

Lecture 1: Introduction

CSCE 5730

Digital CMOS VLSI Design

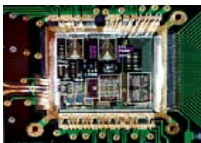
Instructor: Saraju P. Mohanty, Ph. D.

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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

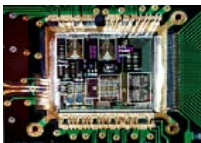


What is a digital Computer ?

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

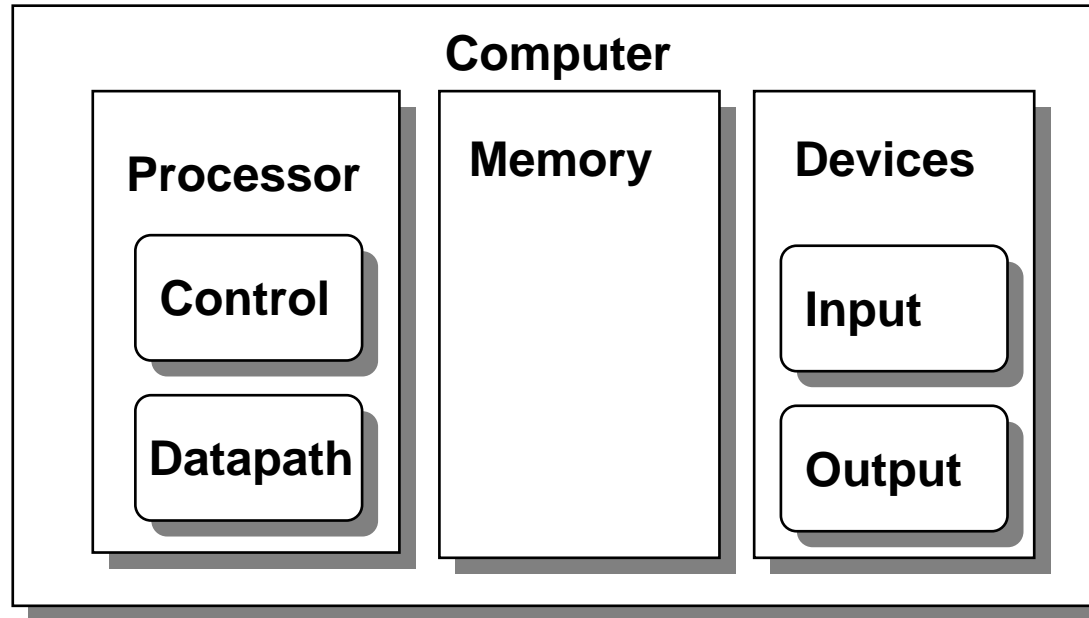


Different Types and Forms of Computer

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



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.
- 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).

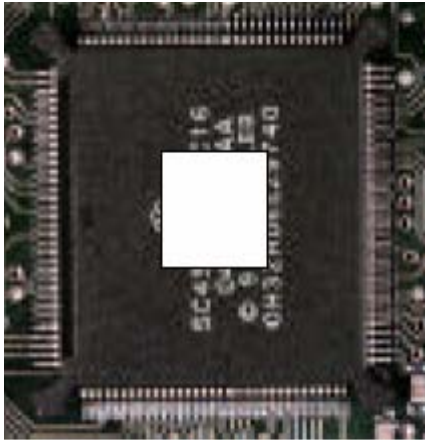


What is an Integrated Circuit ?

- 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.



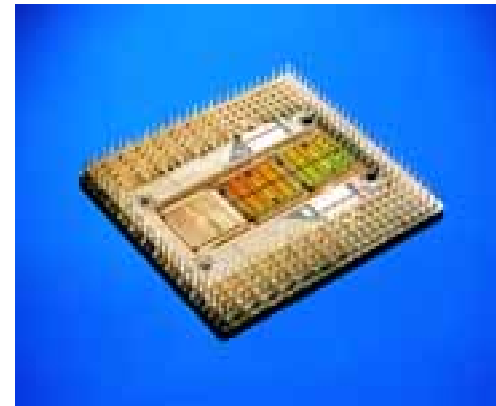
How does a microprocessor look?



(1) ASIC



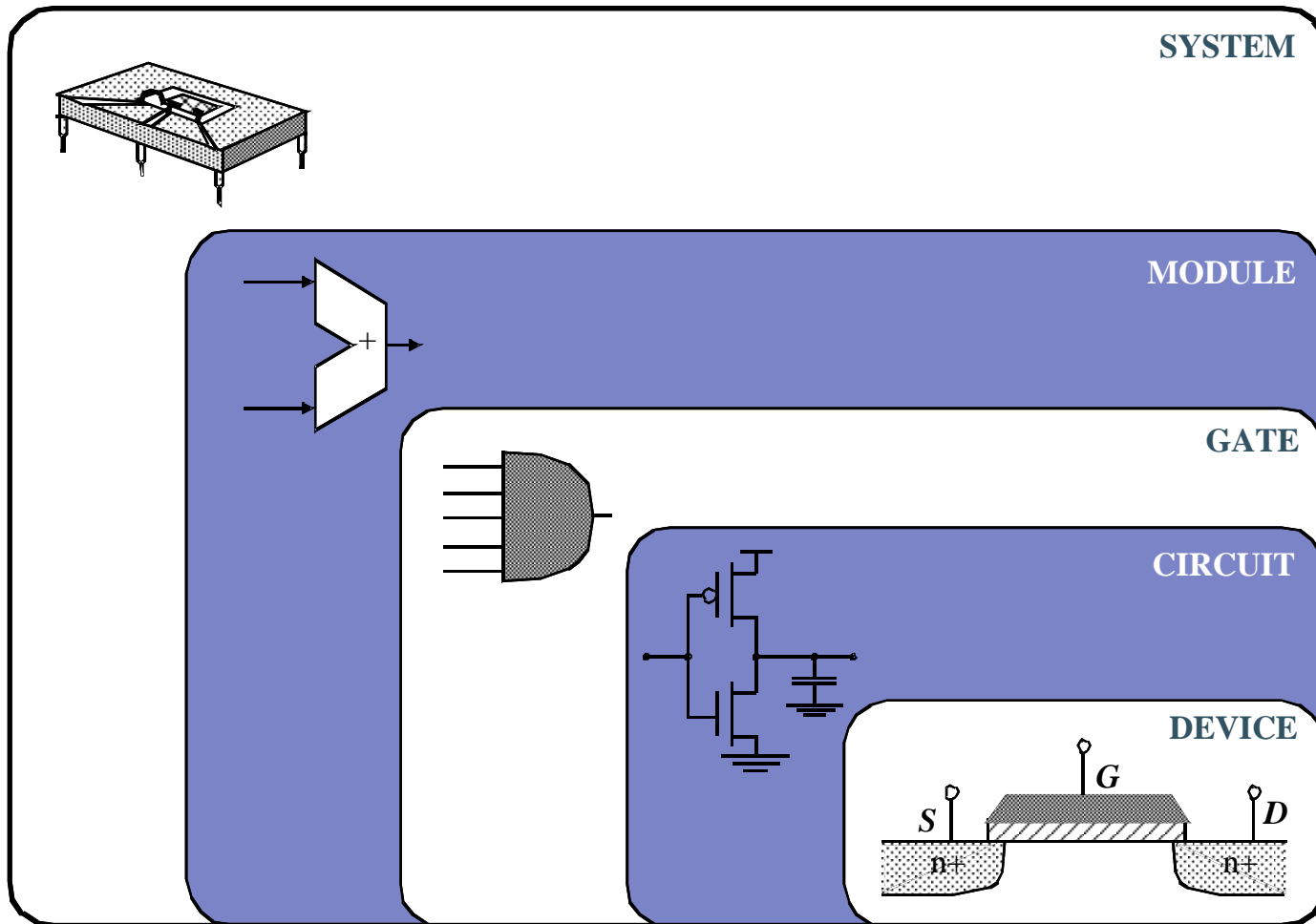
(2) Sun UltraSparc



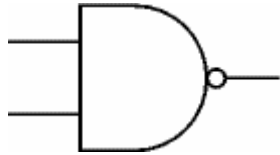
(3) PentiumPro



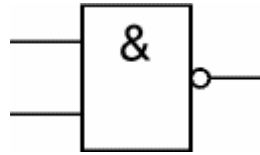
Design Abstraction Levels



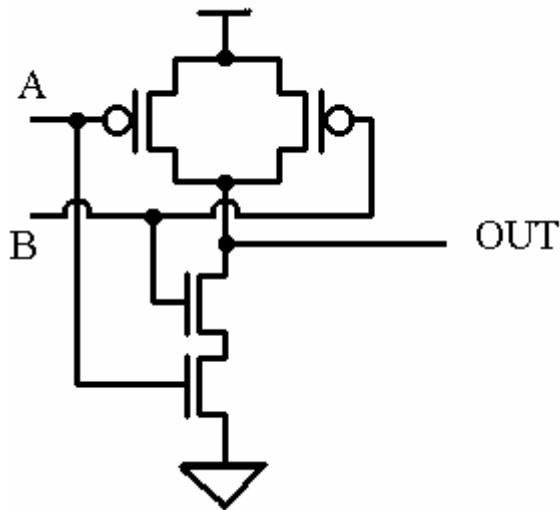
Digital Circuits : Logic to Device



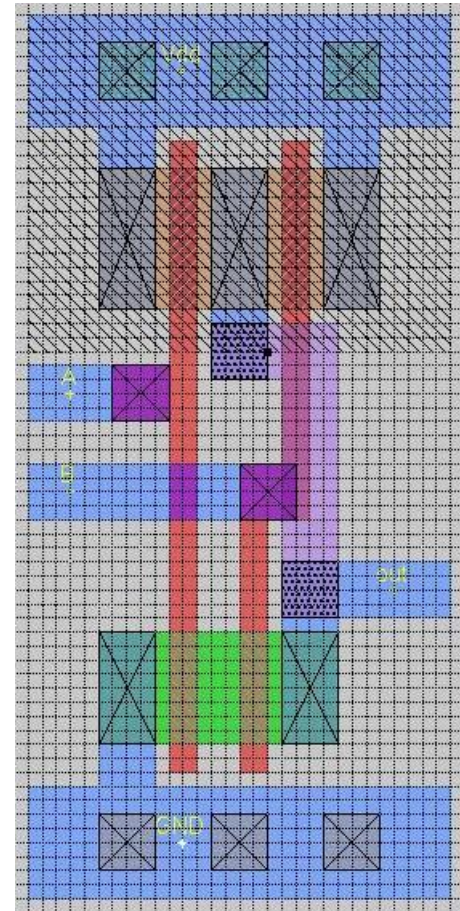
(NAND Gate)



(IEC Symbol)



(Transistor Diagram)

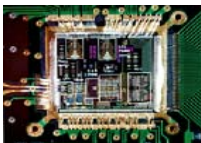


(Layout Diagram)



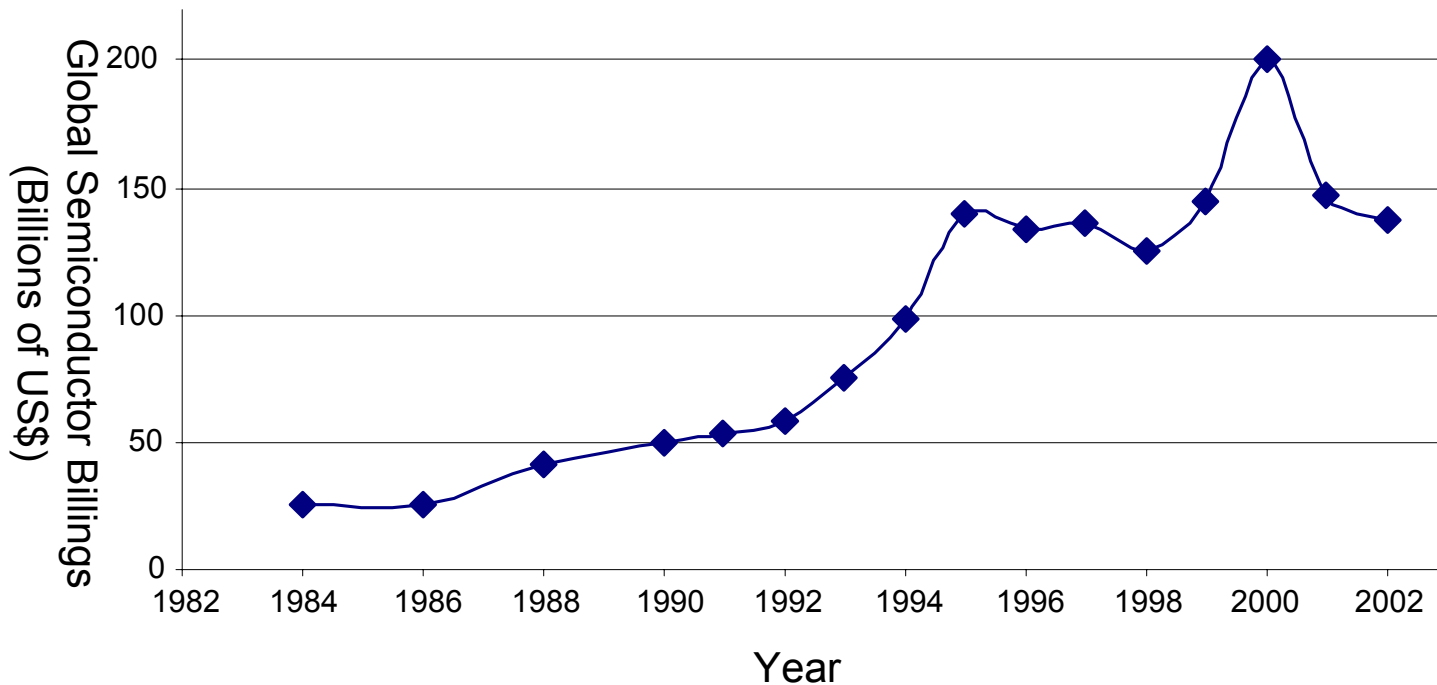
VLSI Technology: Highest Growth in History

- 1958: First integrated circuit
 - Flip-flop using two transistors
 - Built by Jack Kilby at Texas Instruments
- 2003
 - Intel Pentium 4 μ 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



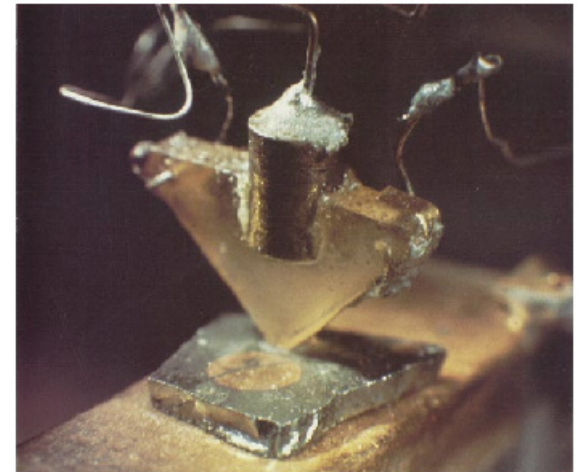
VLSI Industry : Annual Sales

- 10^{18} transistors manufactured in 2003
 - 100 million for every human on the planet



Invention of the Transistor

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

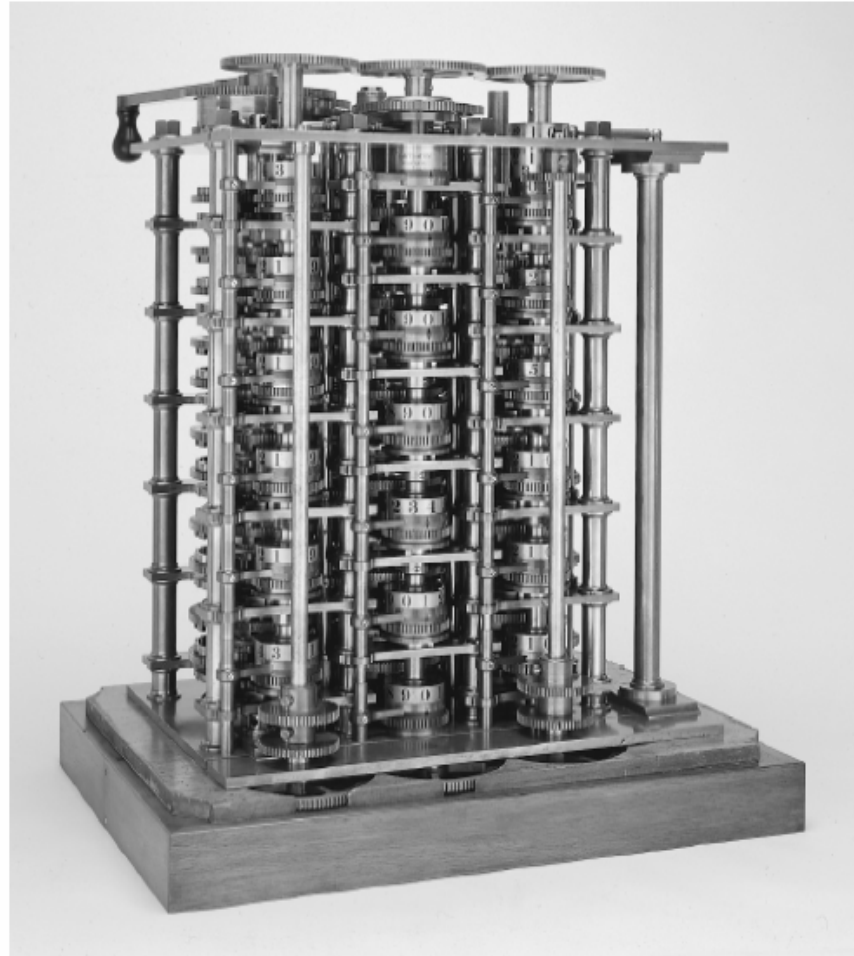


Transistor Types

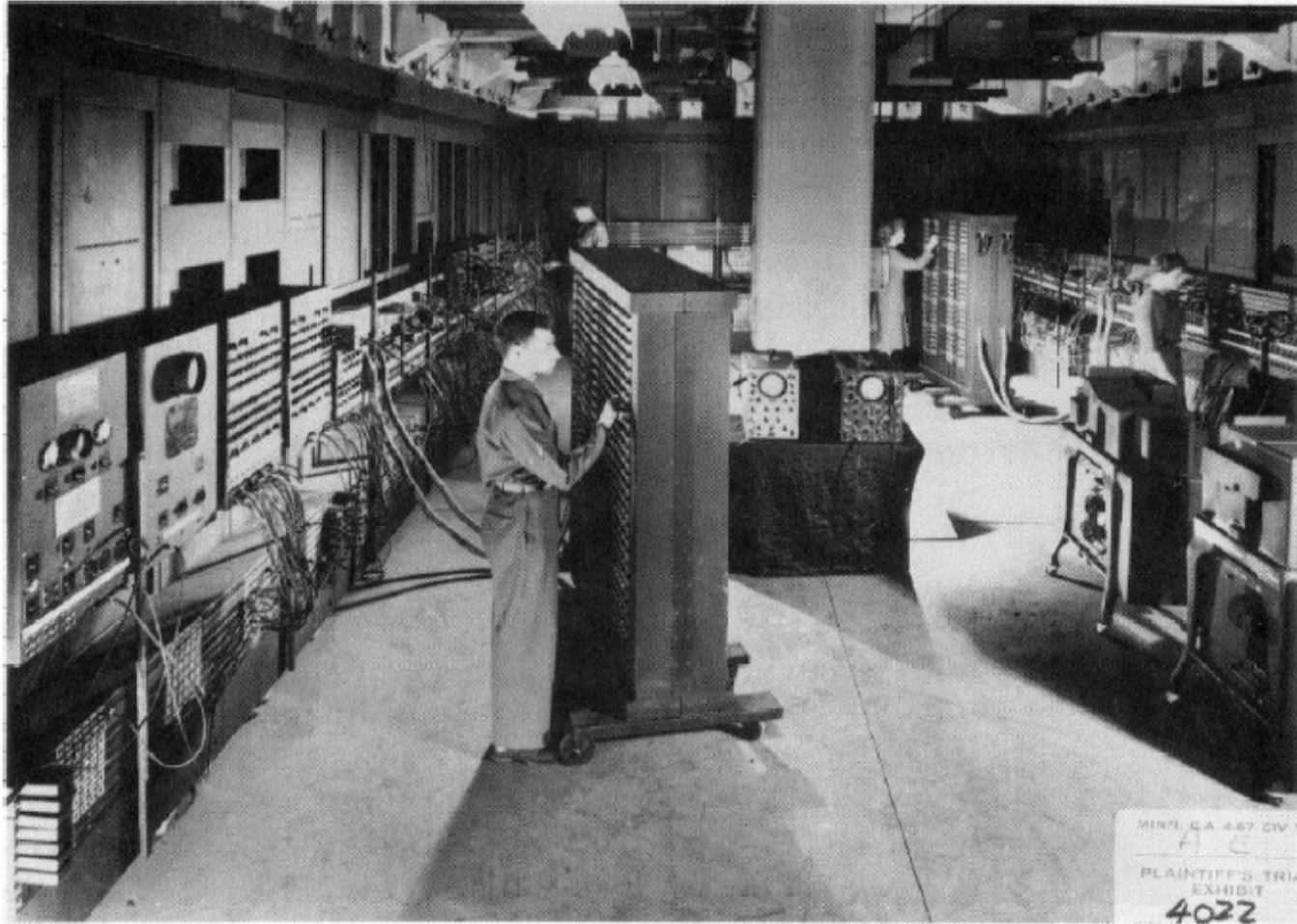
- Bipolar transistors
 - n-p-n or p-n-p silicon structure
 - Small current into very thin base layer controls large currents between emitter and collector
 - Base currents limit integration density
- Metal Oxide Semiconductor Field Effect Transistors (MOSFET)
 - nMOS and pMOS MOSFETS
 - Voltage applied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



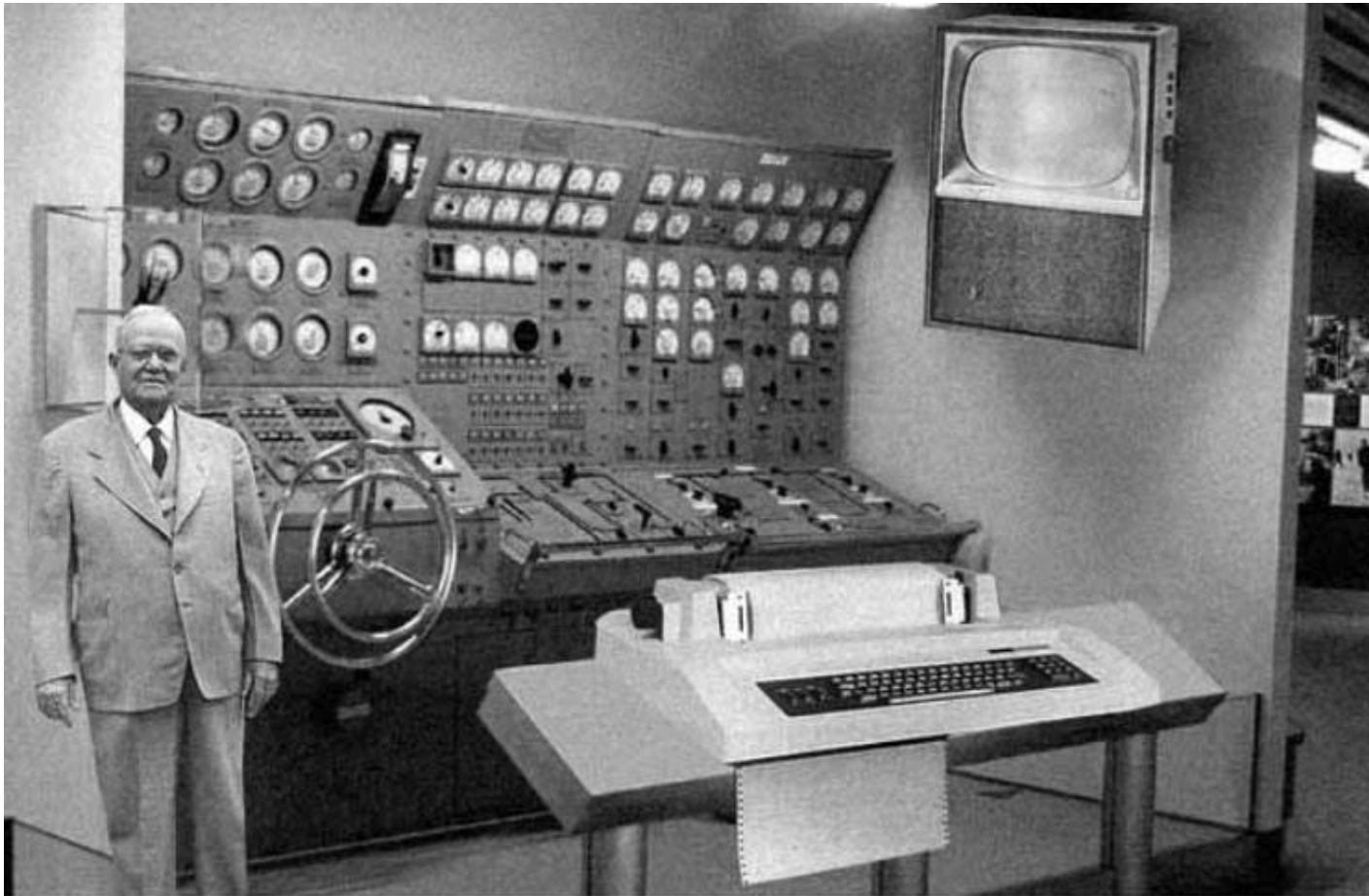
The Babbage Difference Machine in 1832



The First Electronic Computer in 1946 (ENIAC)



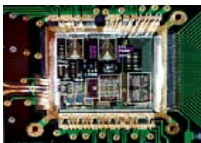
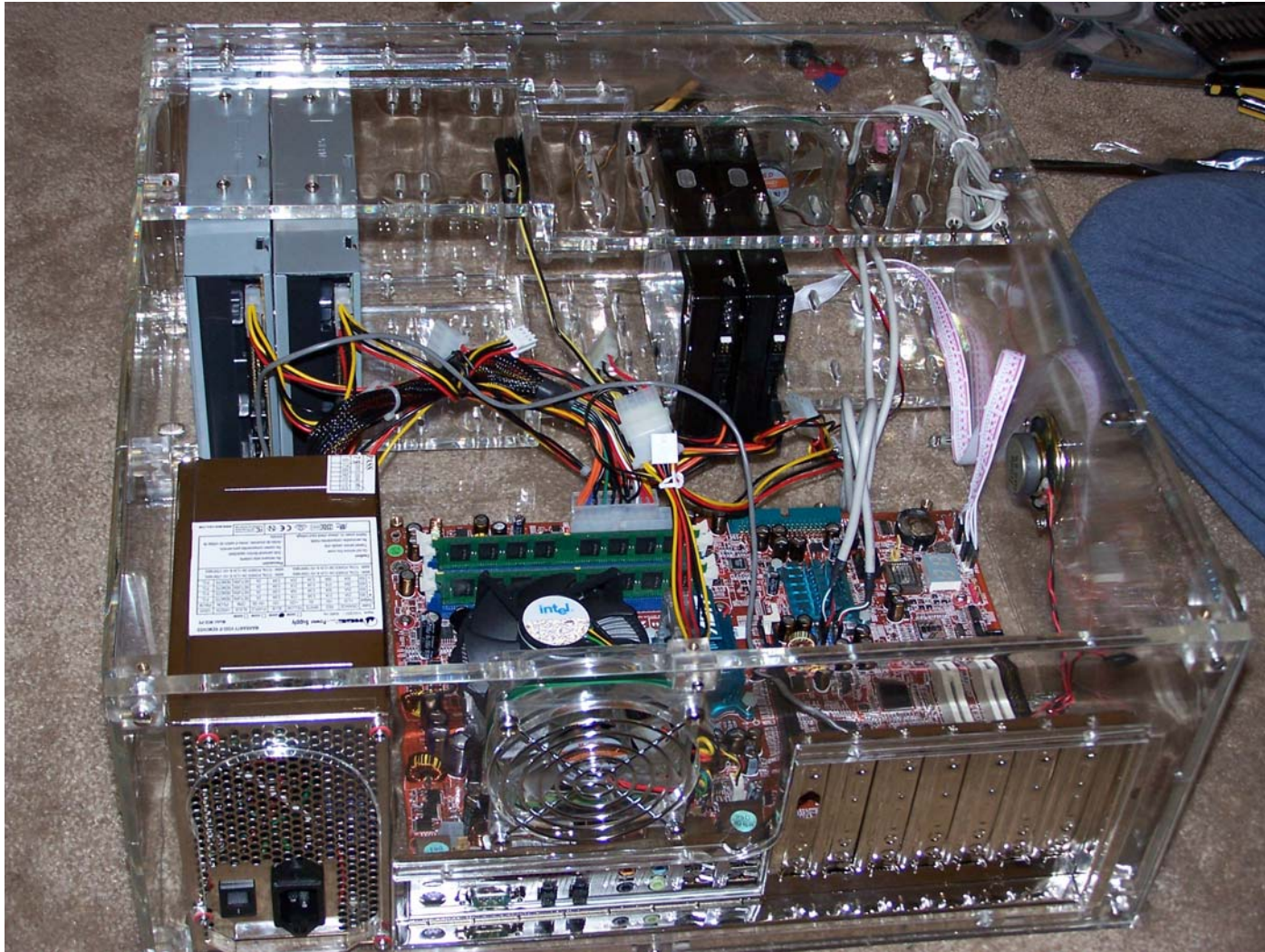
Prediction about Home PC in 1954



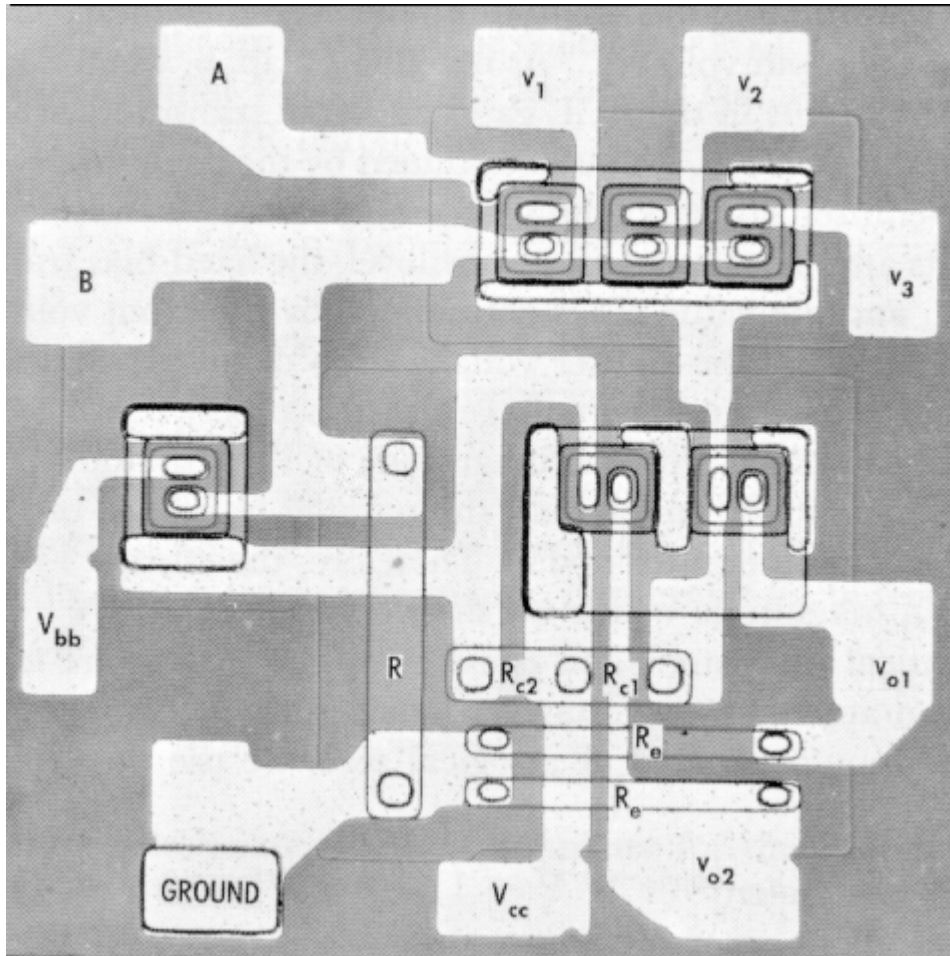
Scientists from the RAND Corporation have created this model to illustrate how a "home computer" could look like in the year 2004. However the needed technology will not be economically feasible for the average home. Also the scientists readily admit that the computer will require not yet invented technology to actually work, but 50 years from now scientific progress is expected to solve these problems. With teletype interface and the Fortran language, the computer will be easy to use.



How a Home PC Looks Today??



The First Integrated Circuits

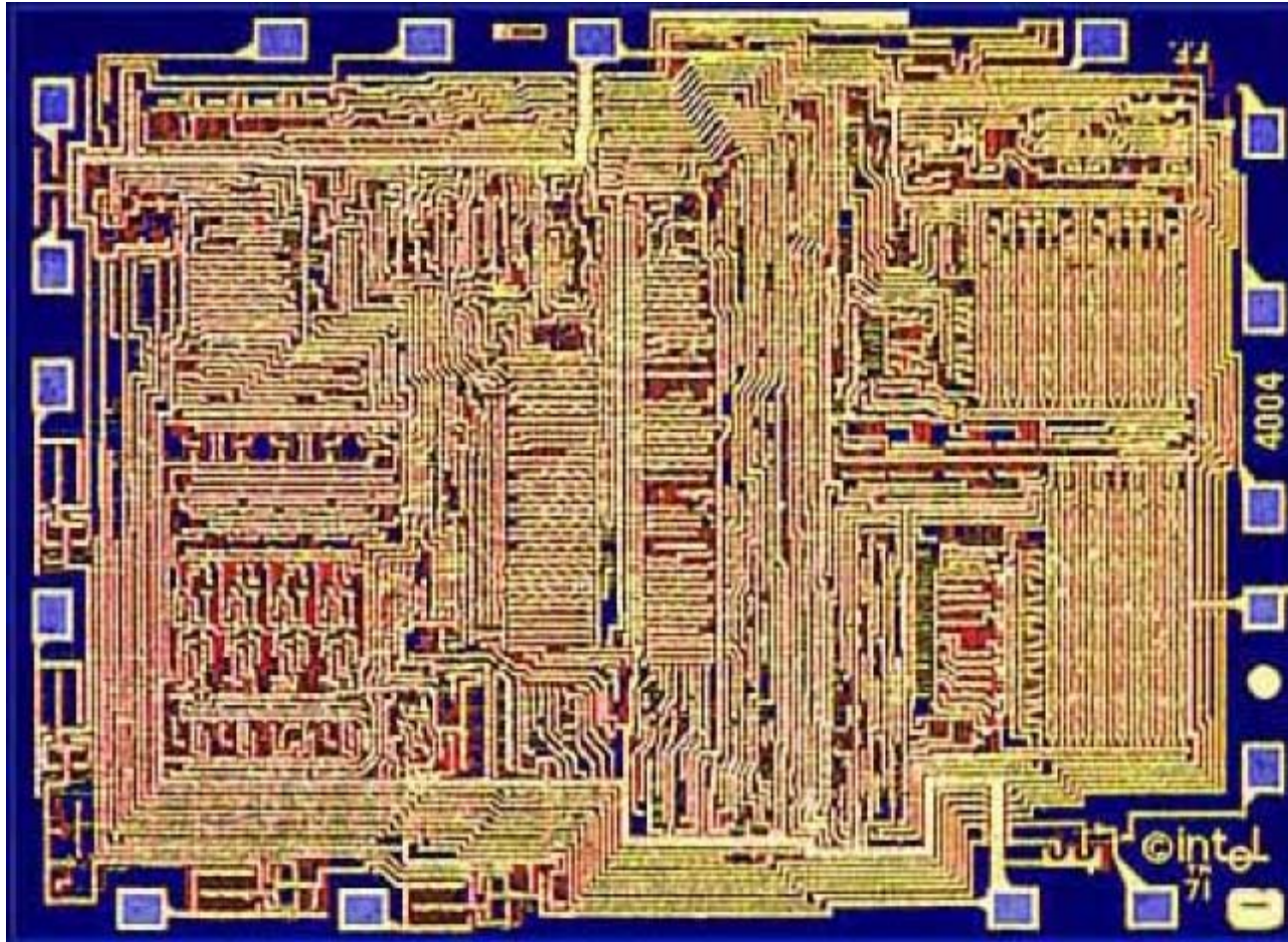


*Bipolar logic
1960's*

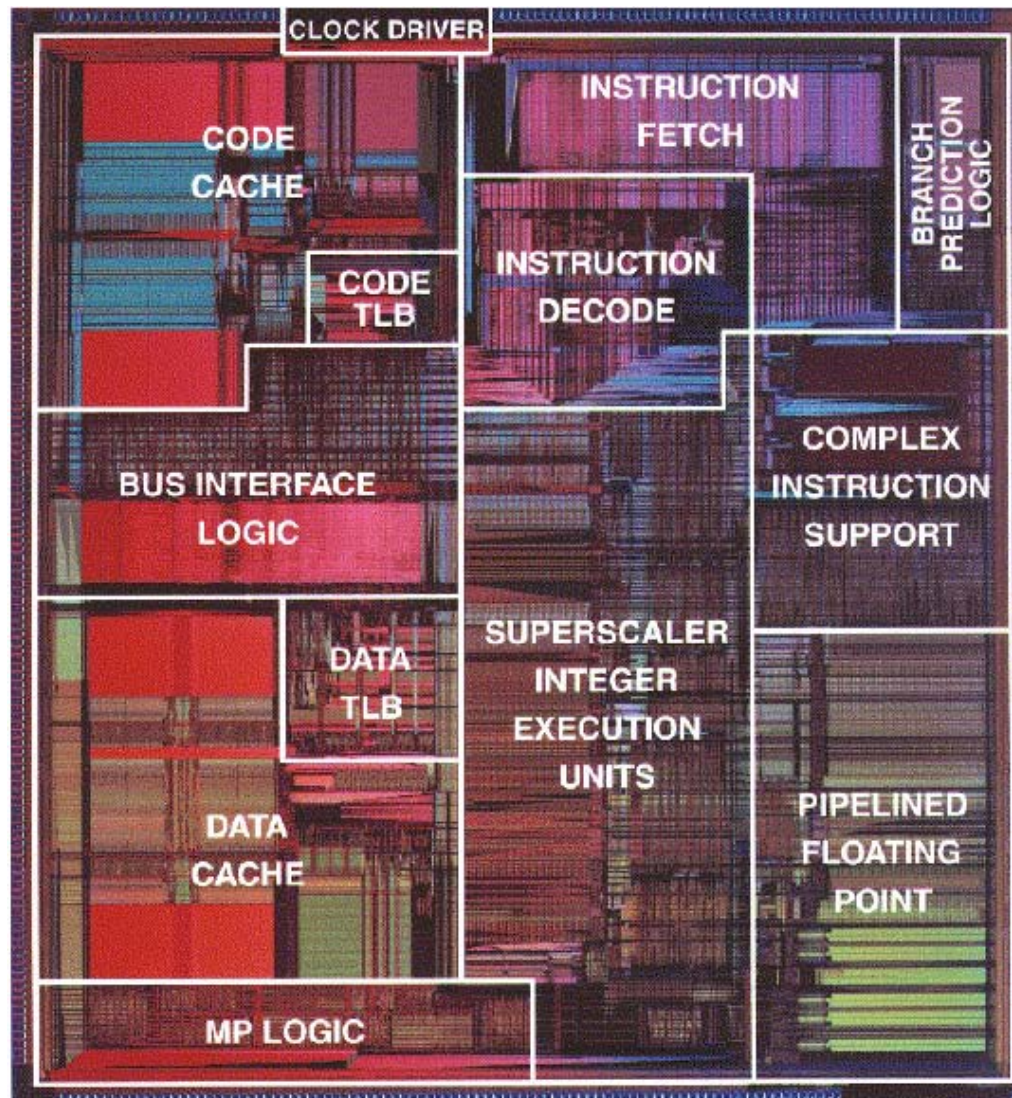
ECL 3-input Gate
Motorola 1966



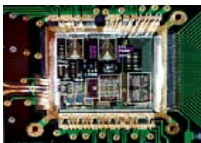
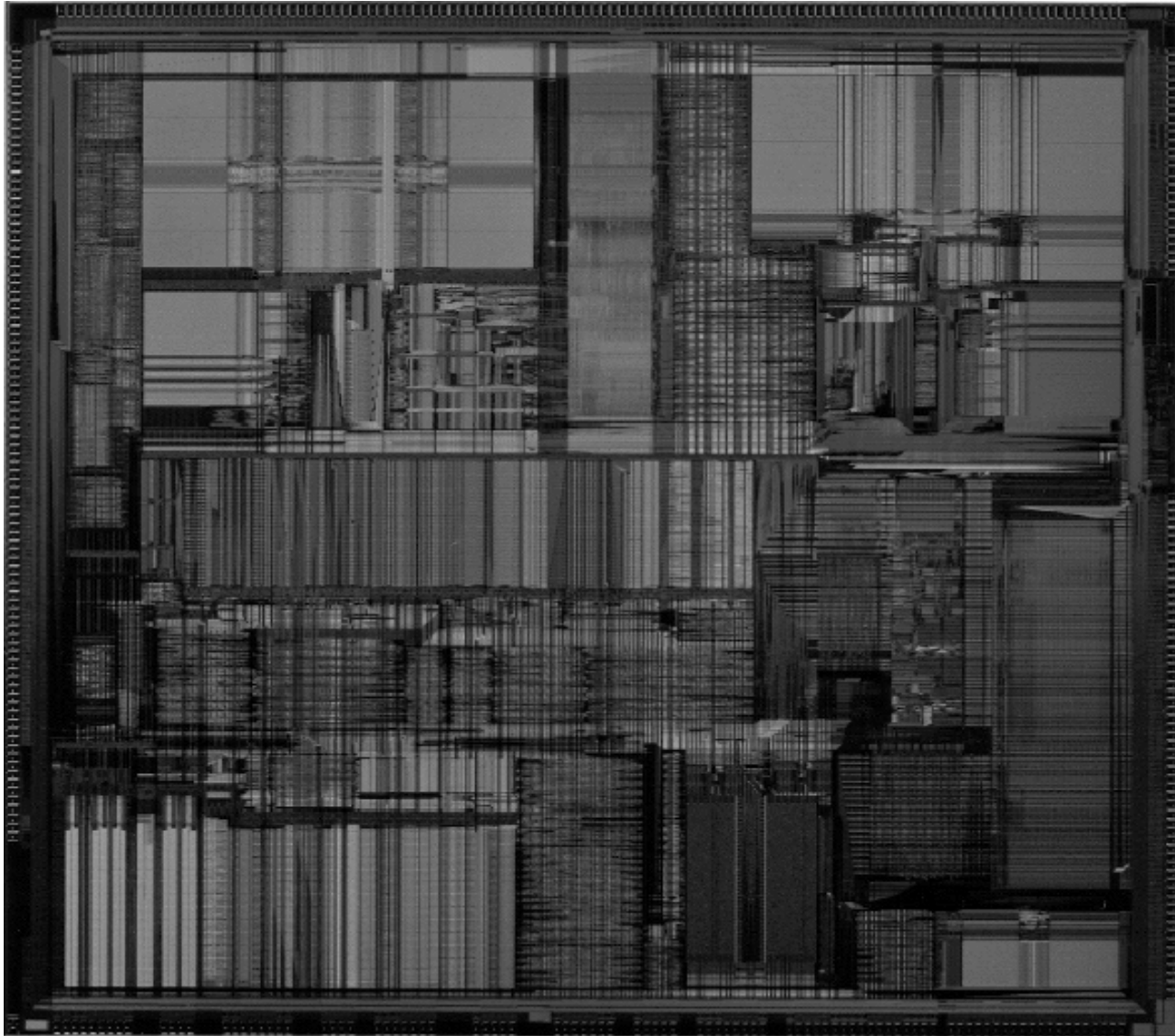
Intel 4004 : 2.3K Transistors (1971)



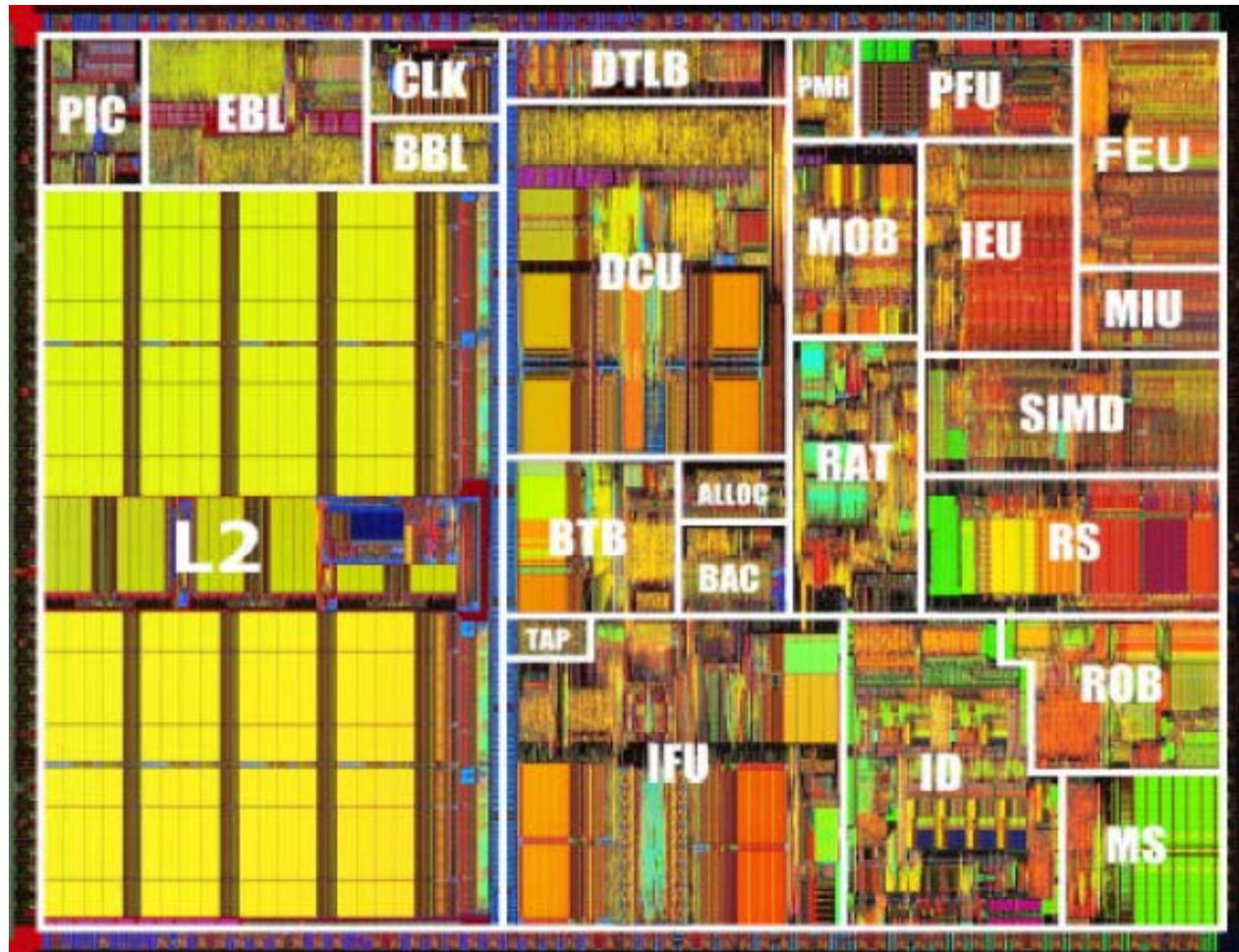
Pentium : 3.1M Transistors (1993)



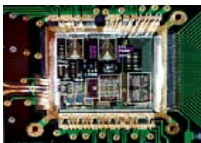
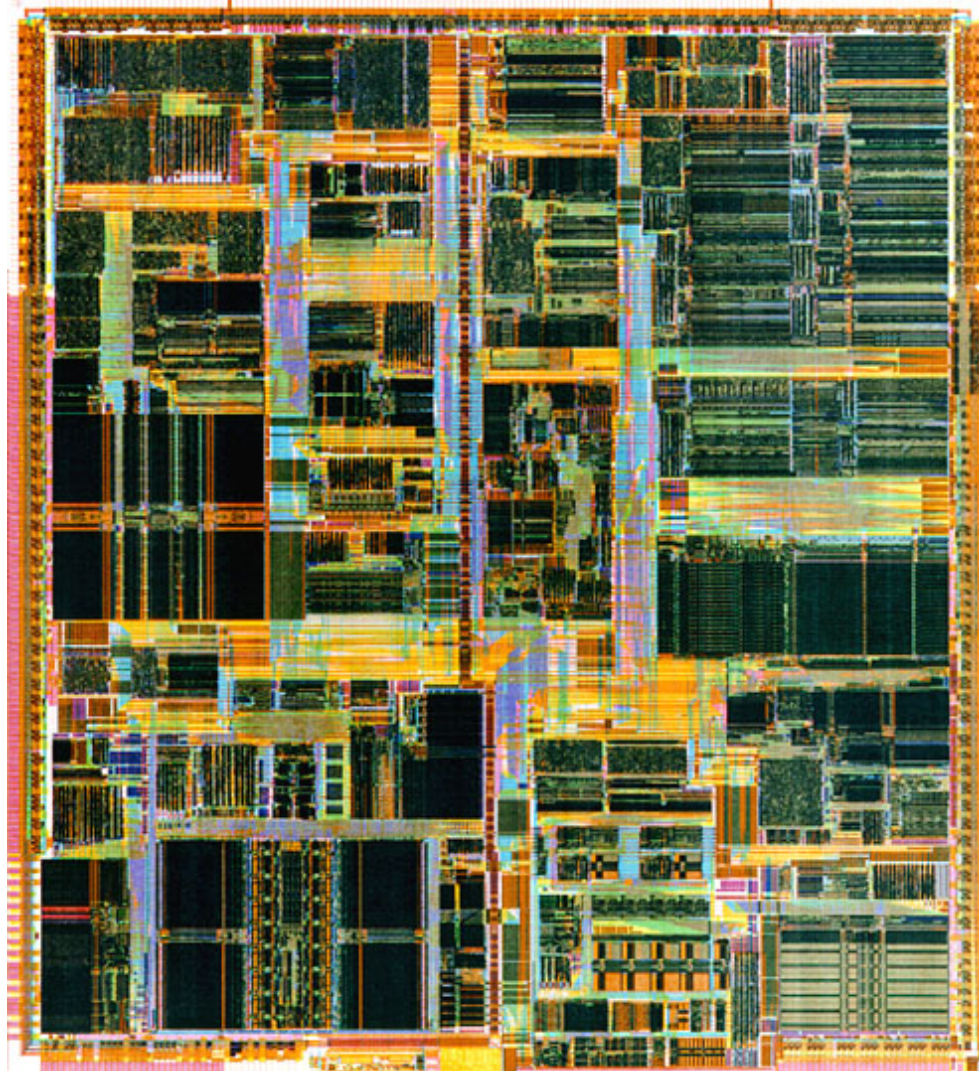
Pentium II : 7.5M Transistors (1997)



Pentium III : 28.1M Transistors (1999)



Pentium IV : 52M Transistors (2001)



Different Attributes of an IC or chip

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

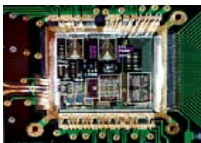
- Transistor count of a chip
- Operating frequency of a chip
- Power consumption of a chip
- Power density in a chip
- Size of a device used in chip

NOTE: Chip is informal name for IC.

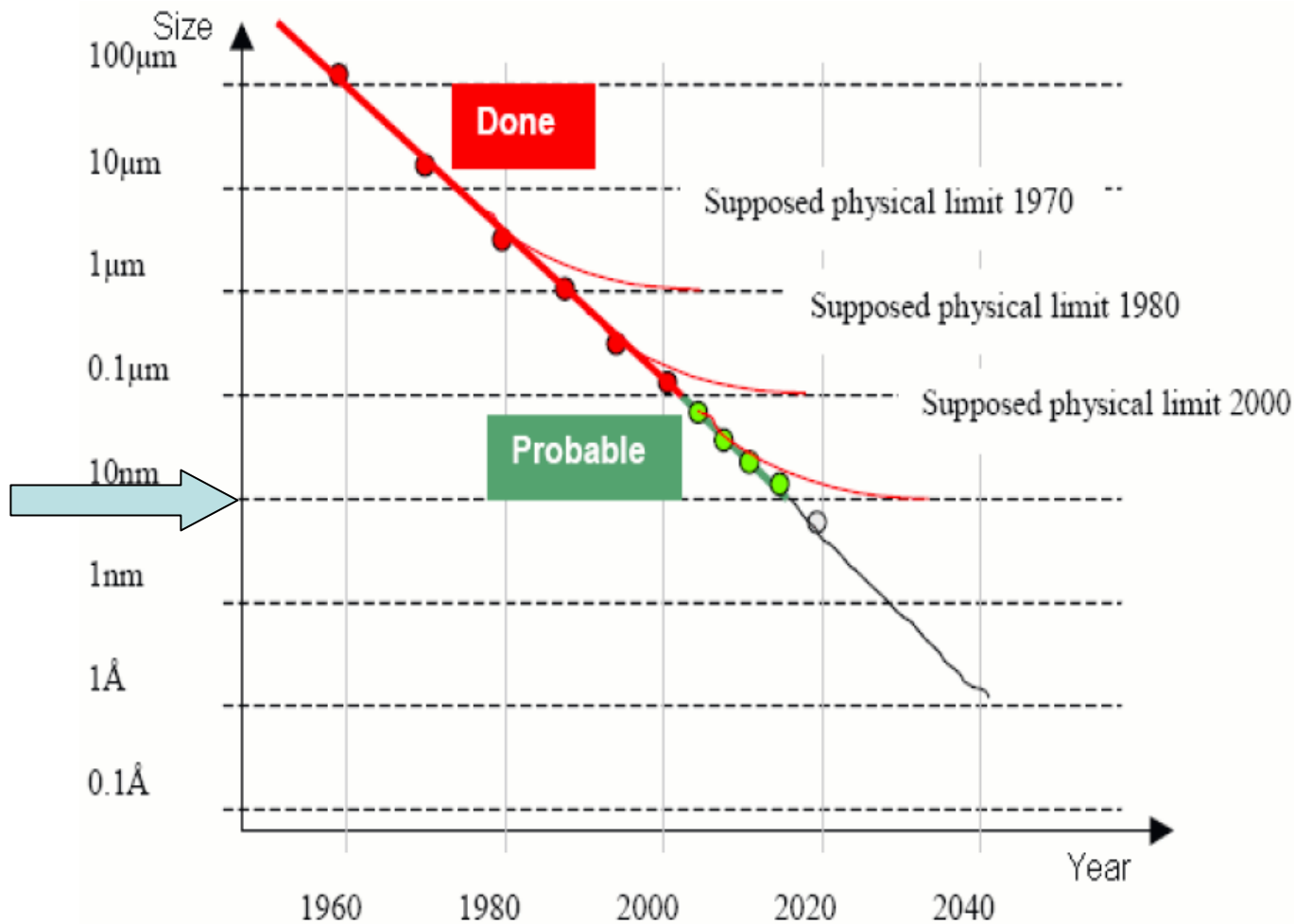


Moore's Law

- 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

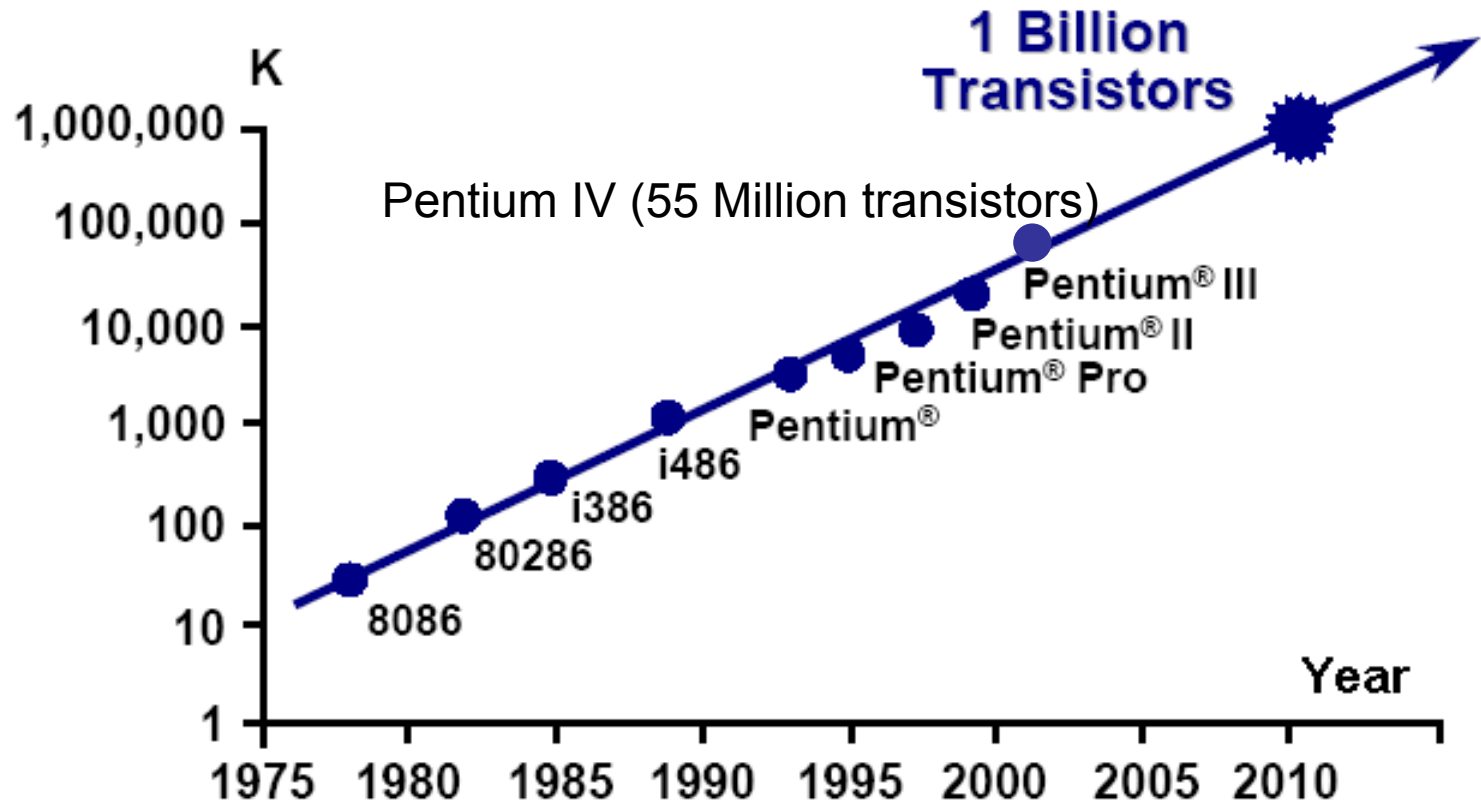


Why Scaling?

- 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



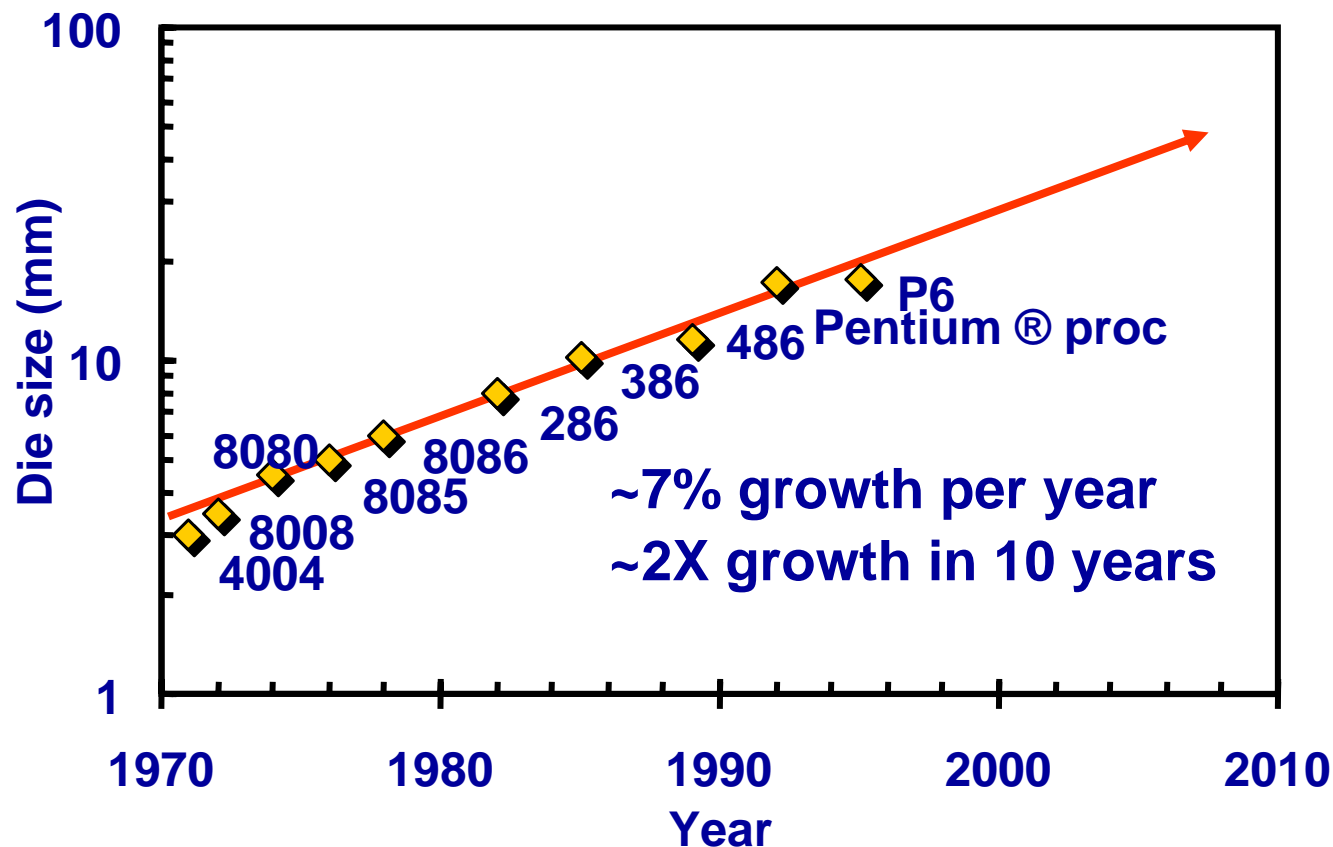
Increase in Transistor Count



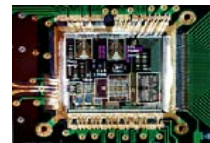
Transistors on Lead Microprocessors double every 2 years



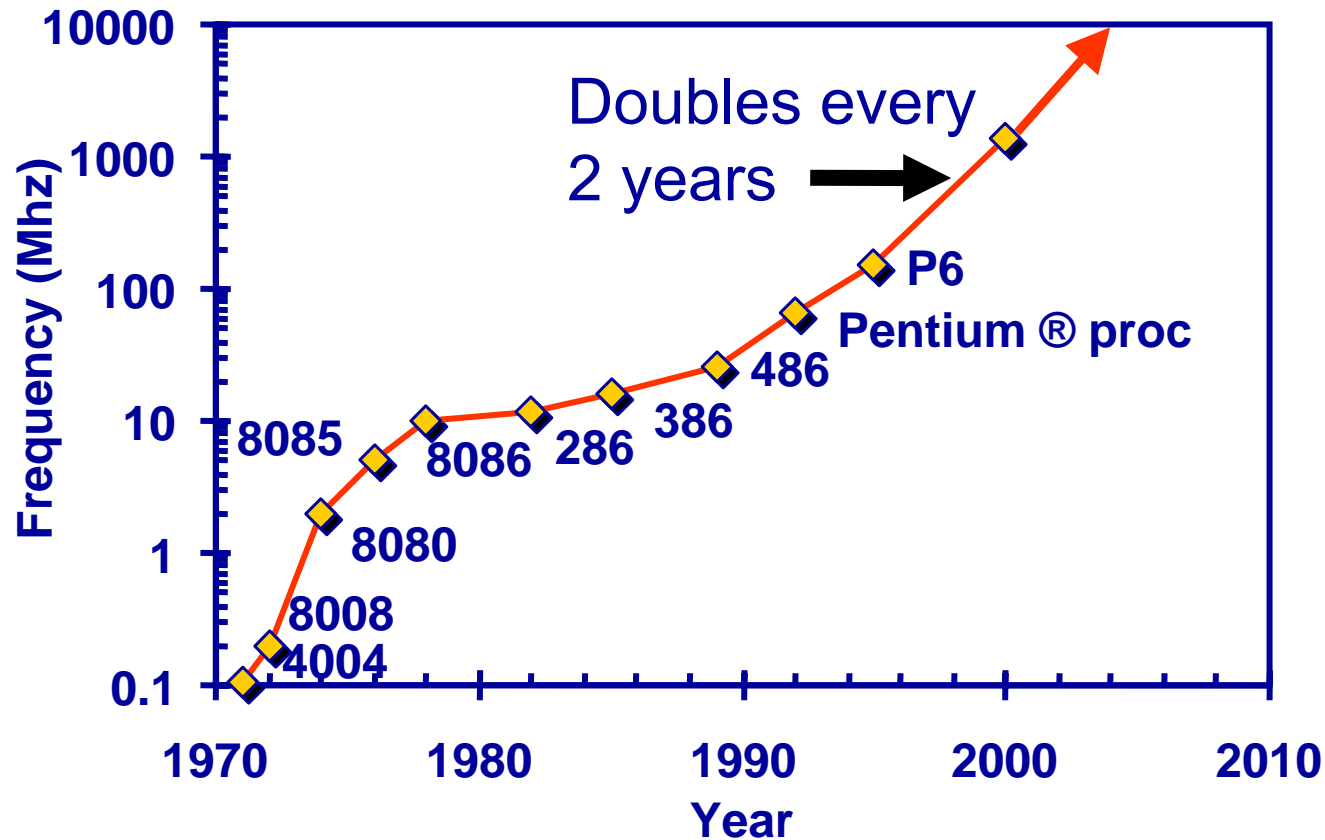
Die Size Growth



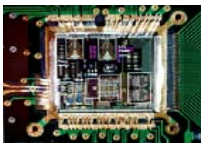
Die size grows by 14% to satisfy Moore's Law



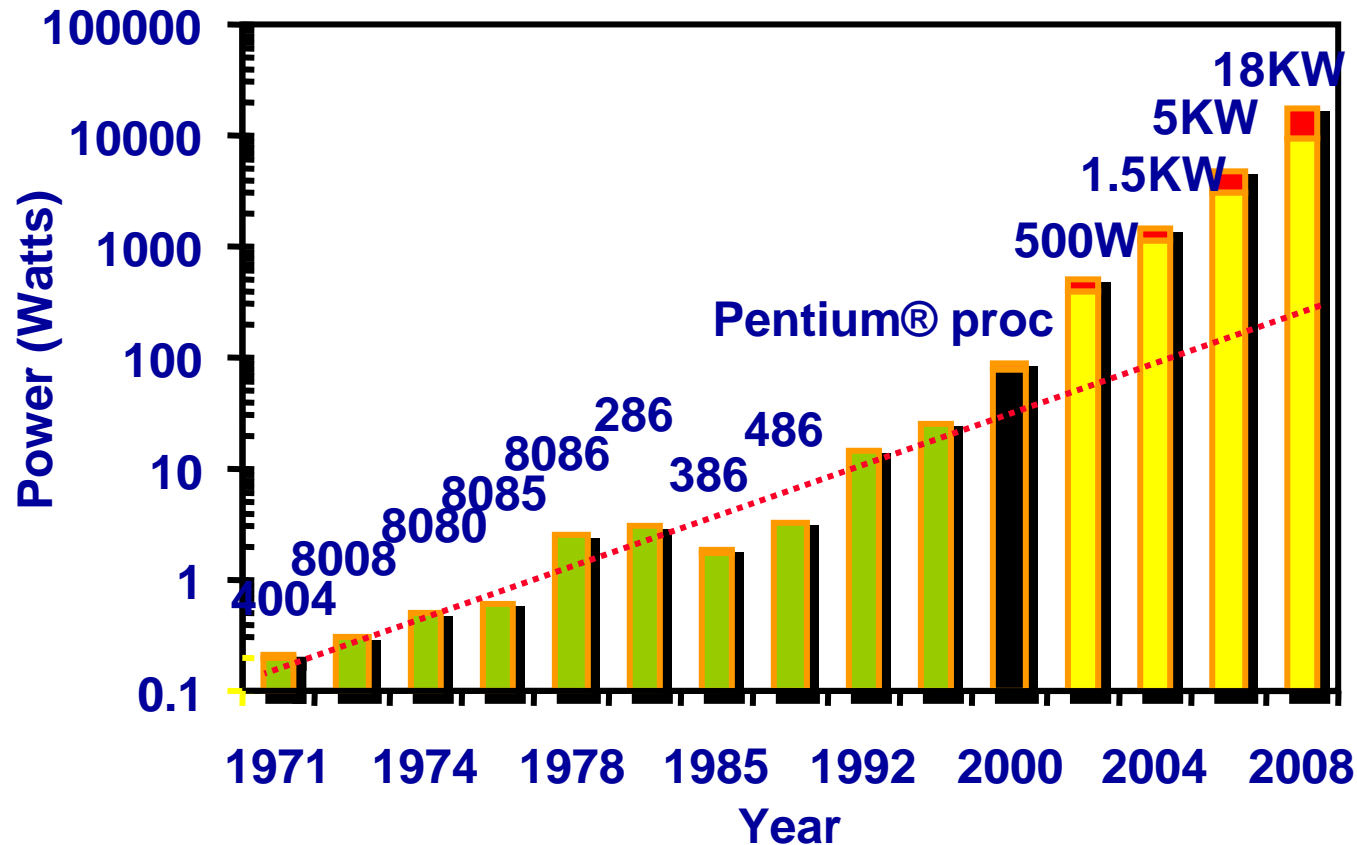
Increase in Operating Frequency



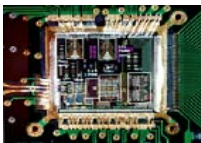
Lead Microprocessors frequency doubles every 2 years



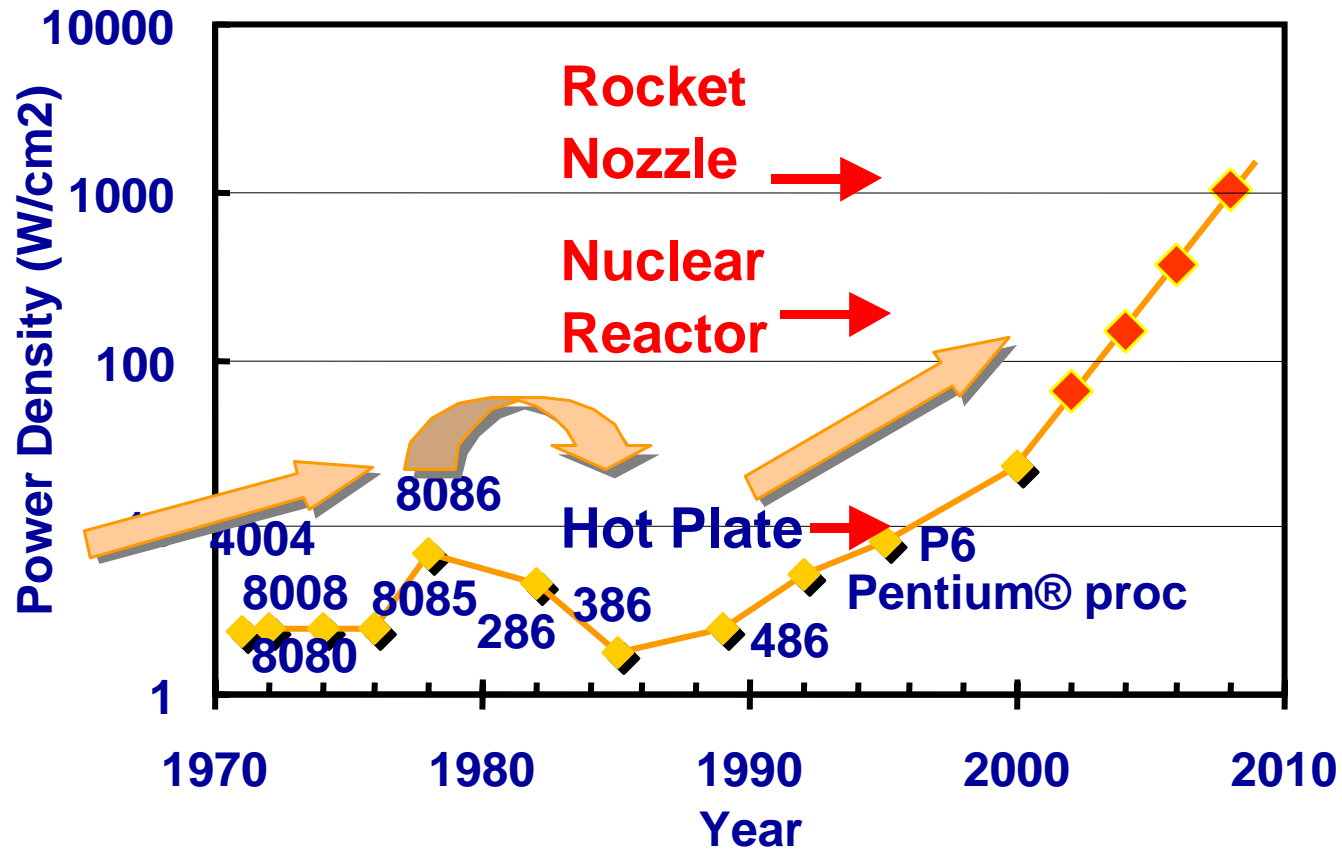
Power will be a major problem



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.

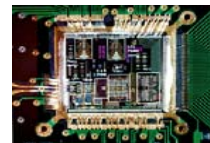


“Macroscopic Issues”

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

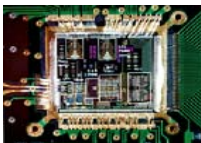
Everything Looks a Little Different

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



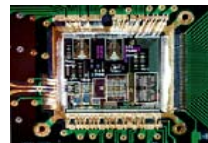
Design Metrics

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

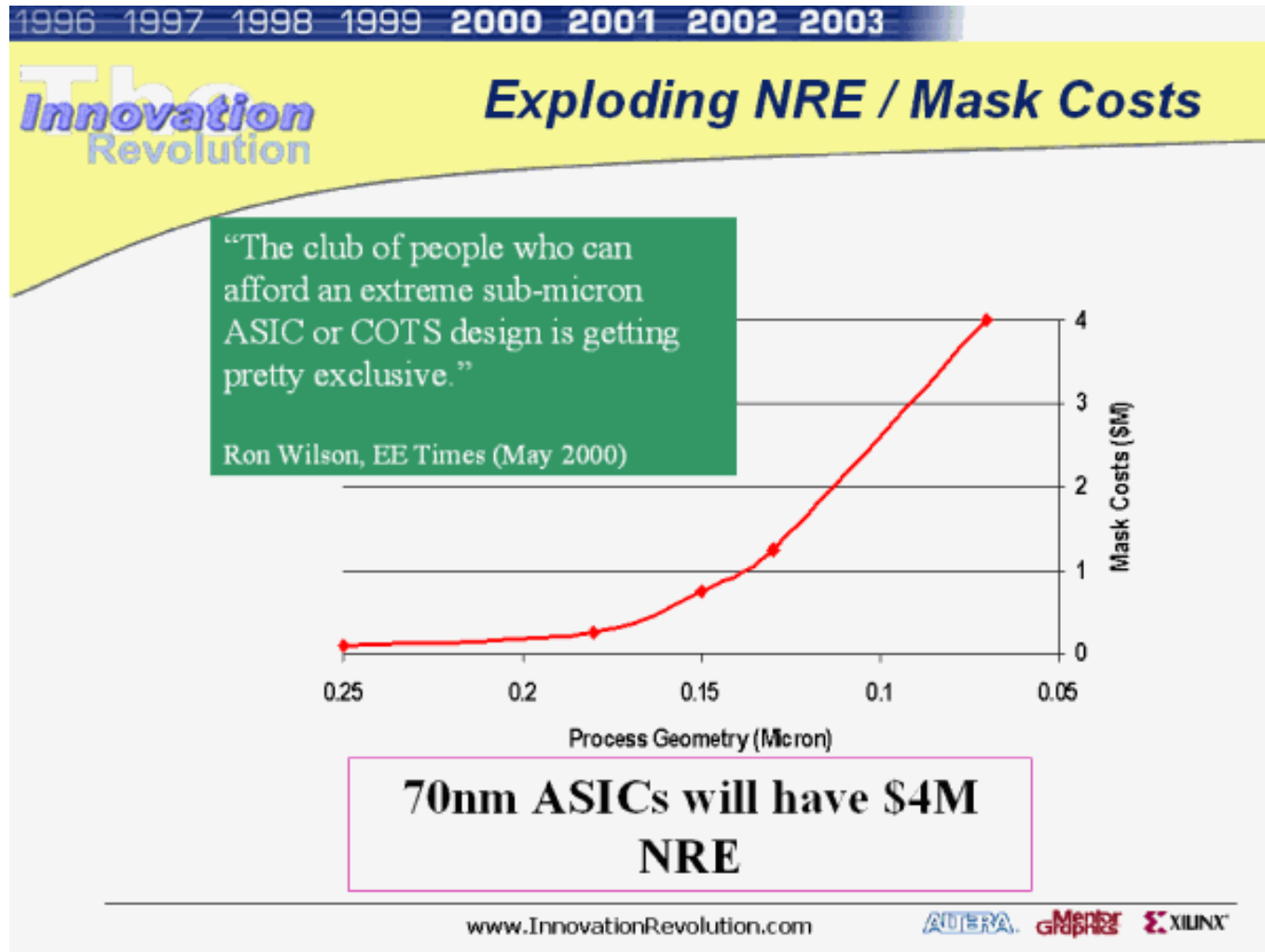


Cost of Integrated Circuits

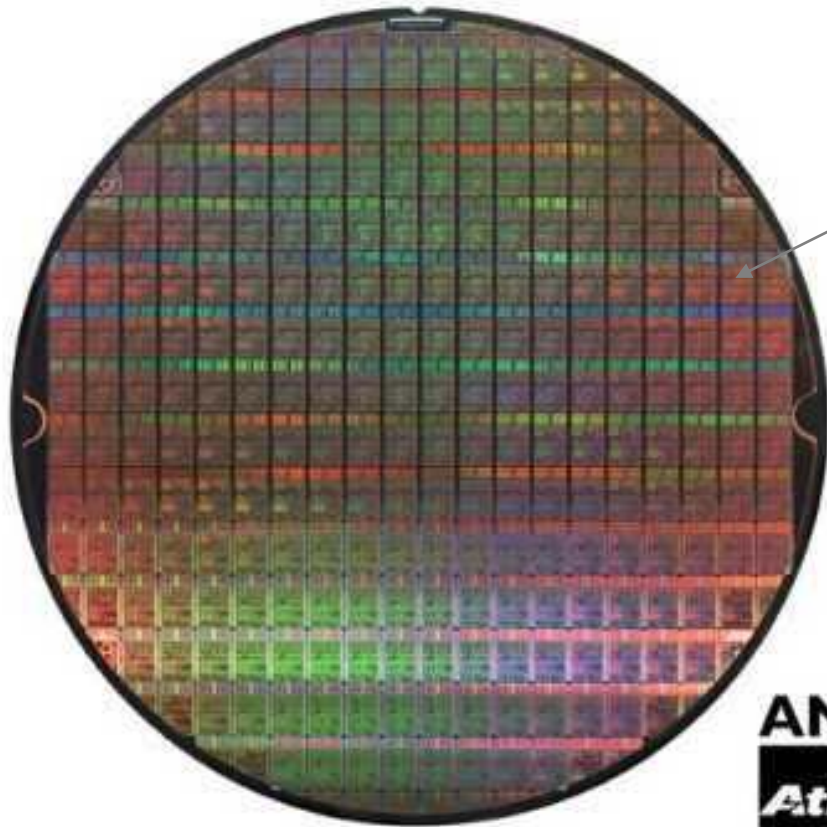
- NRE (non-recurrent engineering) costs
 - design time and effort, mask generation
 - one-time cost factor
- Recurrent costs
 - silicon processing, packaging, test
 - proportional to volume
 - proportional to chip area



NRE Cost is Increasing



Die Cost

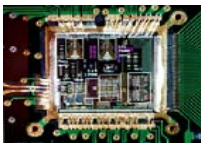


Single die

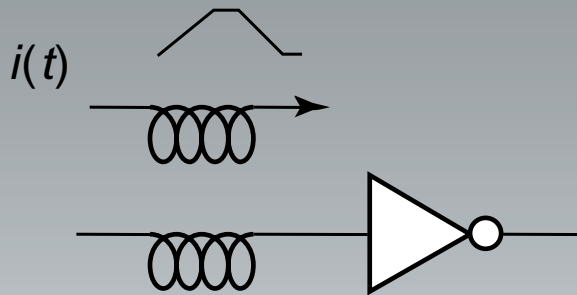
Wafer



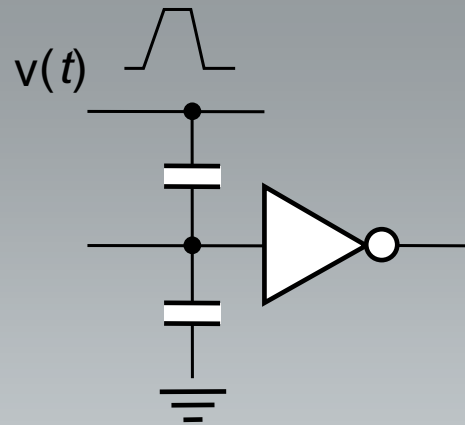
Going up to 12" (30cm)



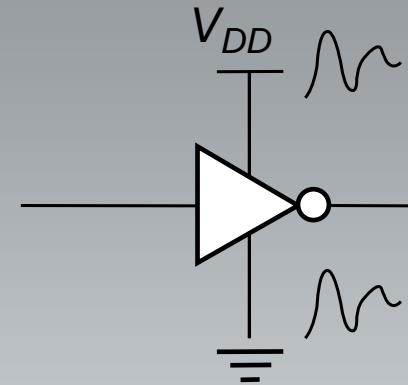
Reliability— Noise in Digital Integrated Circuits



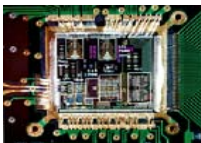
Inductive coupling



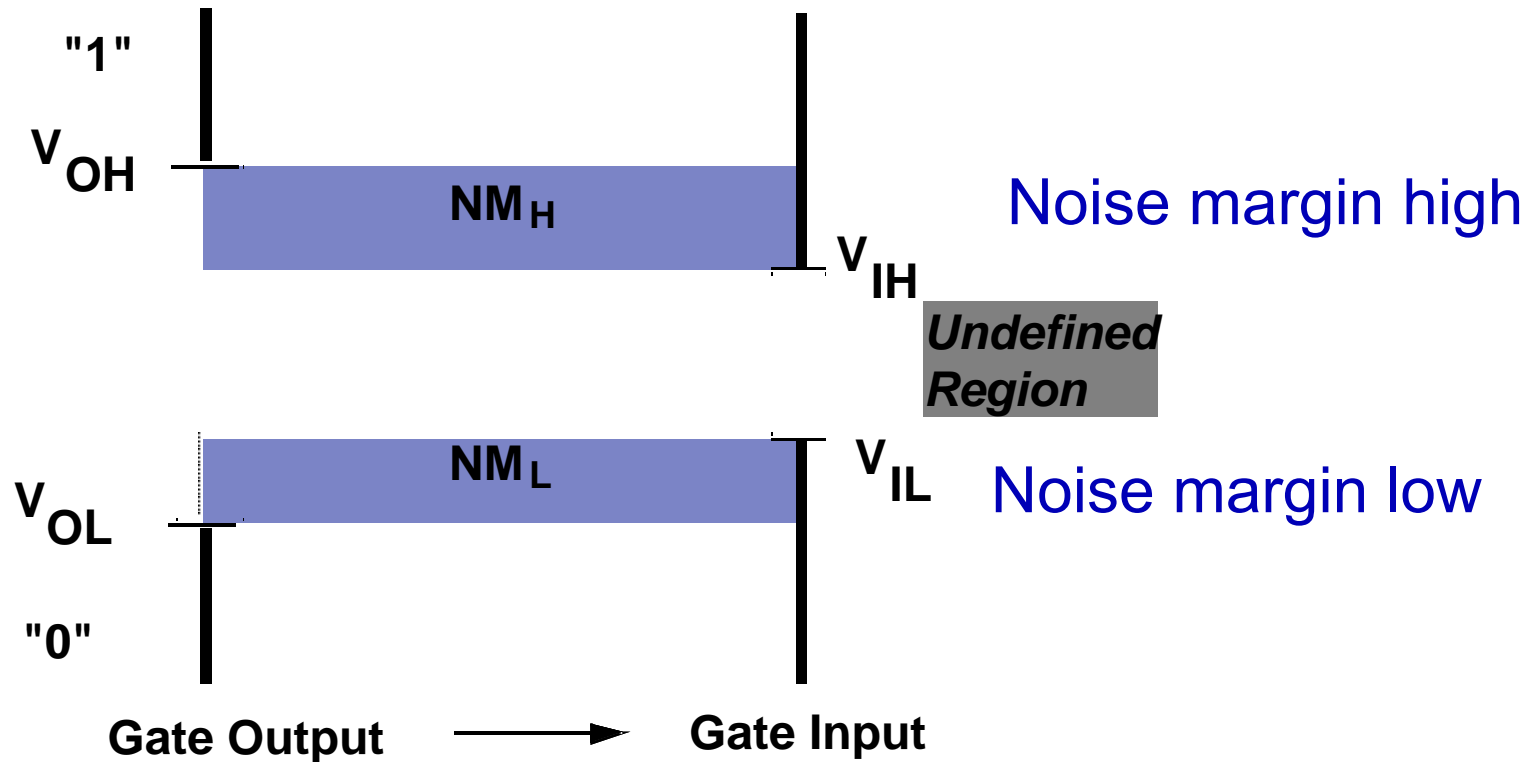
Capacitive coupling



**Power and ground
noise**



Definition of Noise Margins



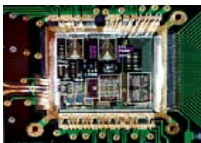
Noise Budget

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

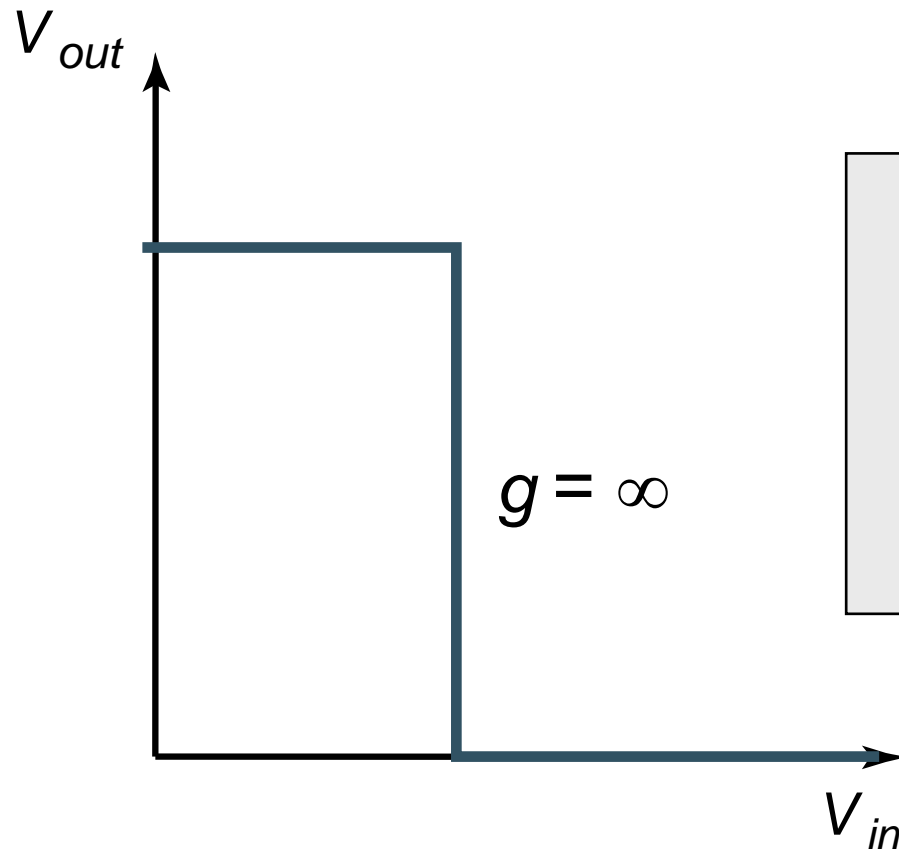


Key Reliability Properties

- 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;



The Ideal Gate



$$R_i = \infty$$

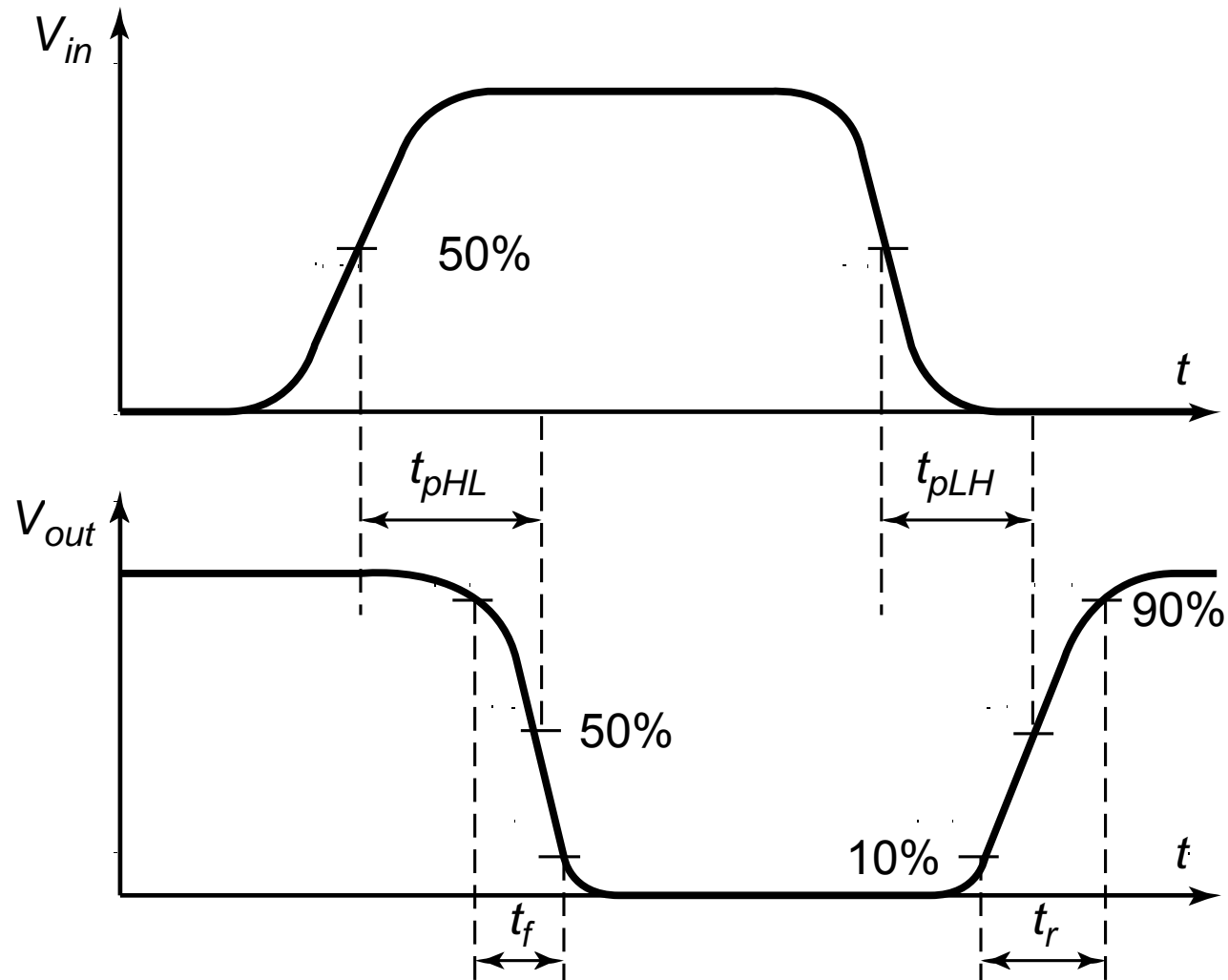
$$R_o = 0$$

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

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



Delay Definitions



Integrated Circuits Categories

There are many different types of ICs as listed below.

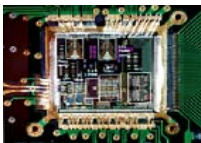
IC Categories	Functions
Analog ICs	Amplifiers
	Filters
Digital ICs	Boolean Gates
	Encoders/Decoders
	Multiplexers / Demultiplexers
	Flip-flops
	Counters
	Shift Registers
Hybrid ICs	Mixed Signal Processors
Interface ICs	Analog-Digital Converters
	Digital-Analog Converters



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



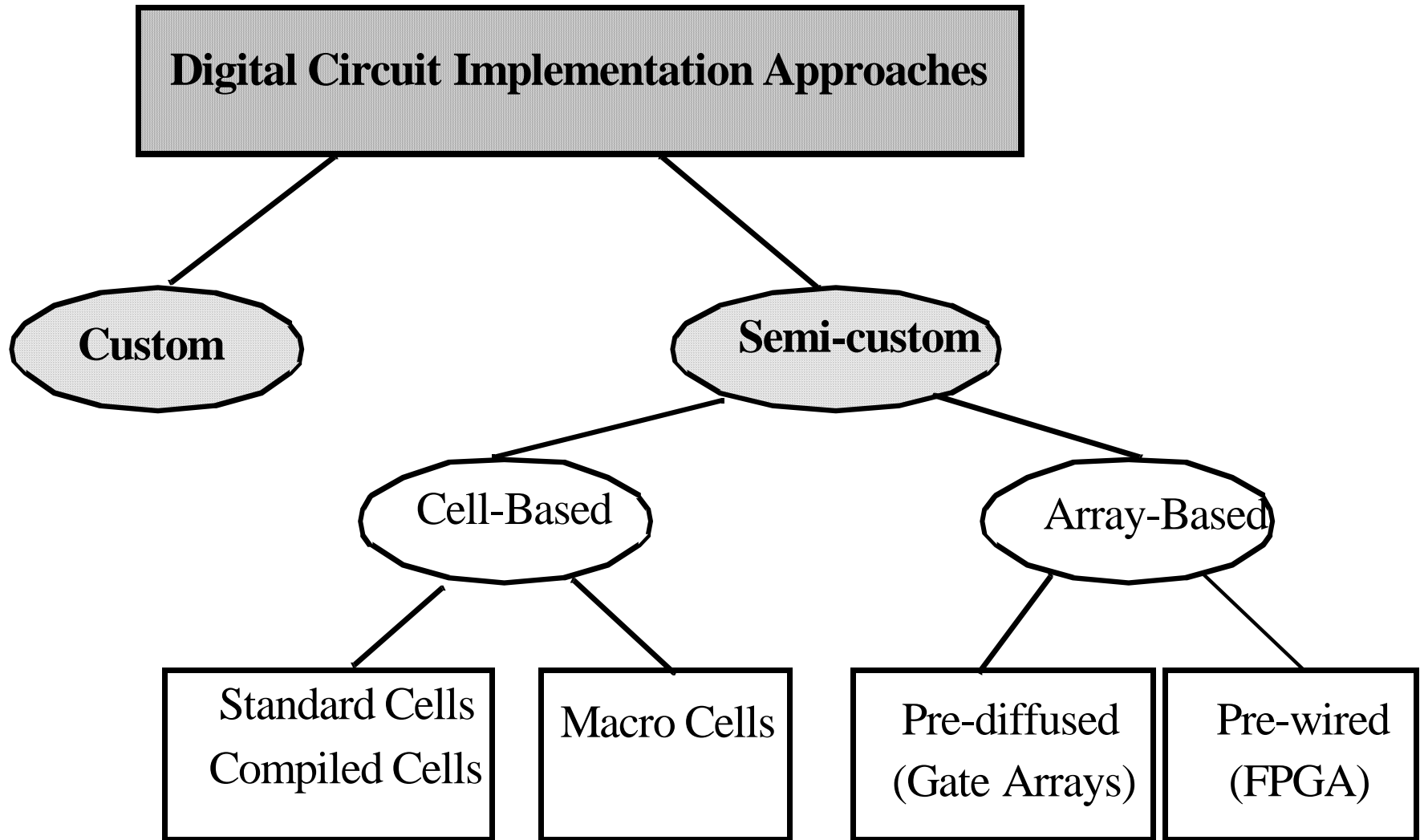
Digital Logic Families

- 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

