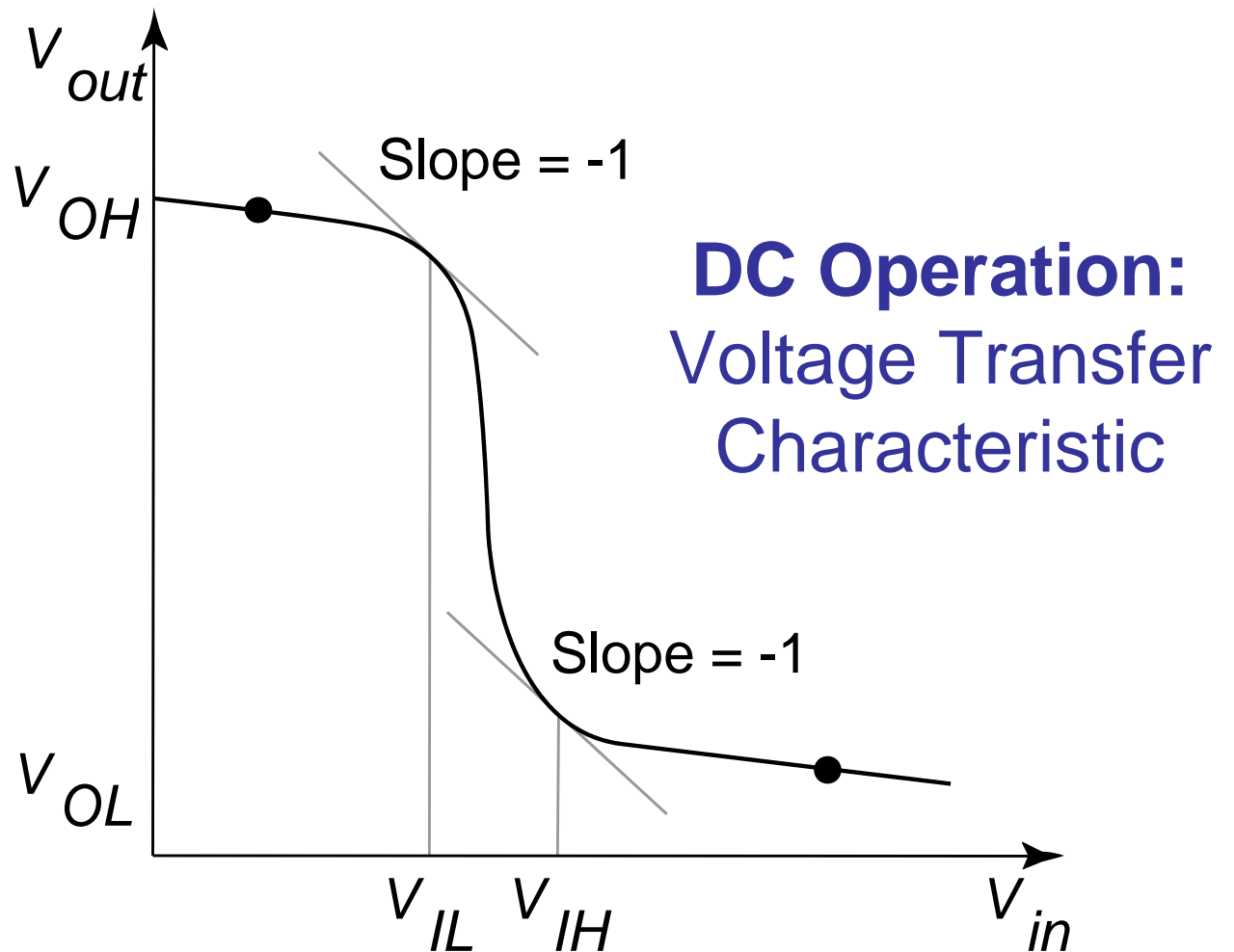
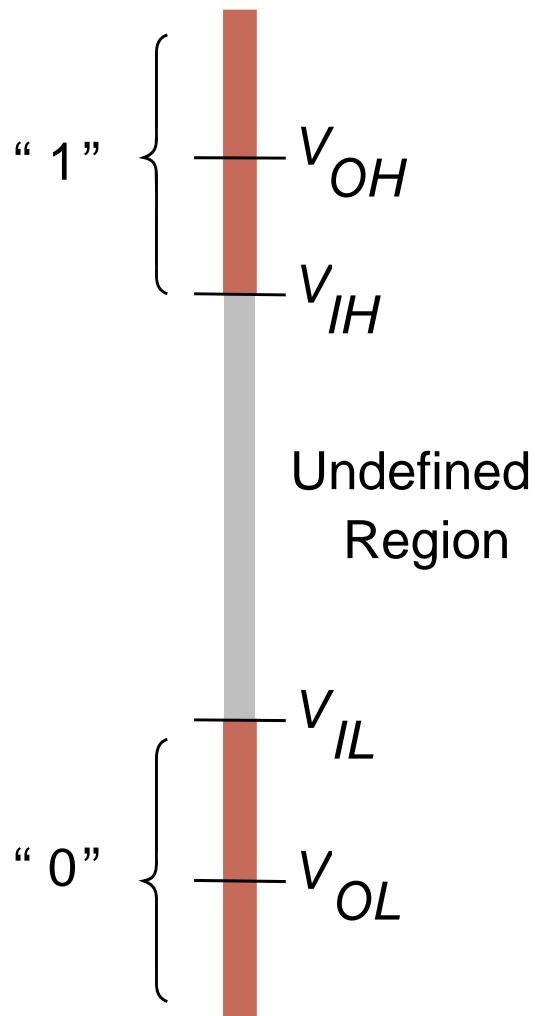


**Power and ground  
noise**

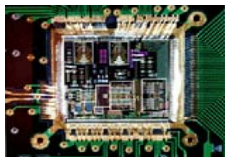
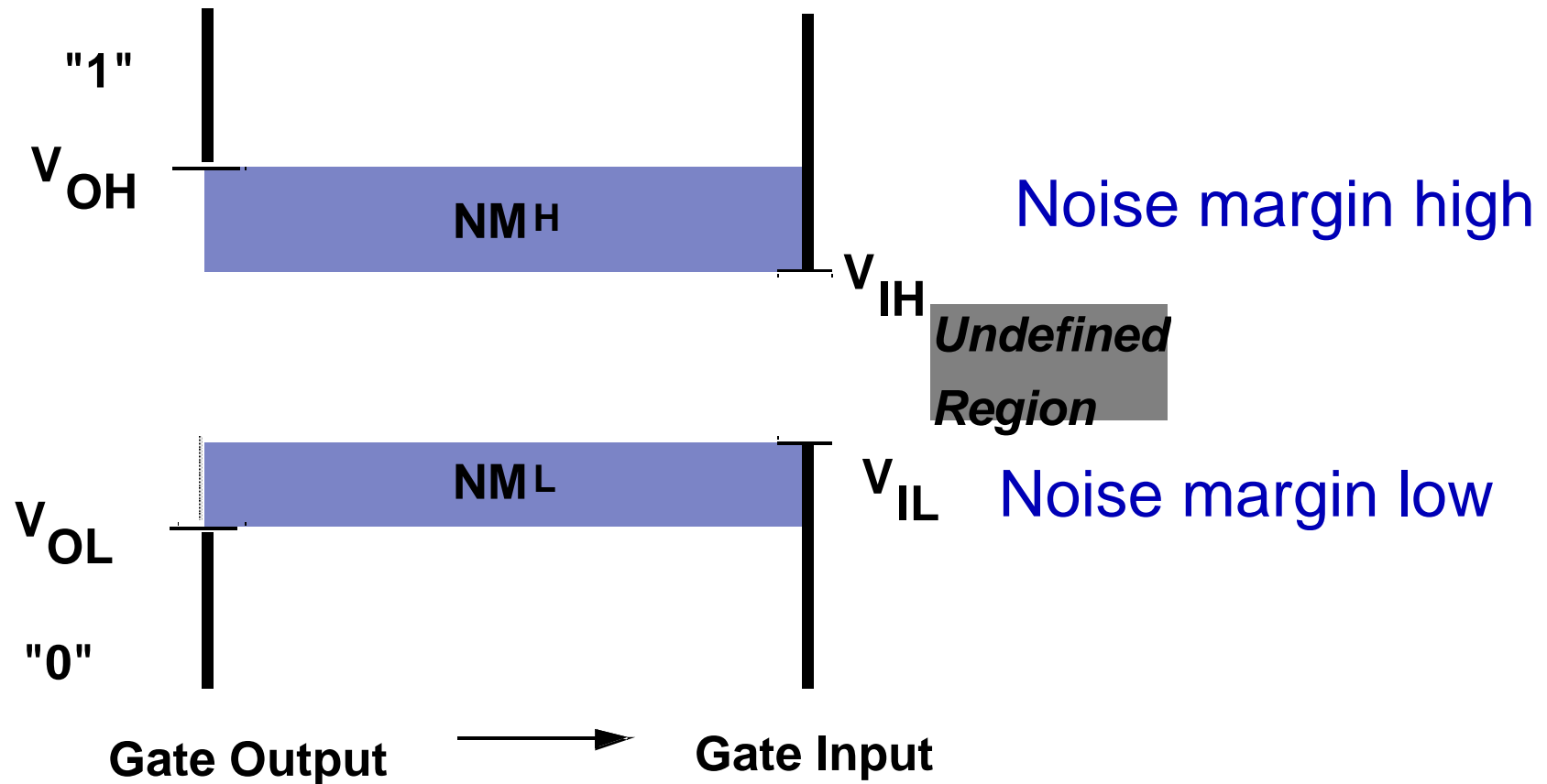




# Mapping between analog and digital signals

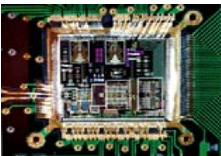


# Definition of Noise Margins



# 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

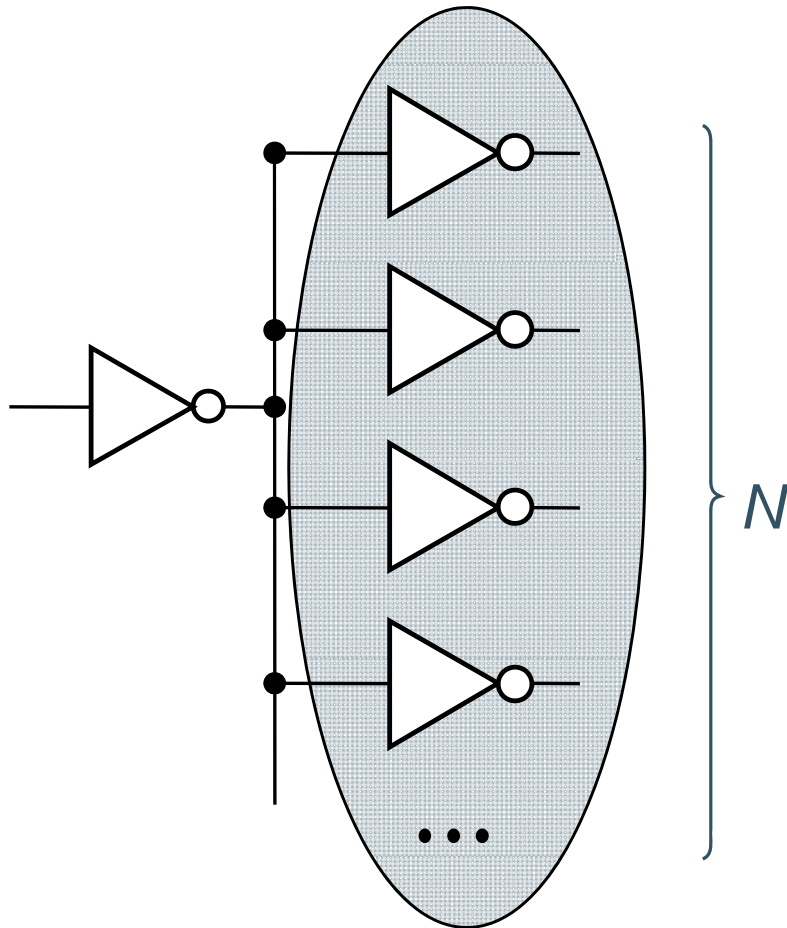


# Key Reliability Properties

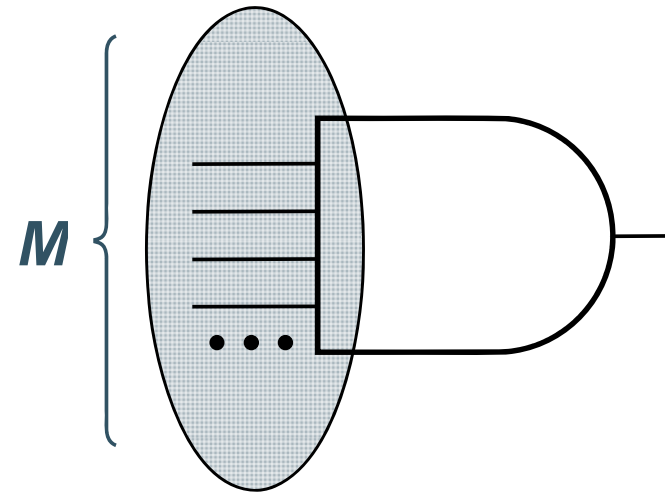
- Absolute noise margin values are deceptive
  - a floating node is more easily disturbed than a node driven by a low impedance (in terms of voltage)
- Noise immunity is the more important metric – **the capability to suppress noise sources**
- Key metrics: Noise transfer functions, Output impedance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



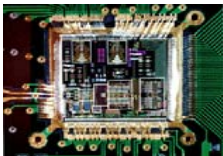
# Fan-in and Fan-out



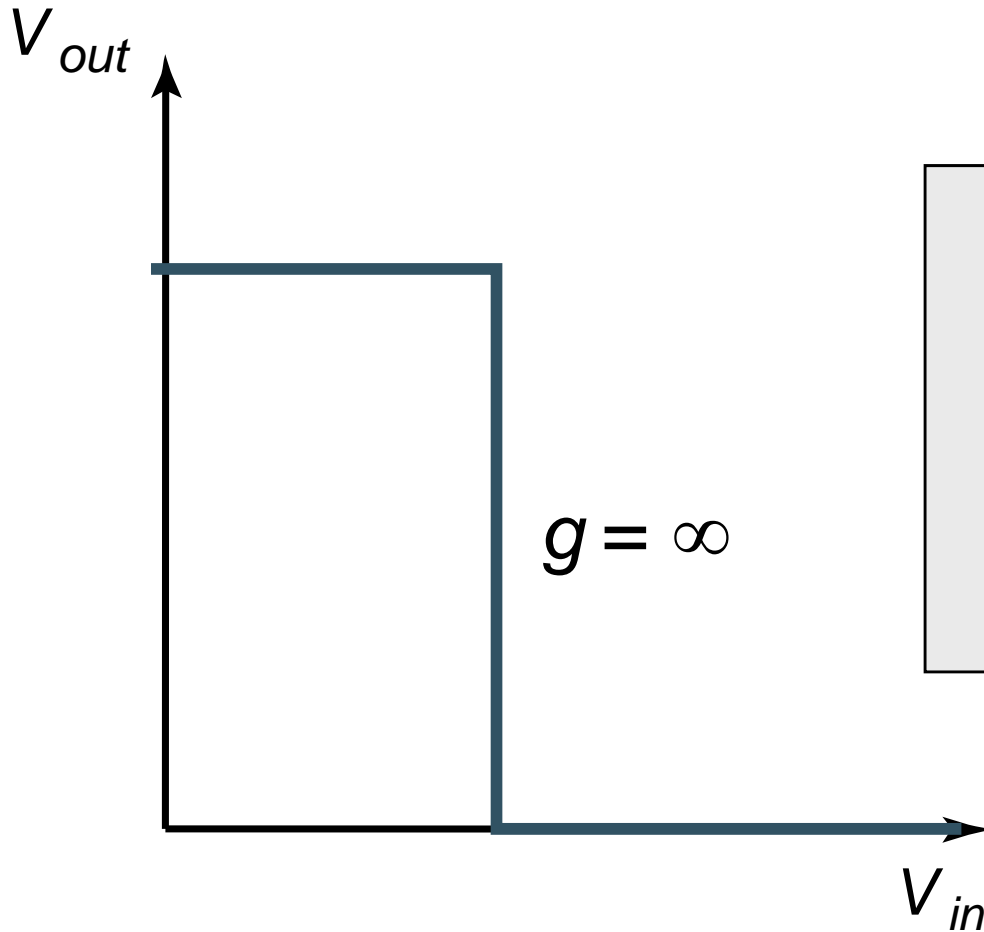
Fan-out  $N$



Fan-in  $M$



# The Ideal Gate



$$R_i = \infty$$

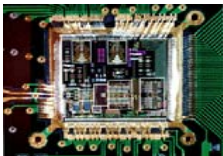
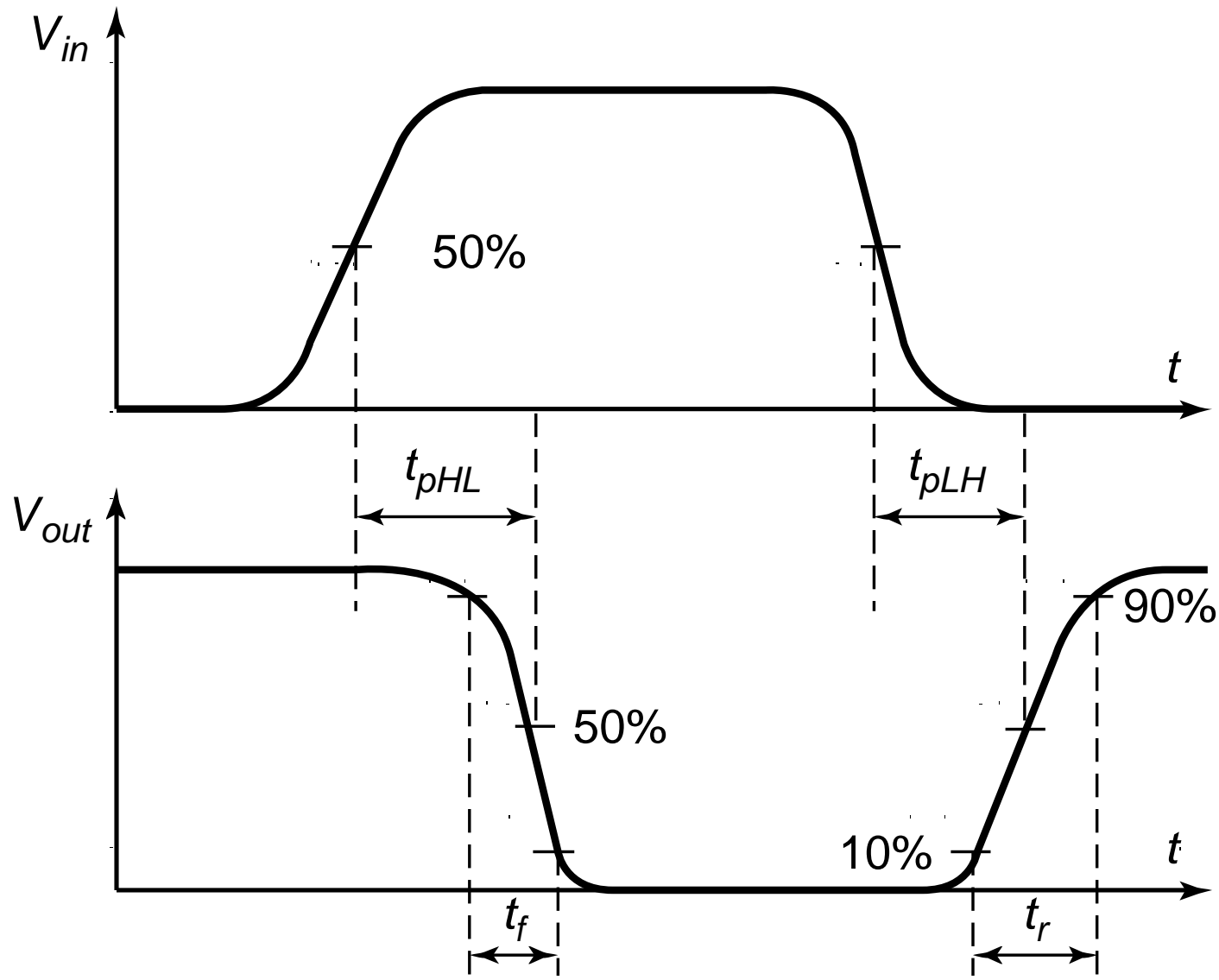
$$R_o = 0$$

$$\text{Fanout} = \infty$$

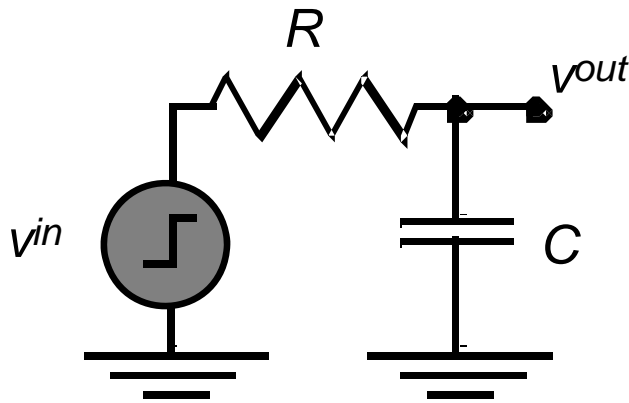
$$NM_H = NM_L = V_{DD}/2$$



# 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:

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



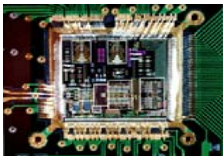
# Energy and Energy-Delay

Power-Delay Product (PDP) =

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

Energy-Delay Product (EDP) =

$$\text{quality metric of gate} = E \times t_p$$



# 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



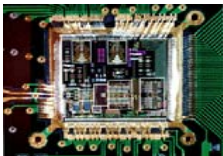
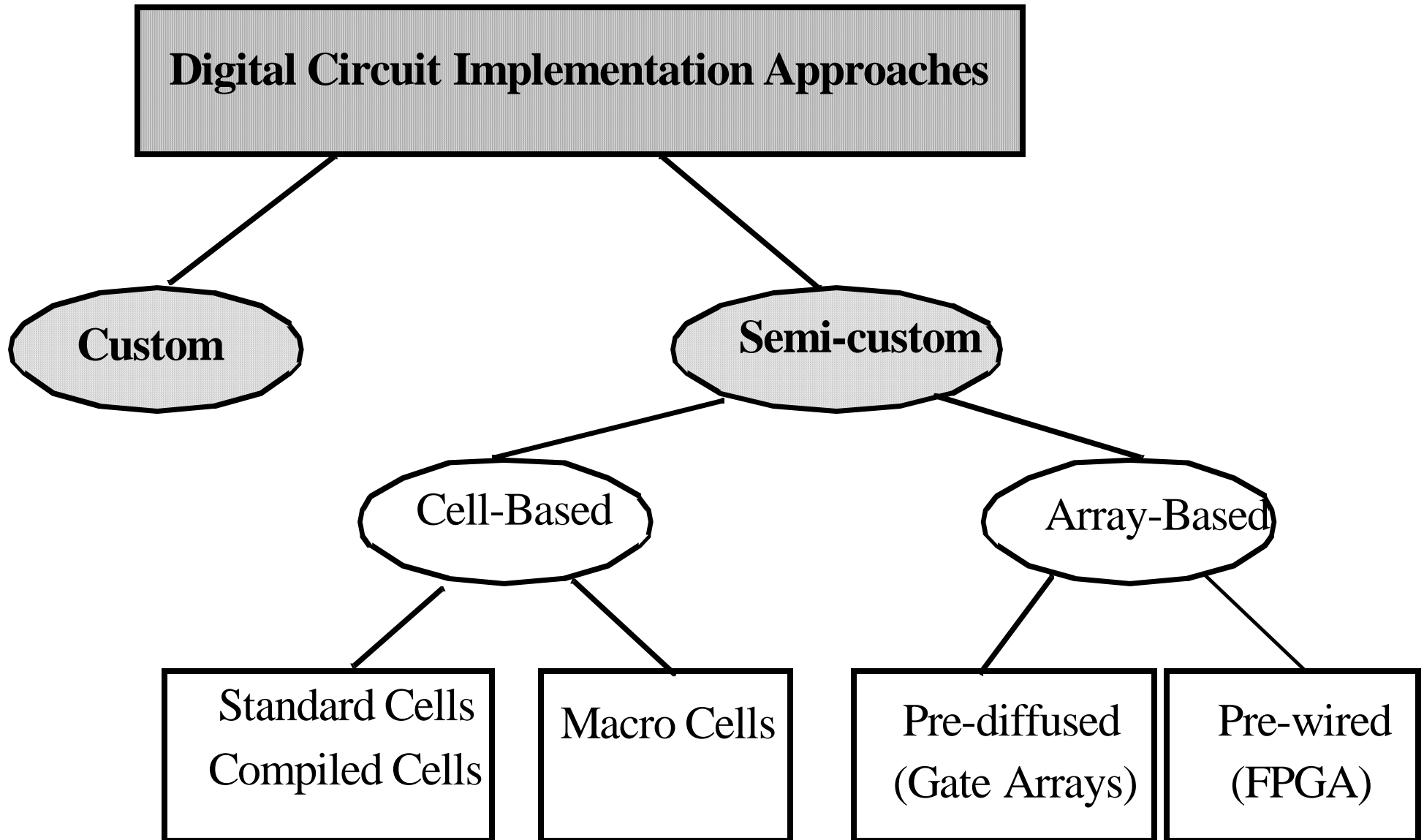
# Digital Logic Families

- 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



# Implementation Approaches for Digital ICs



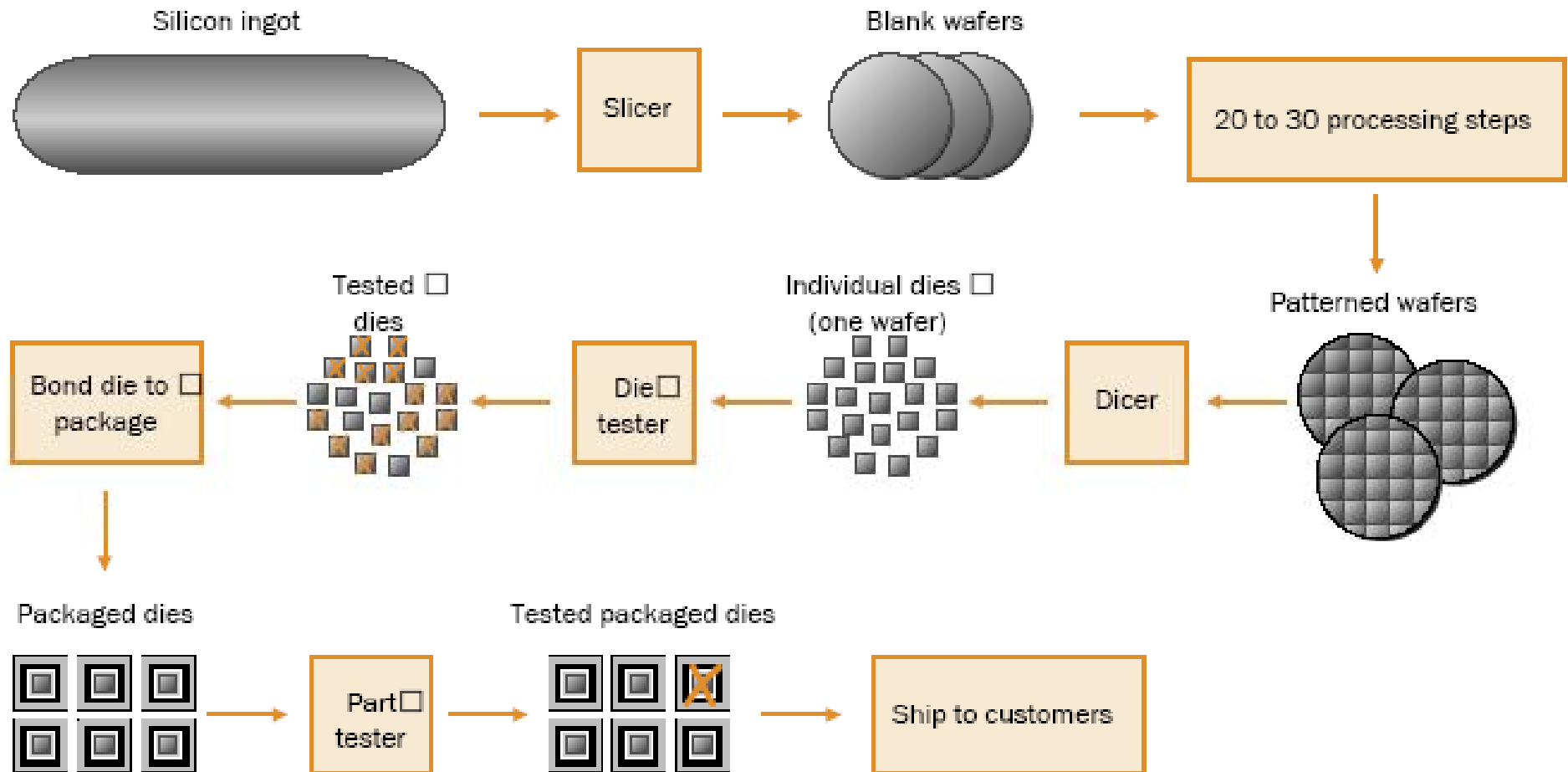
# Implementation Approaches for Digital ICs

- **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 Design Flow



# 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

