

Digital Integrated Circuits
A Design Perspective

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Introduction

Edited by
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What is this Course all about?

- **Introduction to digital integrated circuits.**
  - CMOS devices and manufacturing technology. CMOS inverters and gates. Dynamics, Speed, Propagation delay, noise margins, and Energy-power dissipation. Sequential circuits. Arithmetic, interconnect, and Memories. Programmable logic arrays. Design methodologies.
- **What will you learn?**
  - Understanding, designing, and optimizing digital circuits with respect to different quality metrics: cost, speed, power dissipation, and reliability

Digital Integrated Circuits

Sample Topics:

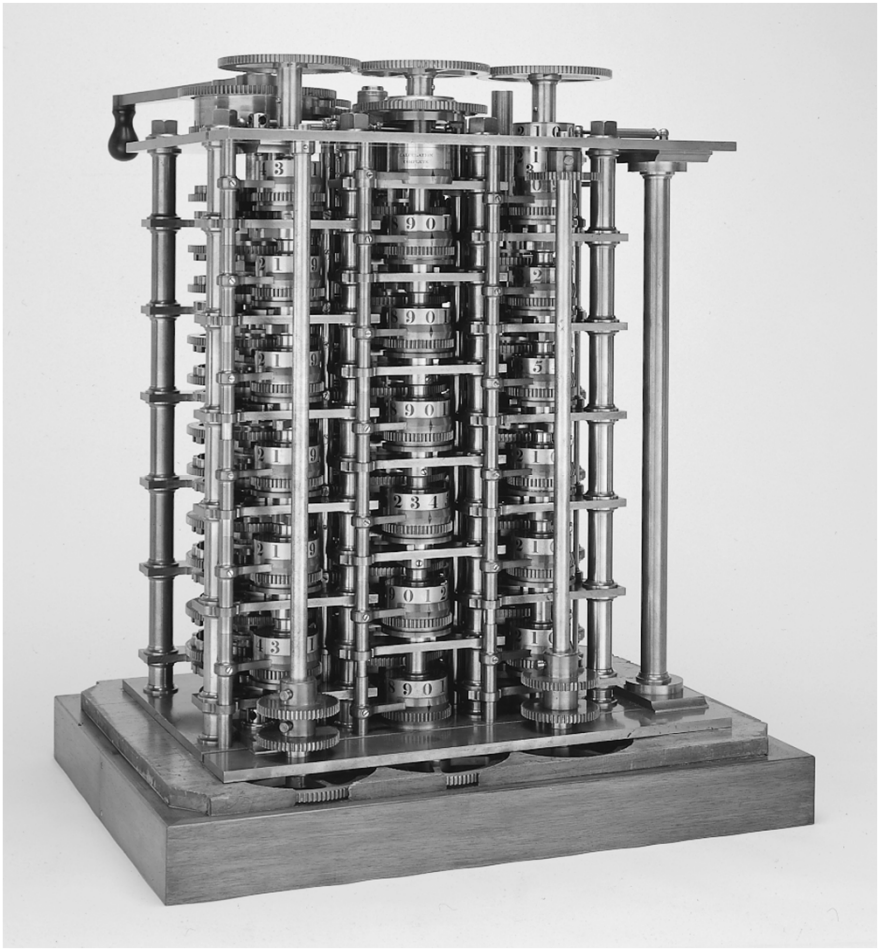
- Introduction: Issues in integrated design
- The CMOS inverter– Basic (building) gate
- Combinational logic structures
- Sequential logic gates
- Design methodologies
- Interconnect: R, L and C
- Timing
- Arithmetic building blocks
- Memories and array structures

Introduction

- Why is designing digital ICs different today than it was before? reaching the quantum wall
- Will it change in future? YES



The First Computer



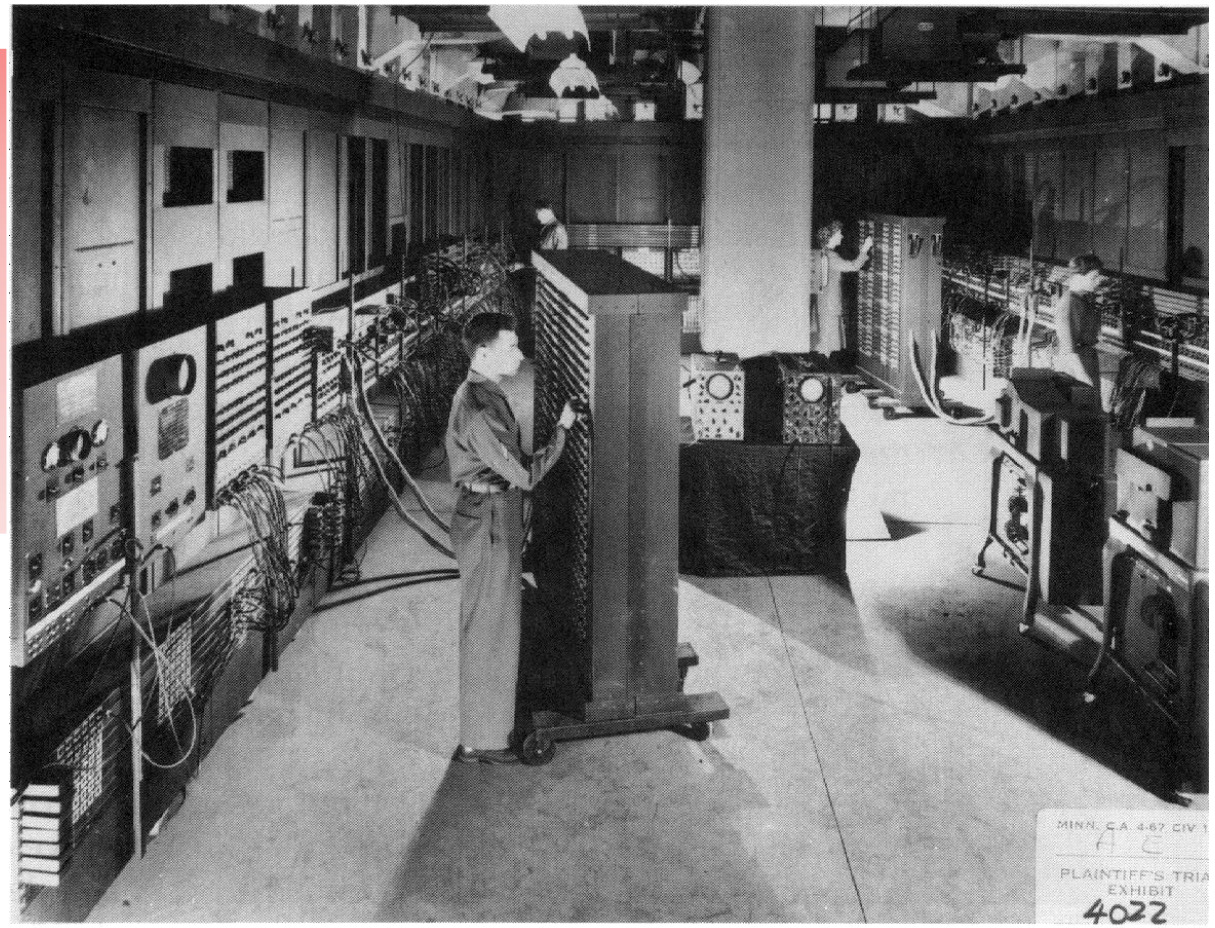
The Babbage Difference Engine (1832)

25,000 parts

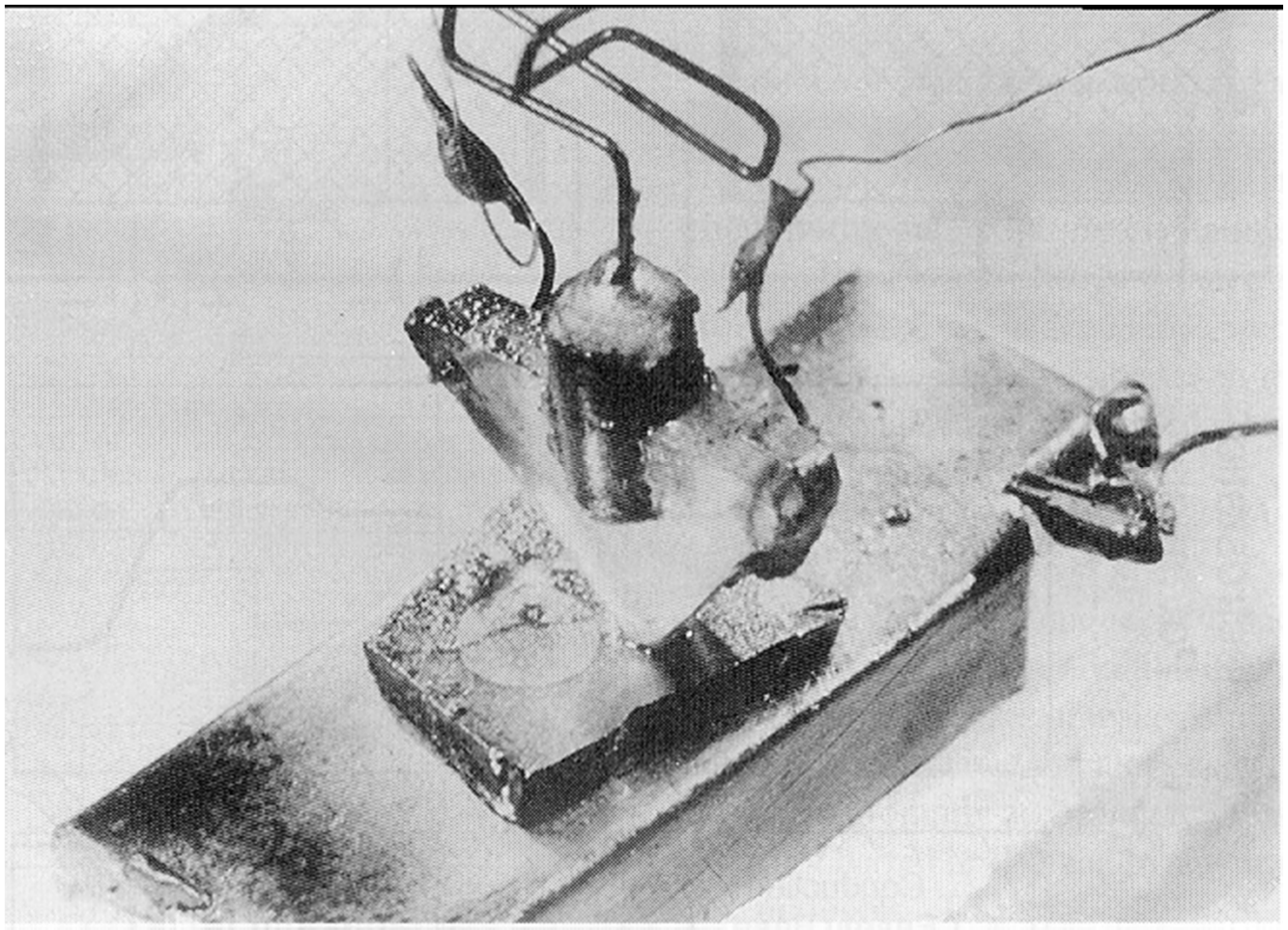
cost: £17,470

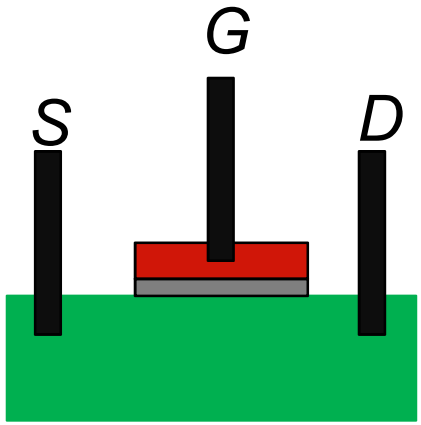
ENIAC - The first electronic computer (1946)

Using Switches, relays, and Vacuum Tubes:



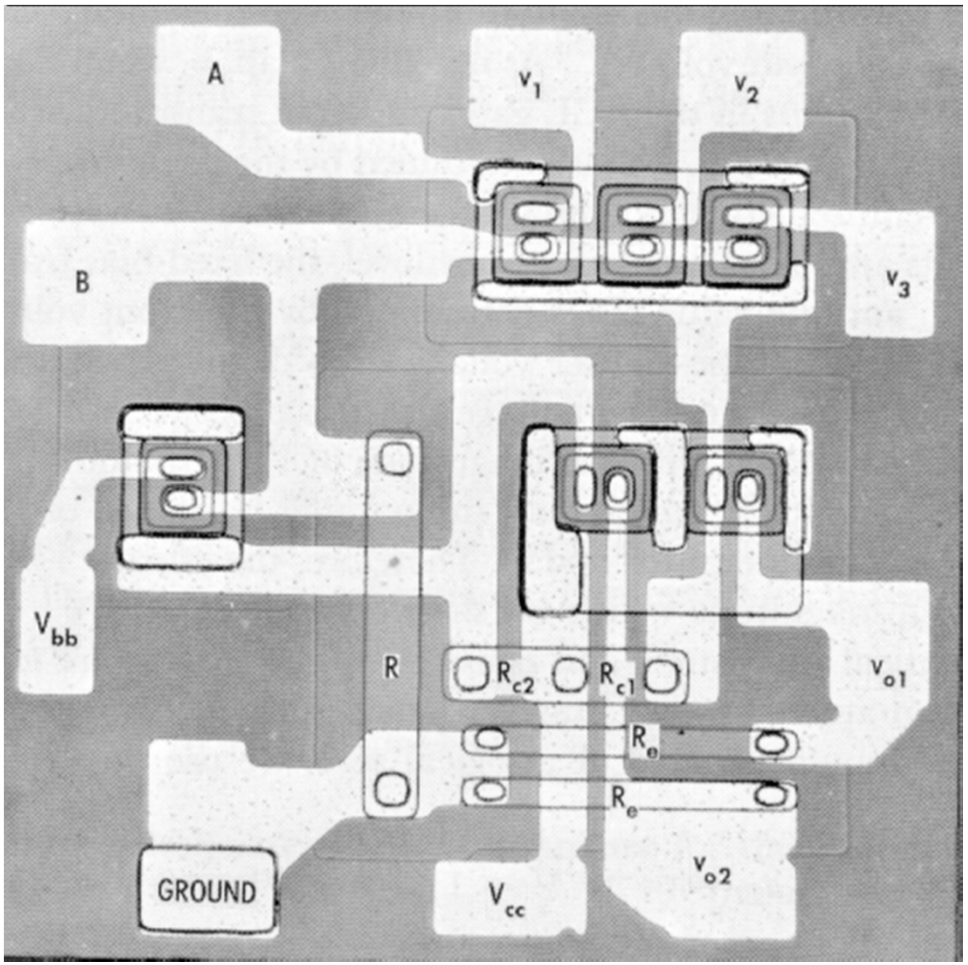
The Transistor Revolution





First transistor
Bell Labs, 1948

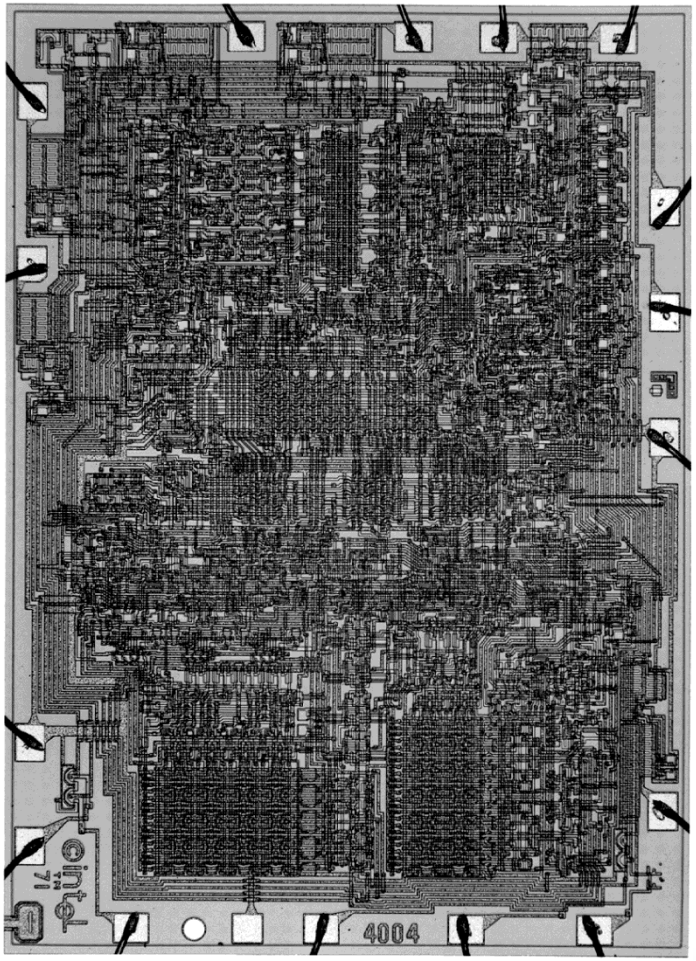
The First Integrated Circuits



Bipolar logic
1960's

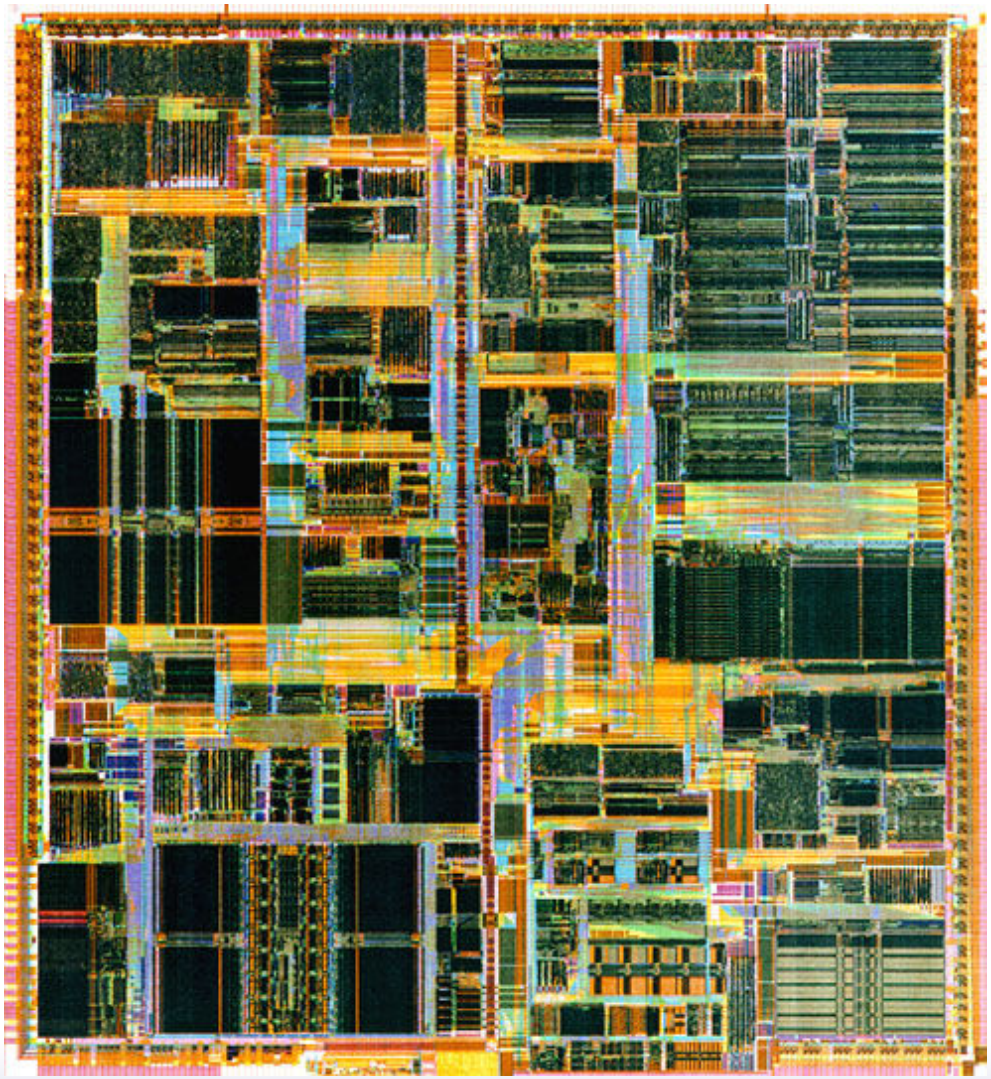
ECL 3-input Gate
Motorola 1966

Intel 4004 Micro-Processor



1971
1000 transistors
1 MHz operation

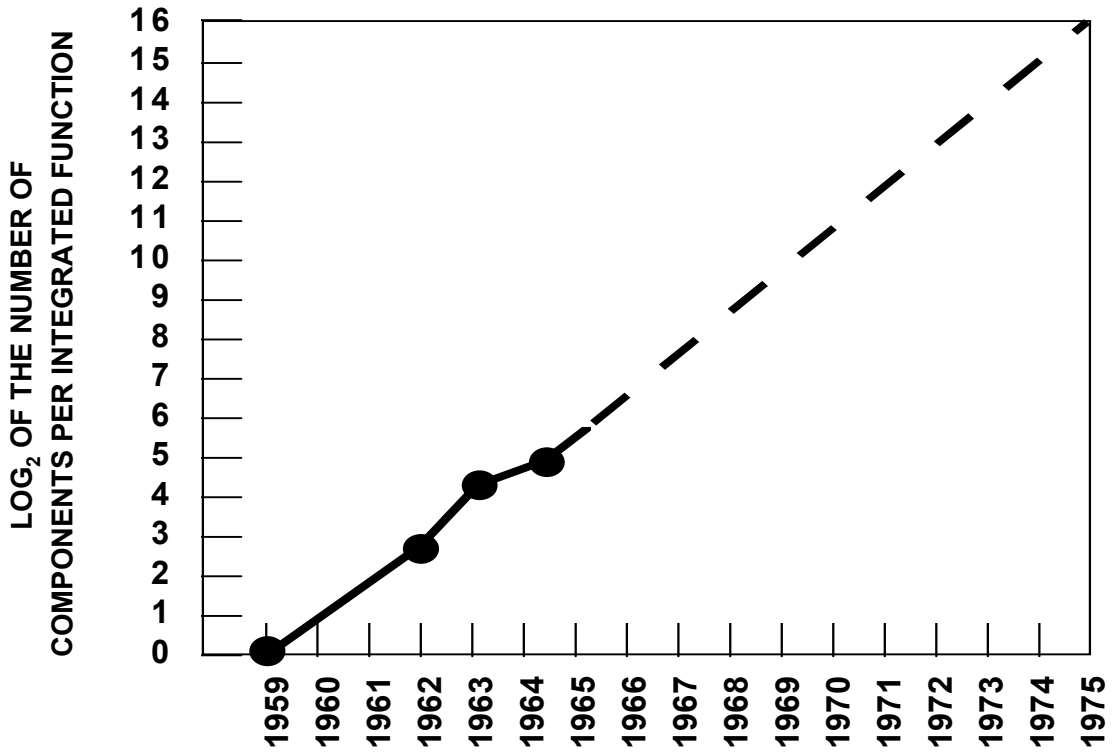
Intel Pentium (IV) microprocessor



Moore's Law

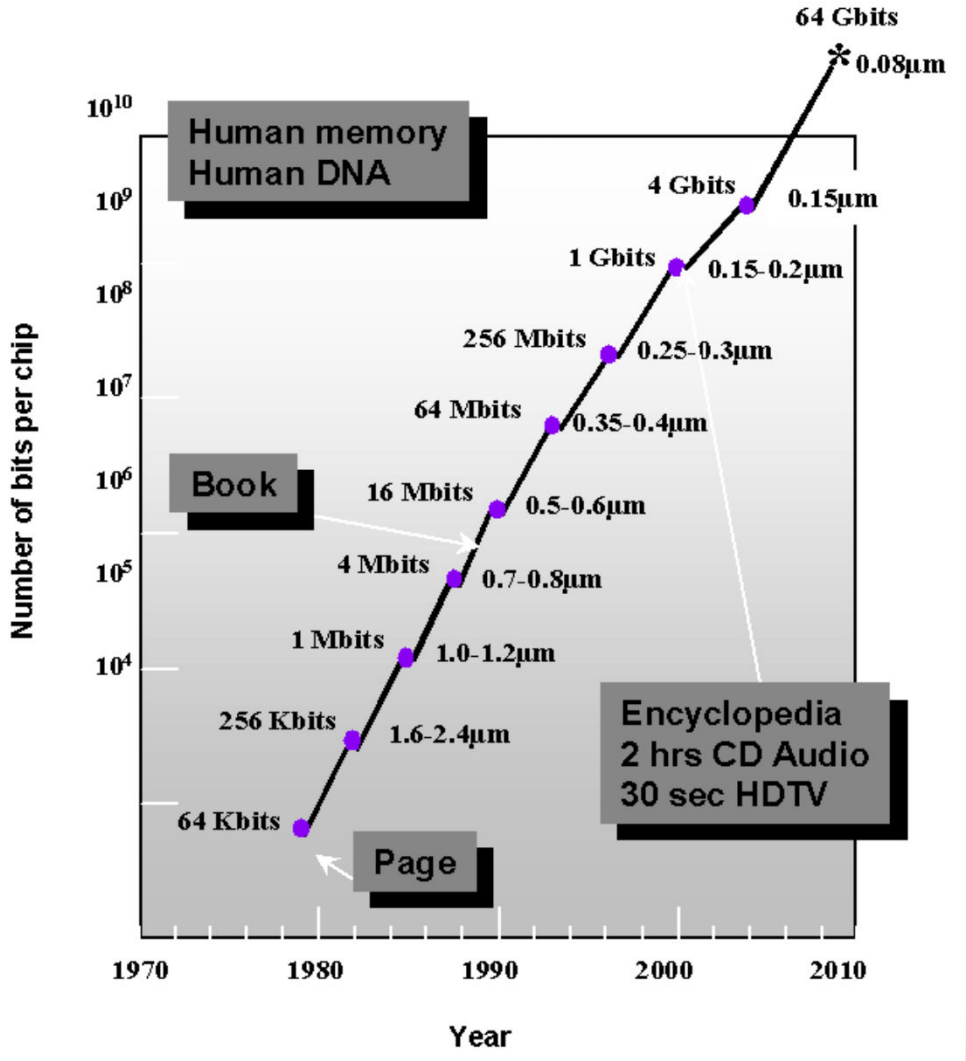
- In 1965, Gordon Moore noted that the number of transistors on a chip doubled every 18 to 24 months.
- He made a prediction that semiconductor technology will double its effectiveness every 18 months

Moore's Law

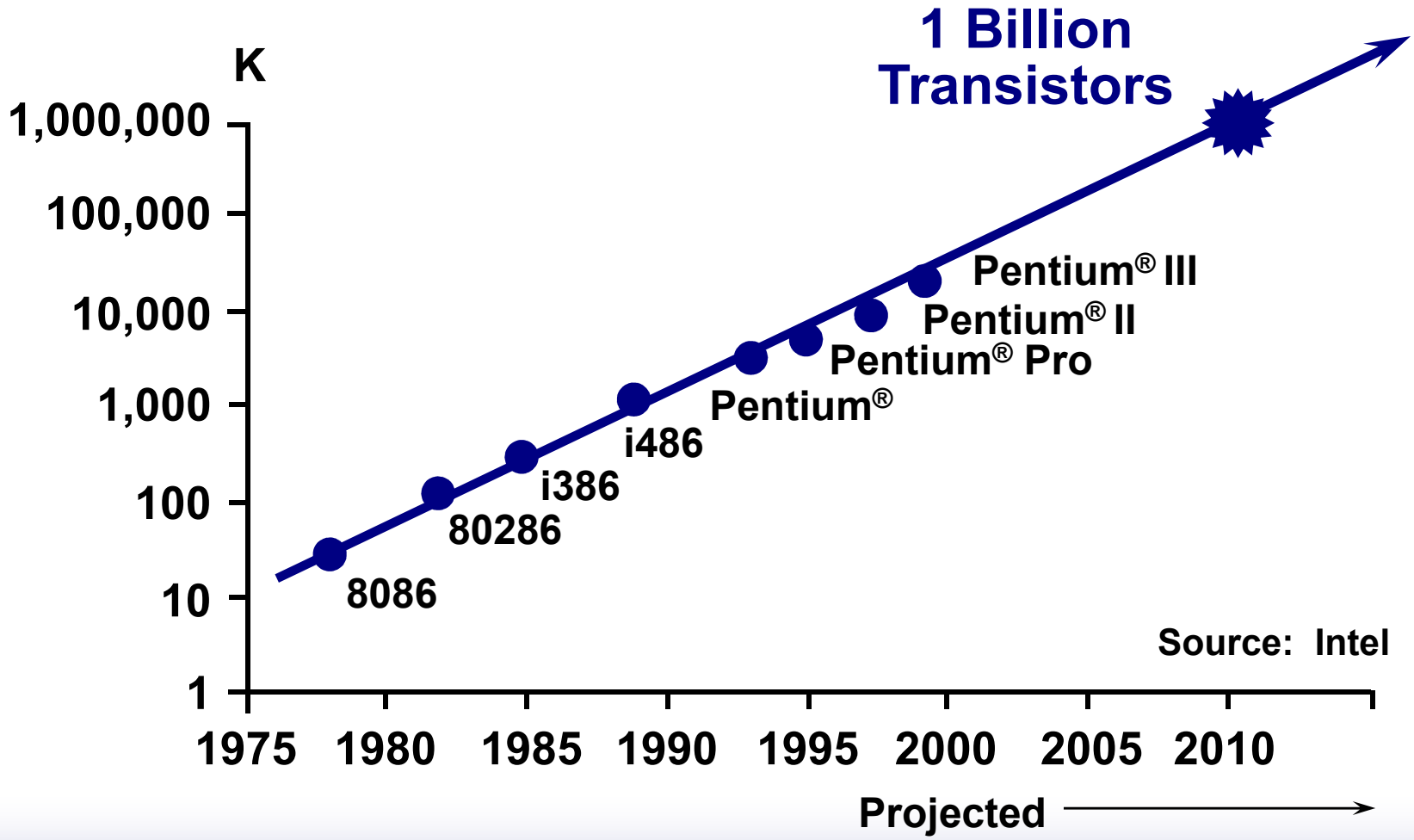


Electronics, April 19, 1965.

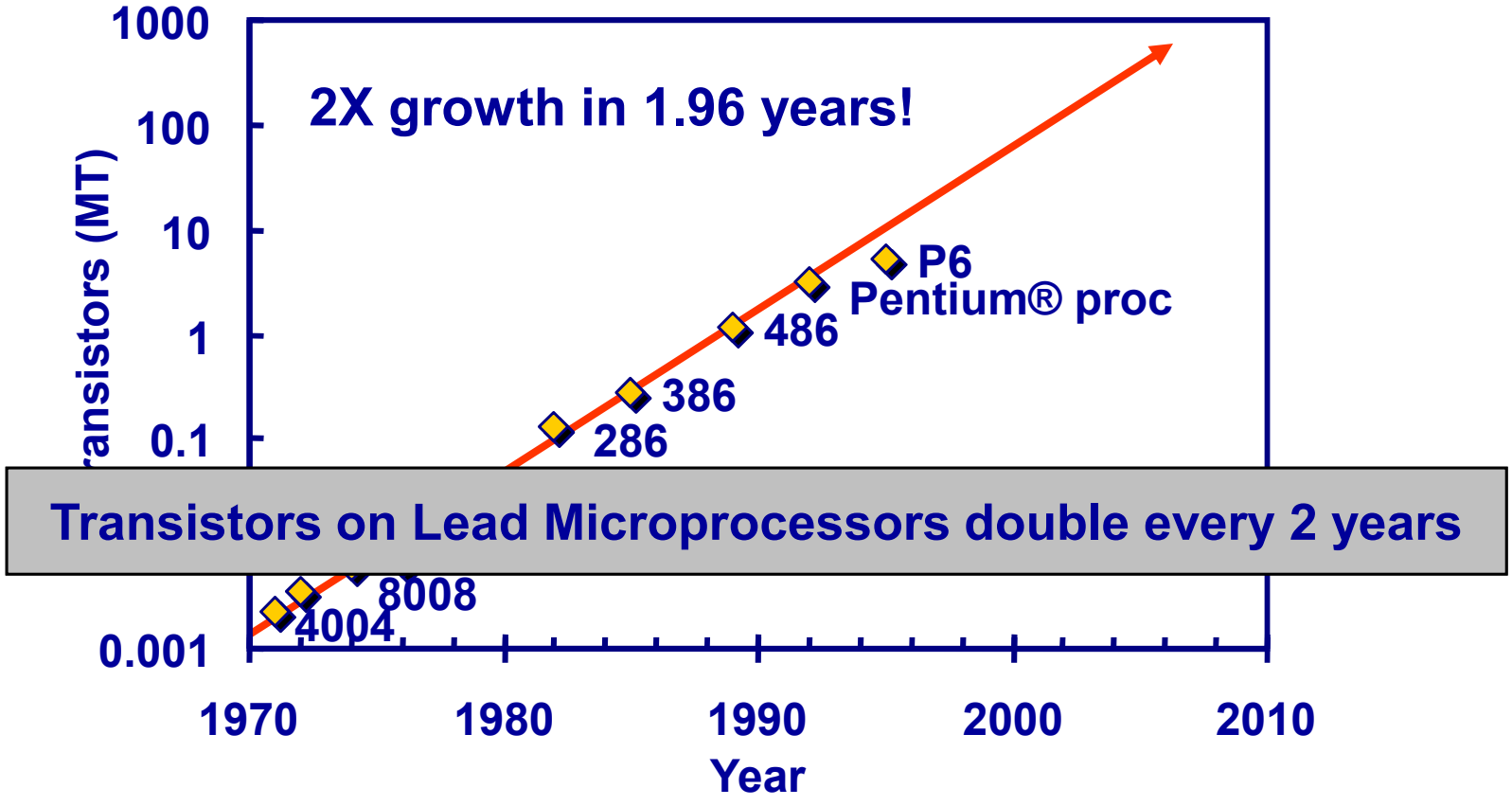
Evolution in Complexity



Transistor Counts



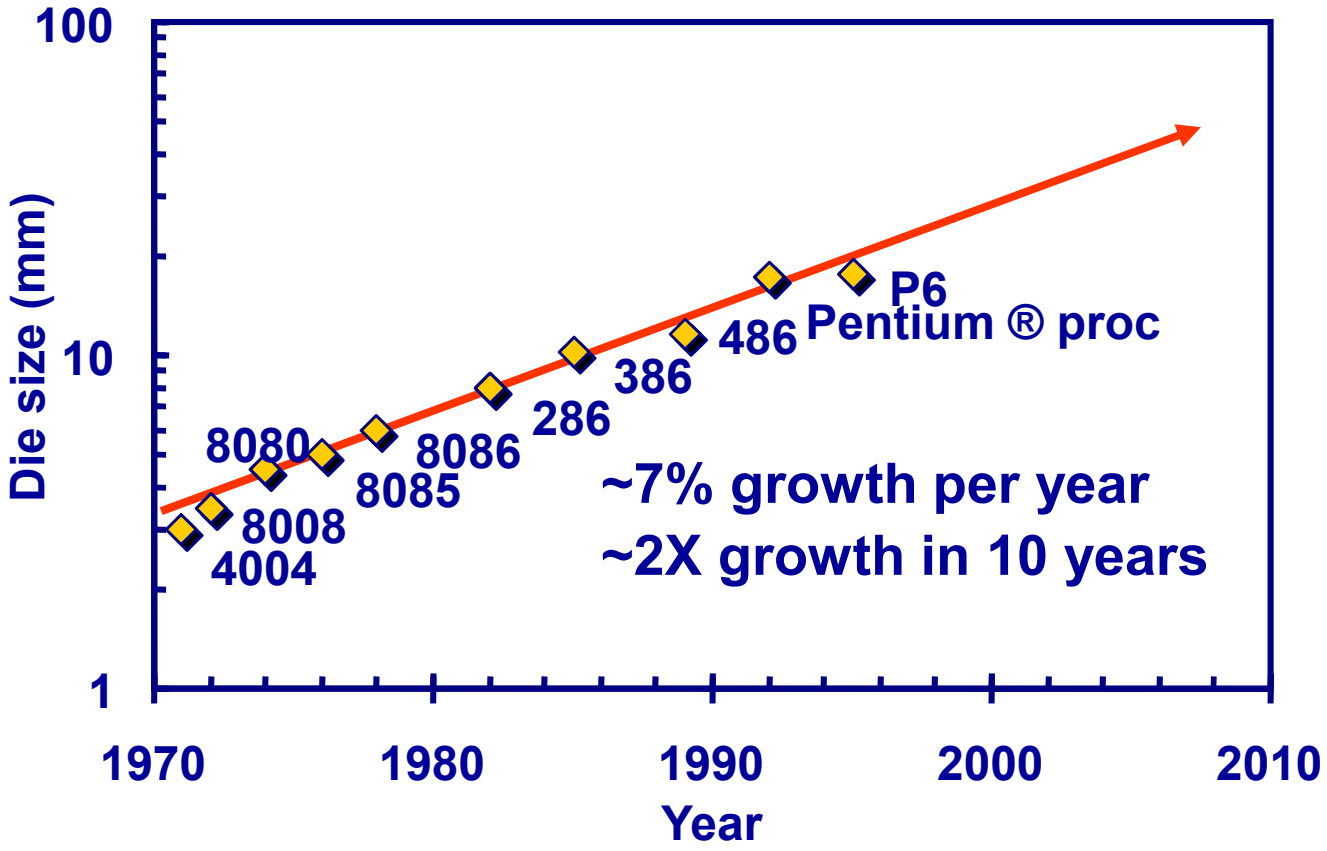
Moore's law in Microprocessors



Transistors on Lead Microprocessors double every 2 years

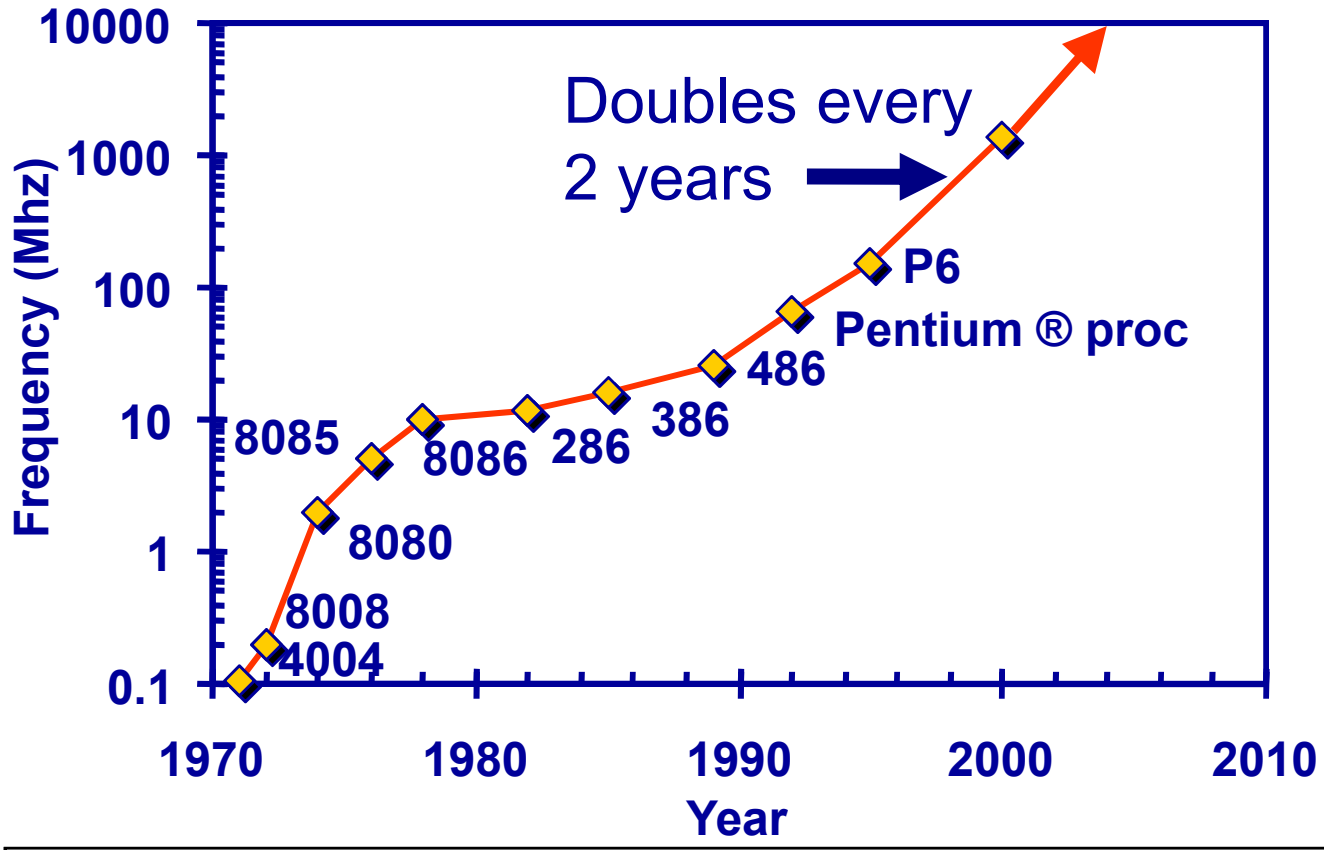
Courtesy, Intel

Die Size Growth



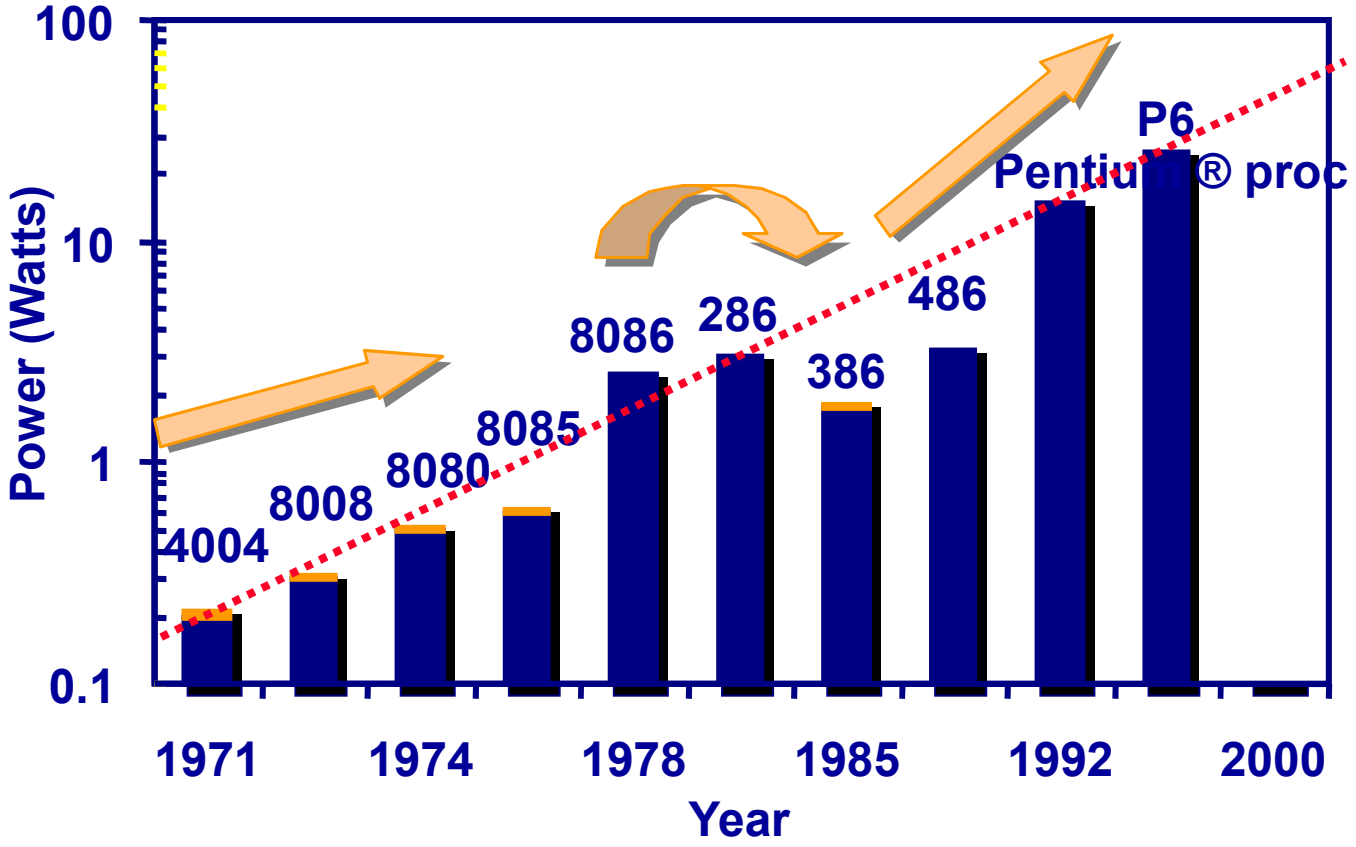
Die size grows by 14% to satisfy Moore's Law

Frequency



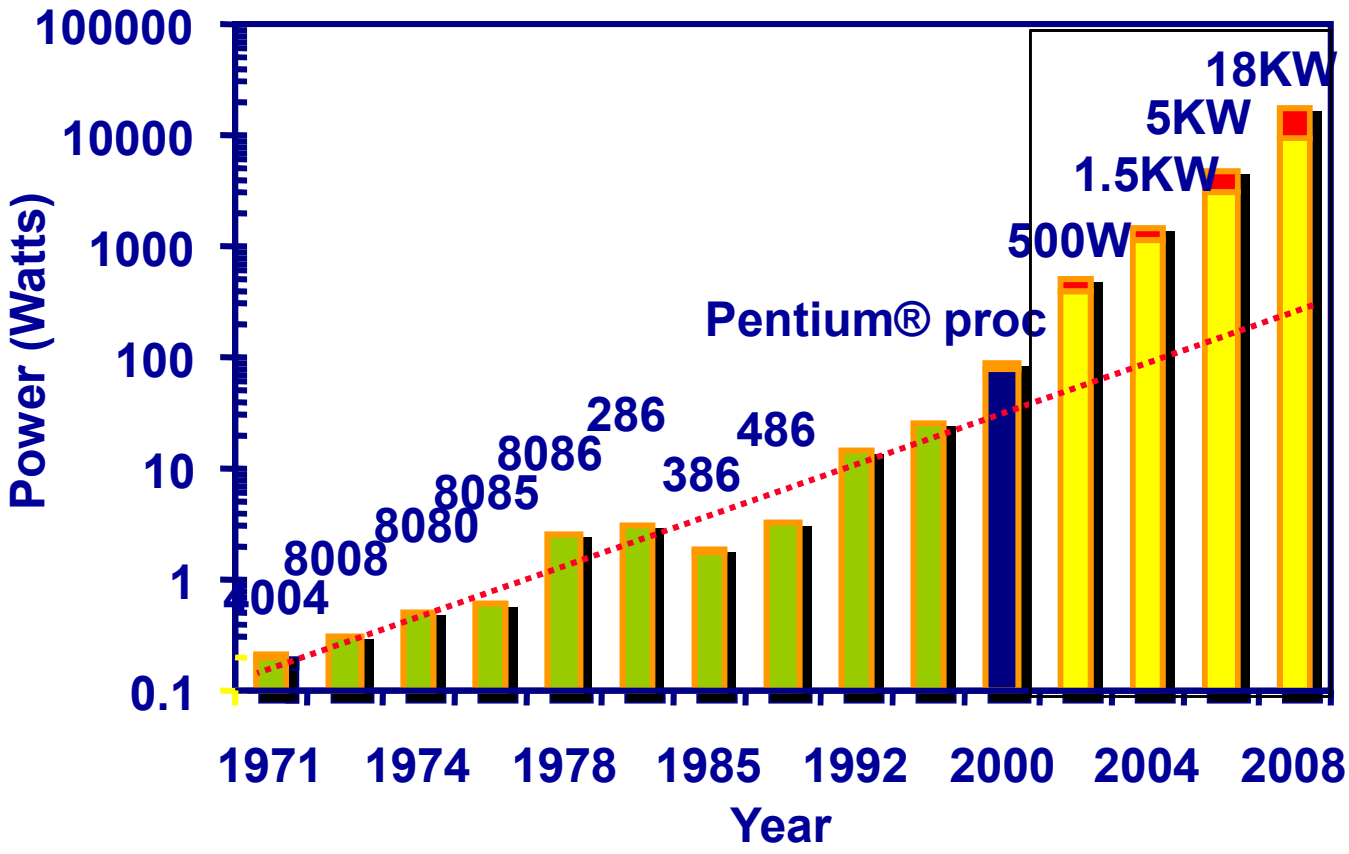
Lead Microprocessors frequency doubles every 2 years

Power Dissipation



Lead Microprocessors power continues to increase

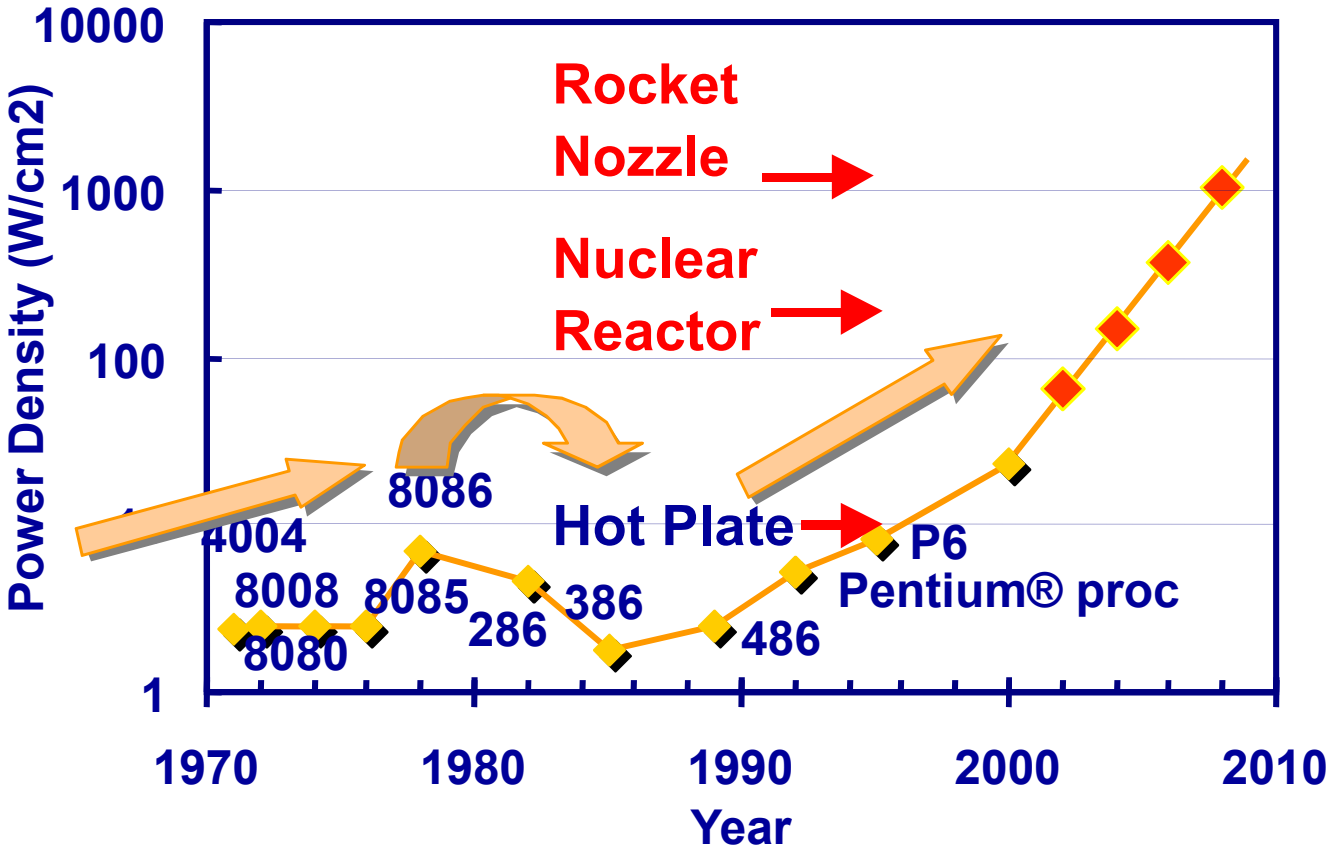
Power will be a major problem



Power delivery and dissipation may become prohibitive

No so-- smart designers have always found a way!!!

Power density



Power density too high to keep junctions at low temp

Not Only Microprocessors

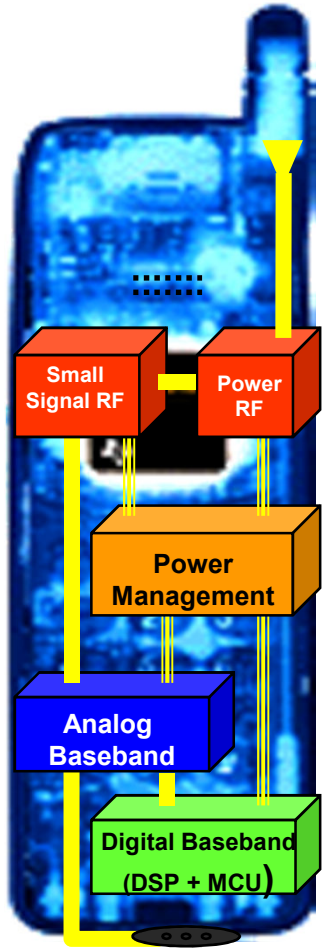
Cell Phone



Digital Cellular Market (Phones Shipped)

	1996	1997	1998	1999	2000
Units	48M	86M	162M	260M	435M

(data from Texas Instruments)



Challenges in Digital Design

∝ 1/DSM

"Microscopic Problems"

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



"Macroscopic Issues"

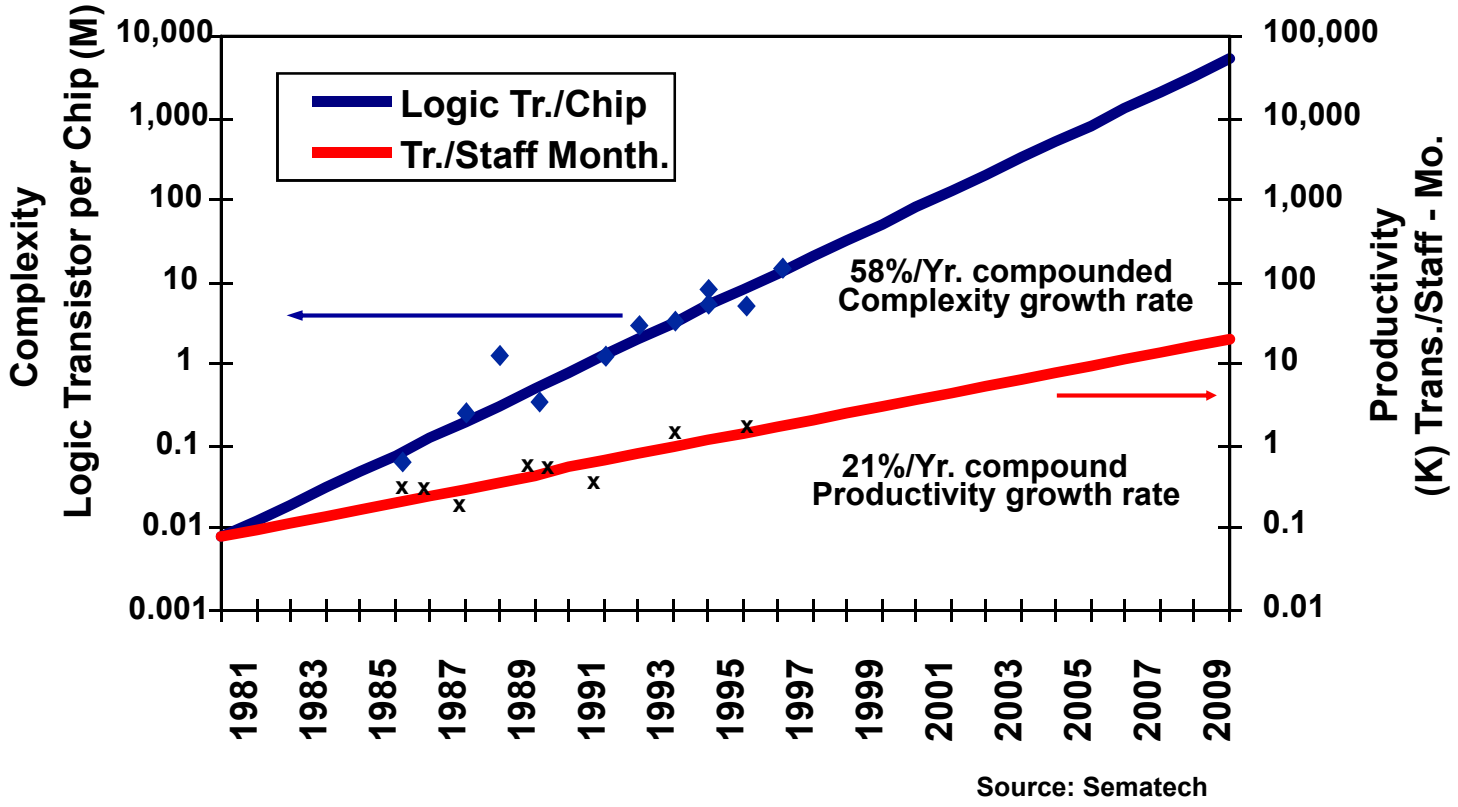
- Time-to-Market
- Millions of Gates
- High-Level Abstractions
- Reuse & IP: Portability
- Predictability
- etc.

Everything Looks a Little Different

?

…and There's a Lot of Them!

Productivity Trends

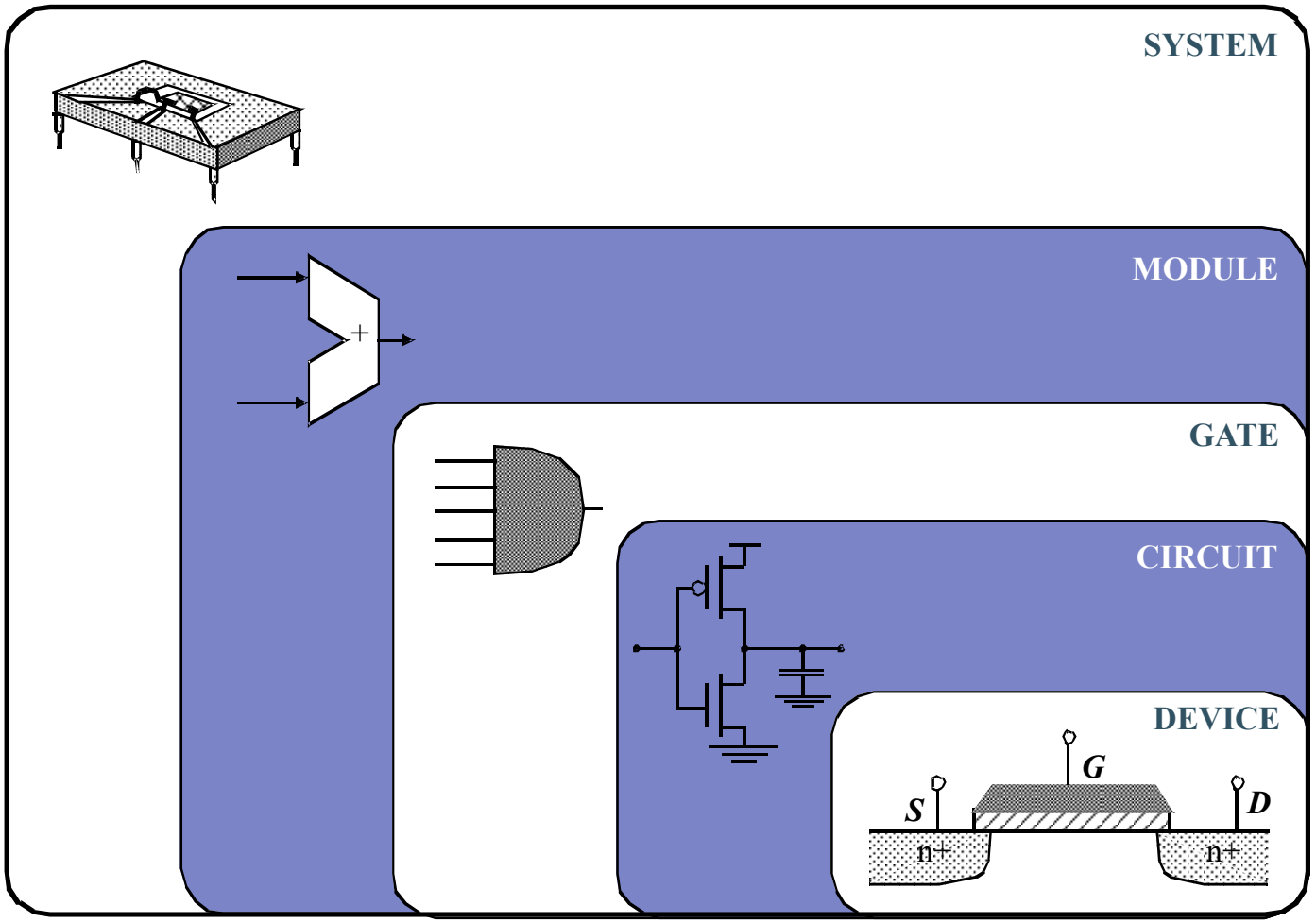


Complexity outpaces design productivity

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

Design Abstraction Levels



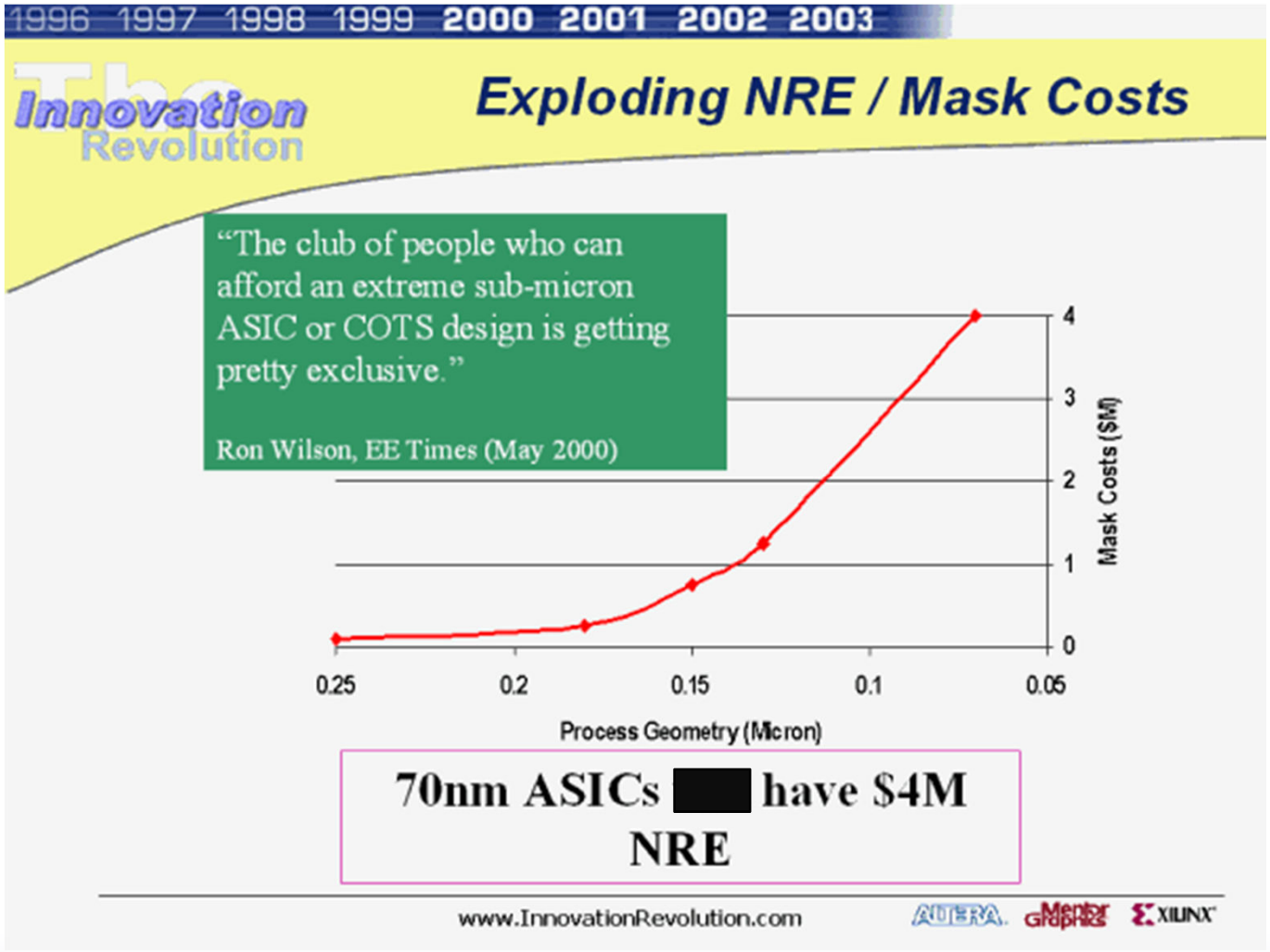
Design Metrics

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

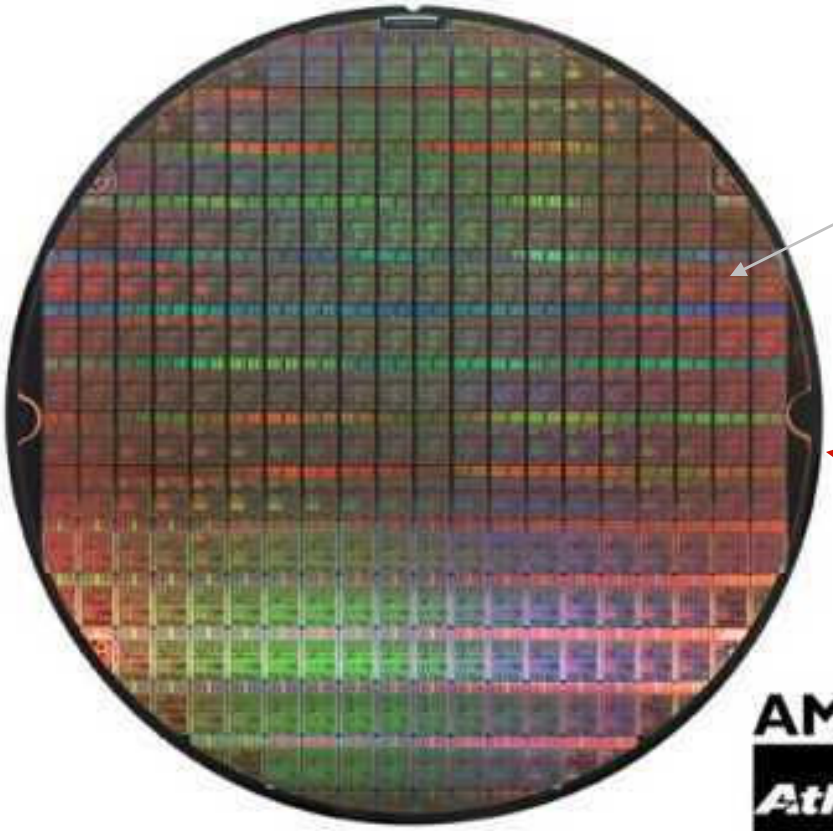
Cost of Integrated Circuits

- 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



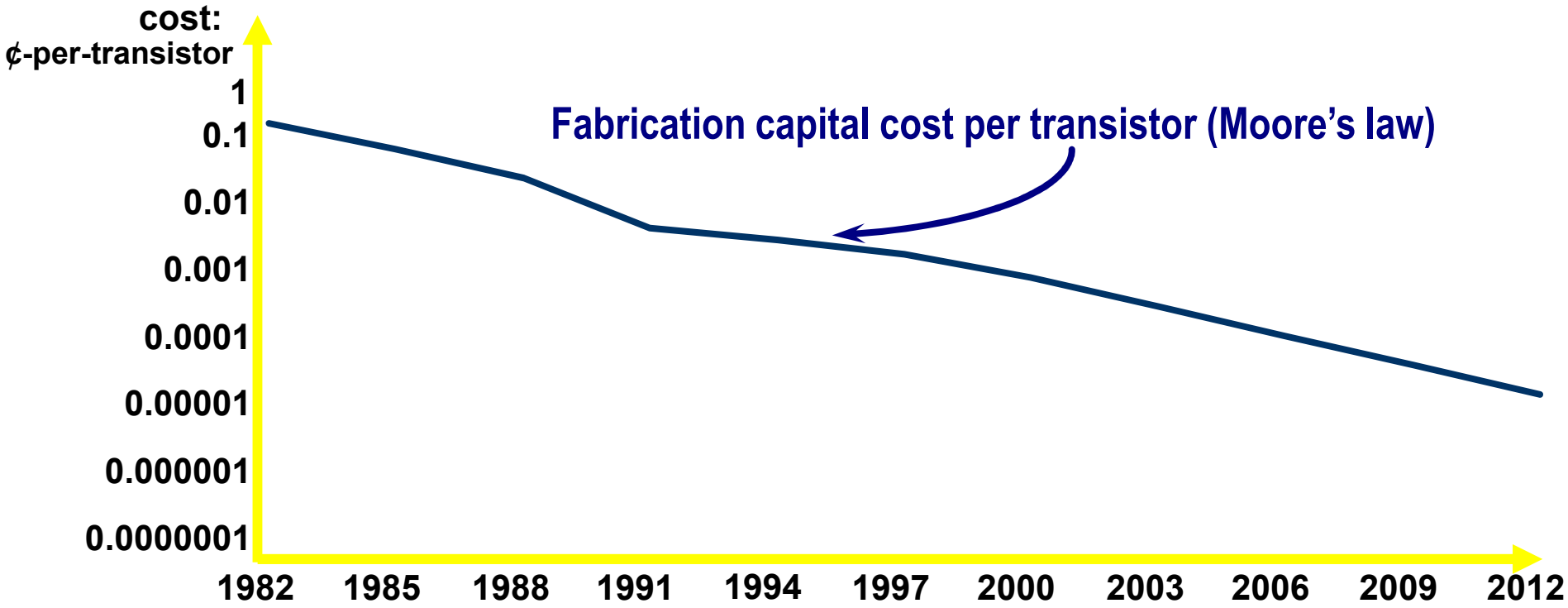
Die Cost



Going up to 12" (30cm)

From http://www.amd.com

Cost per Transistor

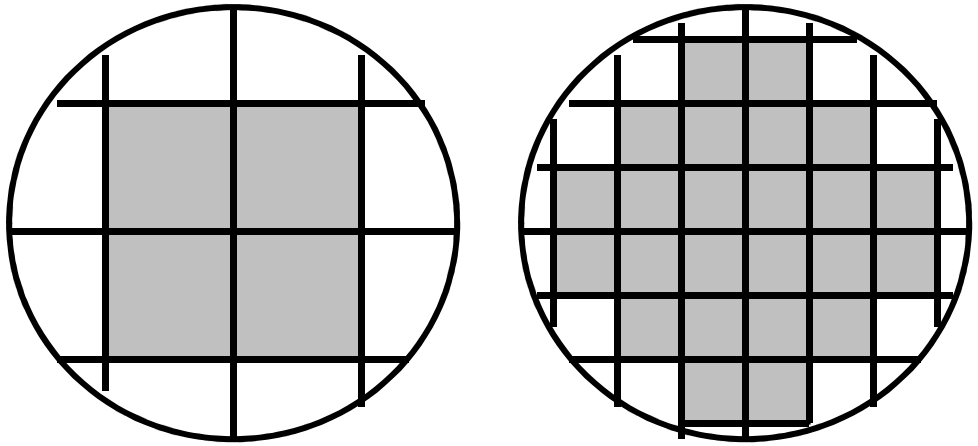


Yield

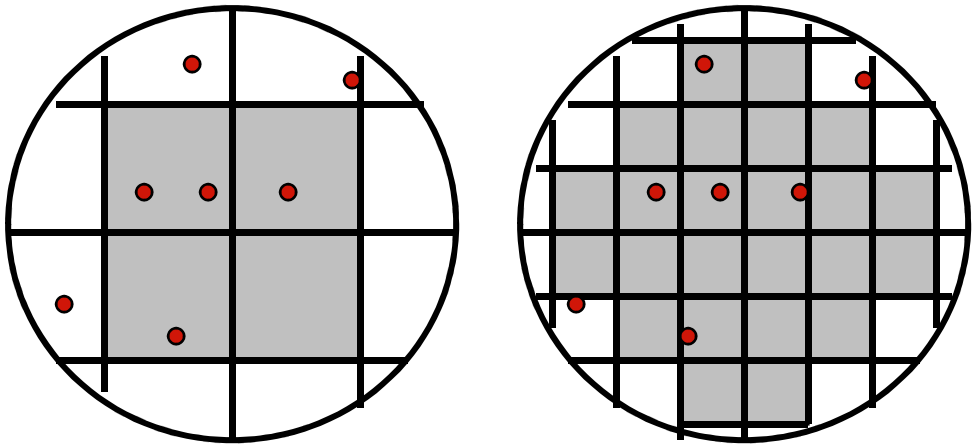
$$Y = \frac{\text{No. of good chips per wafer}}{\text{Total number of chips per wafer}} \times 100\%$$

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

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



Defects



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

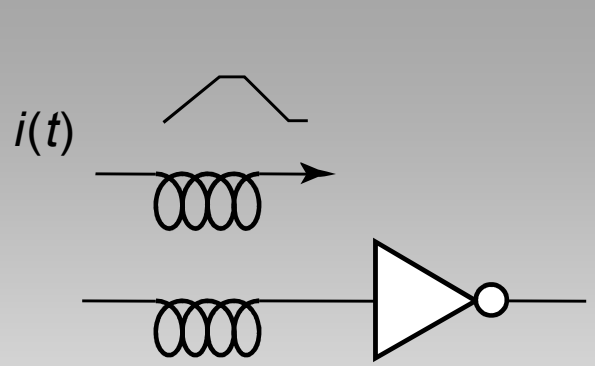
α is approximately 3

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

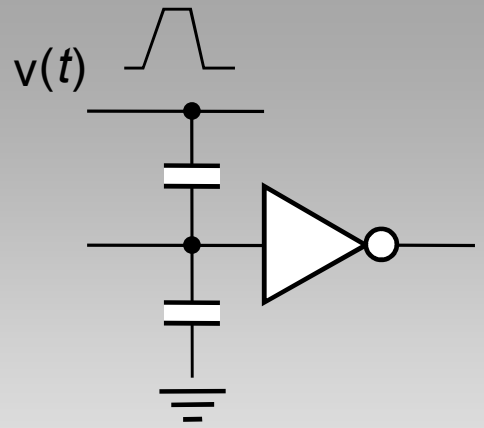
Some Examples (1994)

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

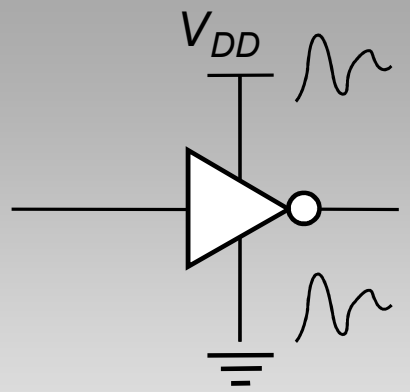
Reliability—
Noise in Digital Integrated Circuits



Inductive coupling



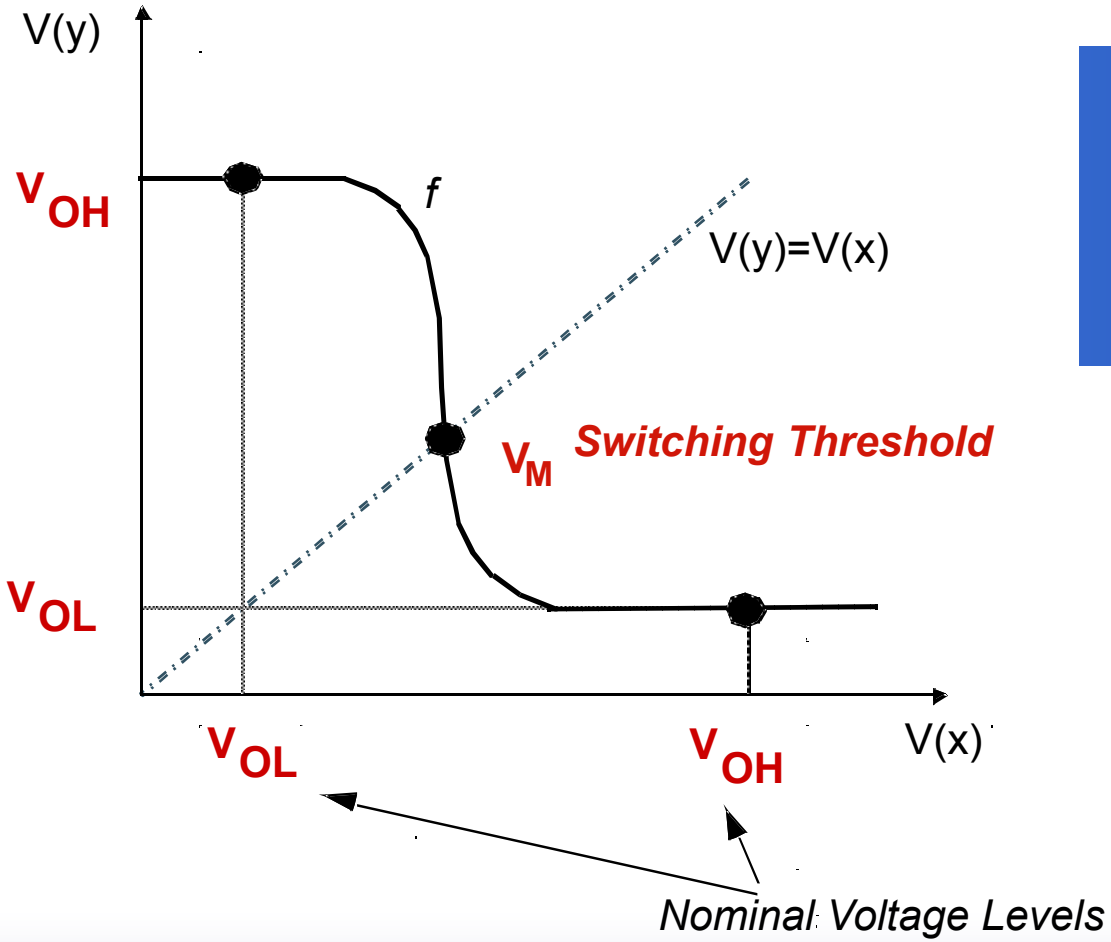
Capacitive coupling



Power and ground noise

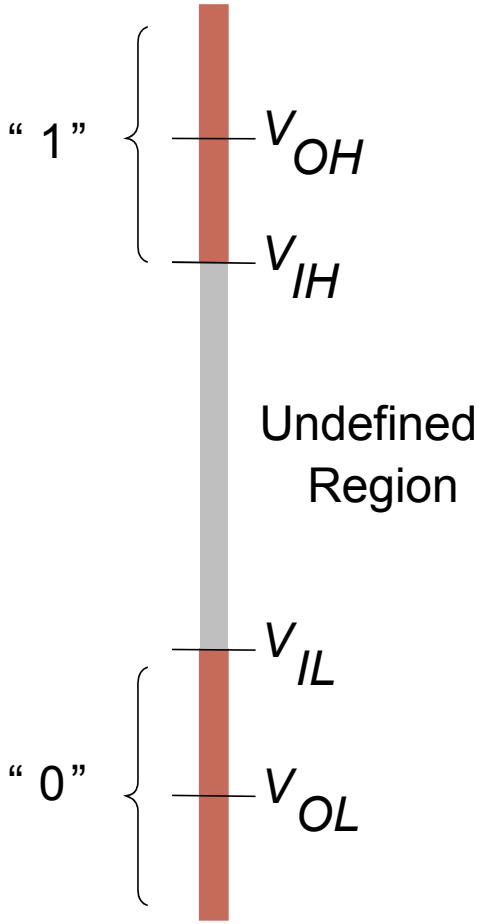
DC Operation
Voltage Transfer Characteristic

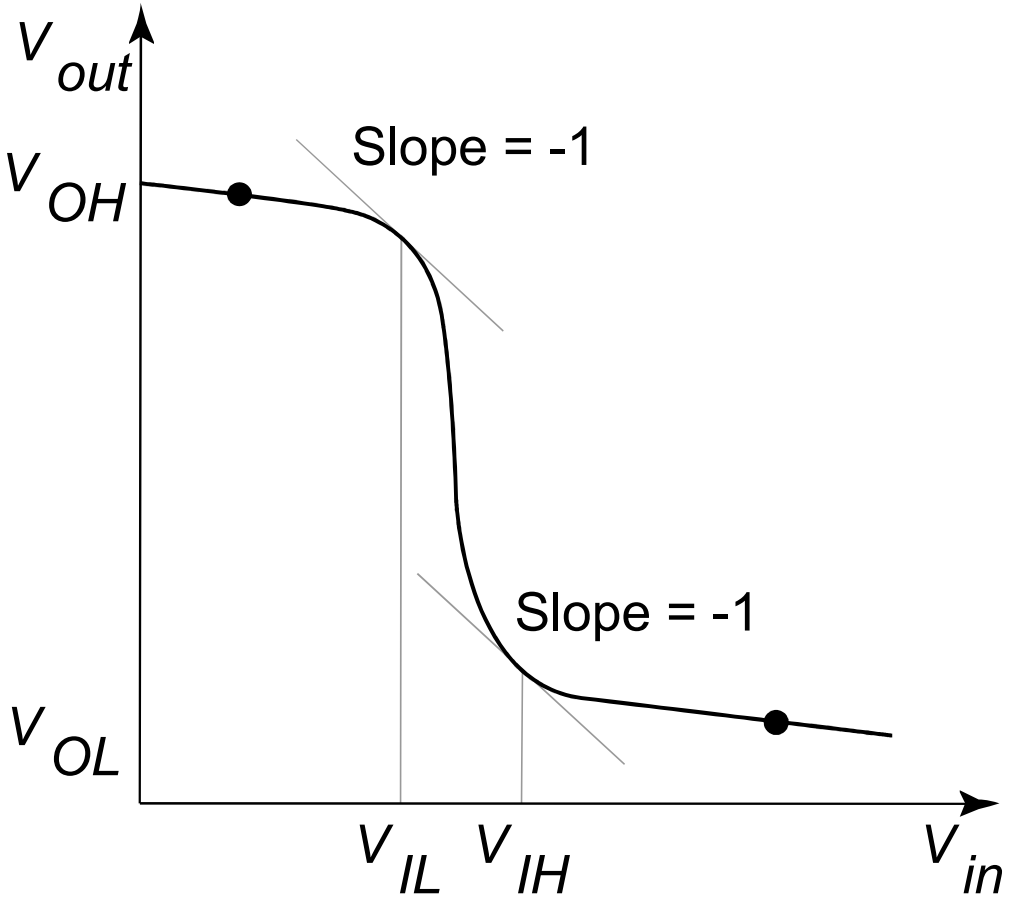
Will be discussed later



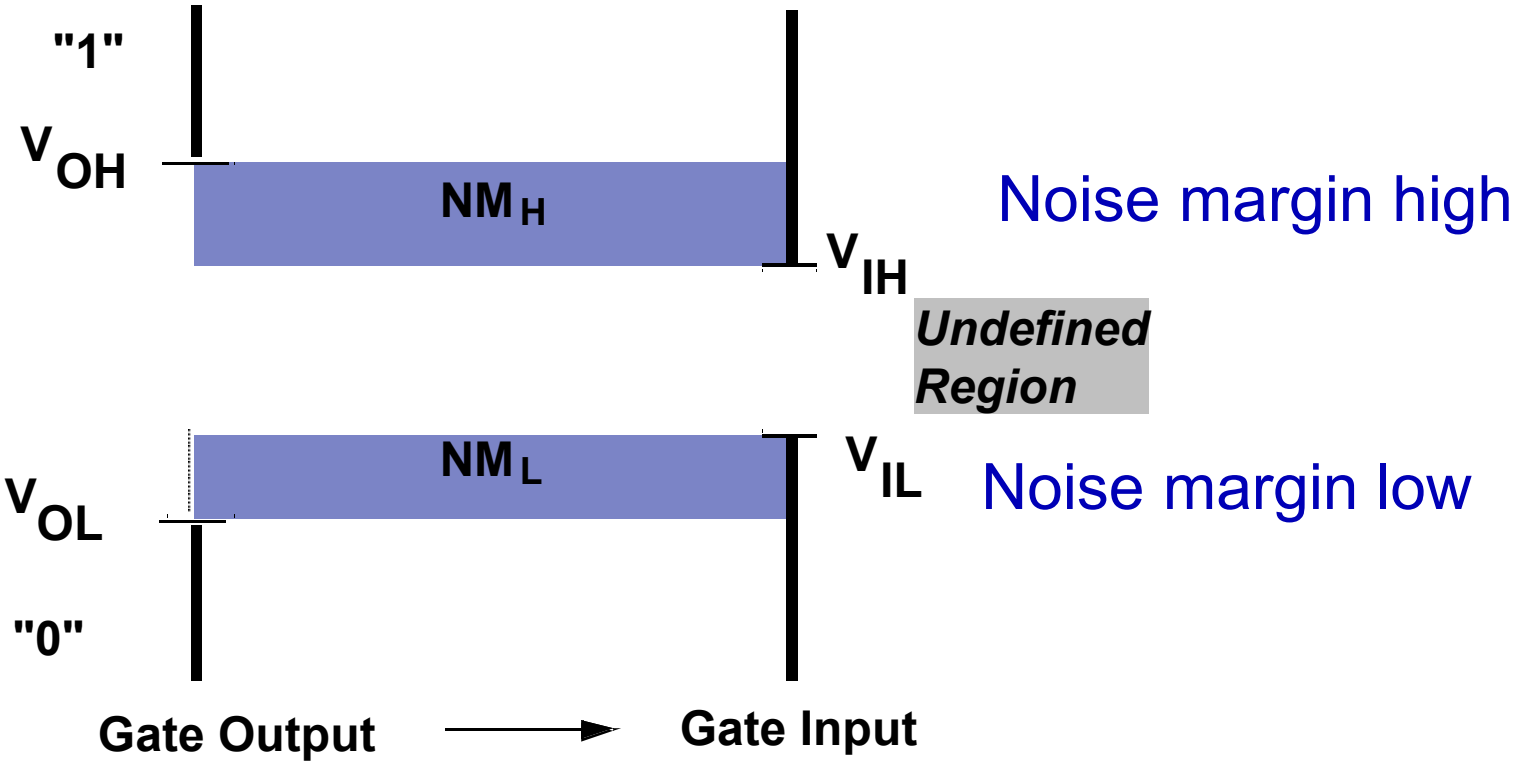
VOH = *f*(VOL)
VOL = *f*(VOH)
VM = *f*(VM)

Mapping between analog and digital signals





Definition of Noise Margins



Noise Budget

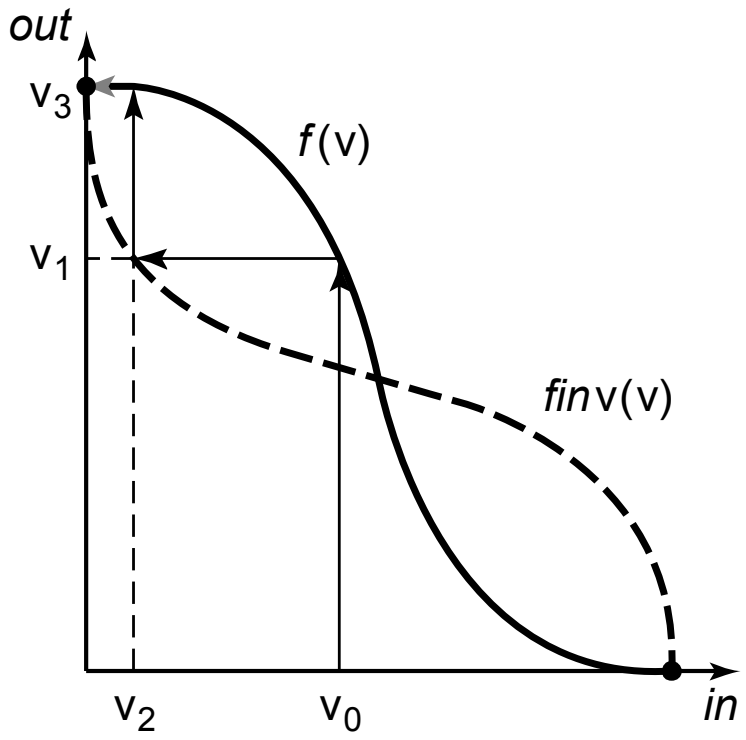
- Allocates gross noise margin to expected sources of noise
- Sources: supply noise, cross talk, interference, offset
- Differentiate between fixed and proportional noise sources

Key Reliability Properties

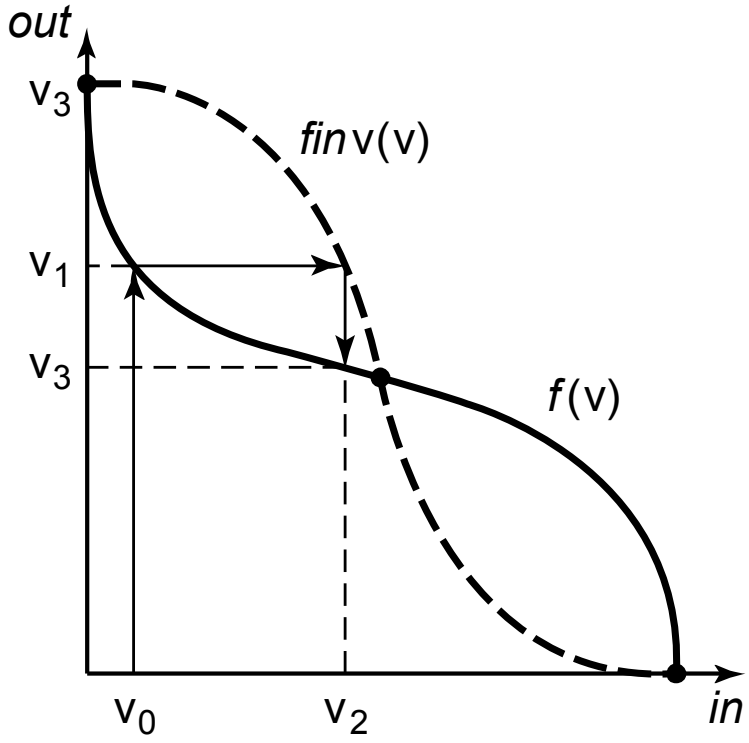
- Absolute noise margin values are deceptive
  - a floating node is more easily disturbed than a node driven by a low impedance (in terms of voltage)
- Noise immunity is the more important metric – the capability to suppress noise sources
- Key metrics: Noise transfer functions, Output impedance of the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

Regenerative Property

Will be discussed later

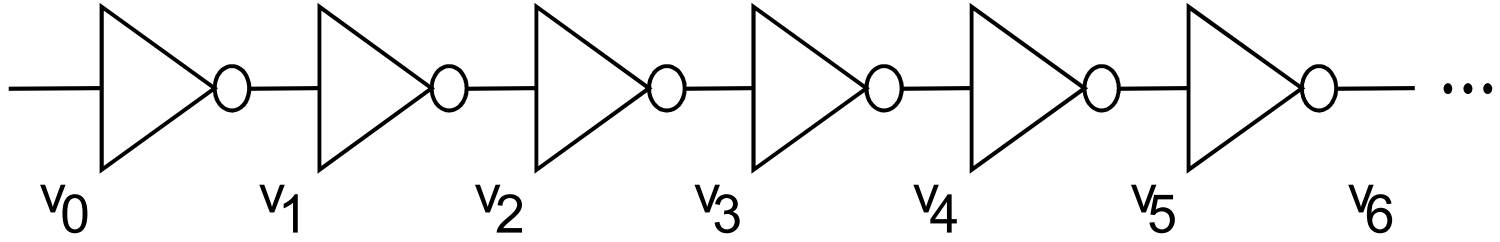


Regenerative

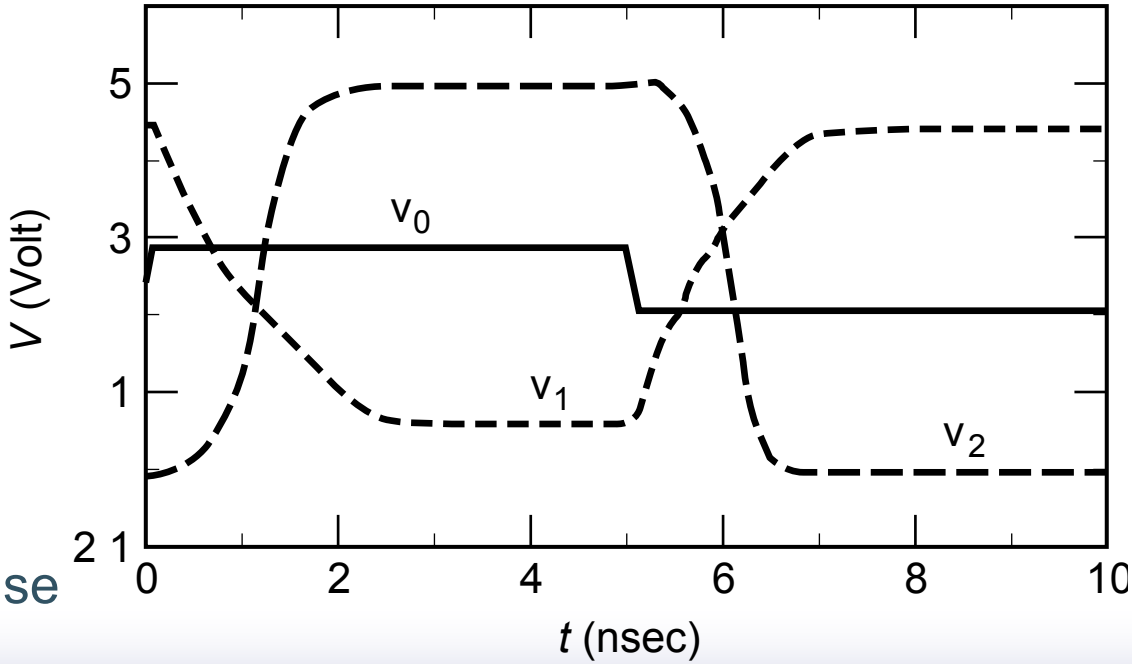


Non-Regenerative

Regenerative Property

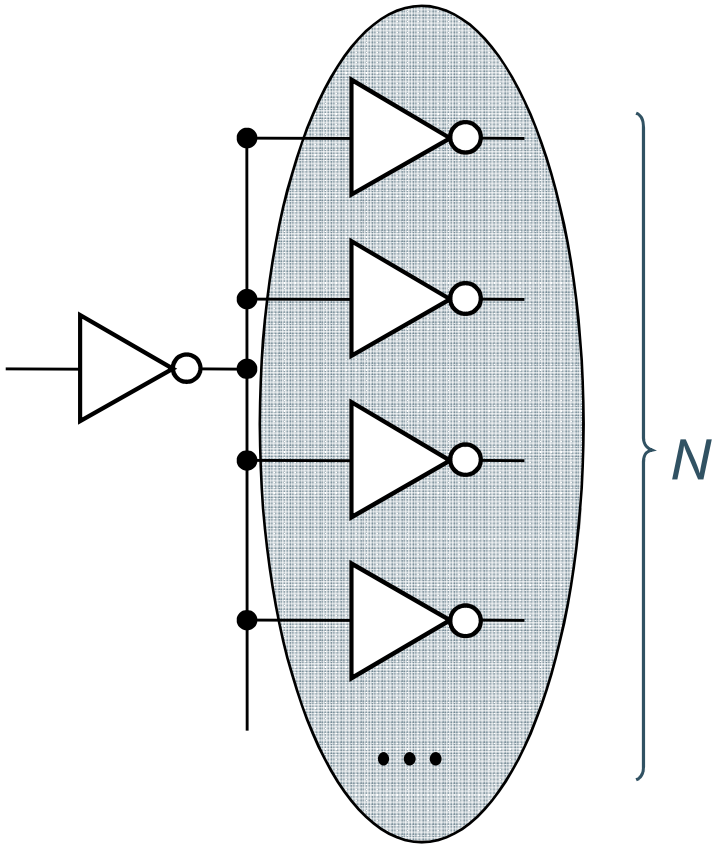


A chain of inverters

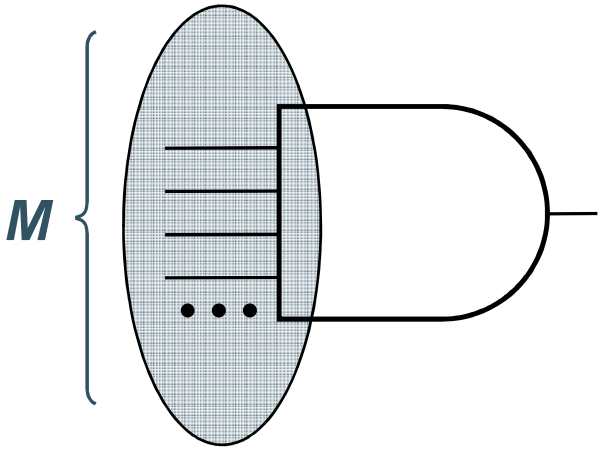


Simulated response

Fan-in and Fan-out

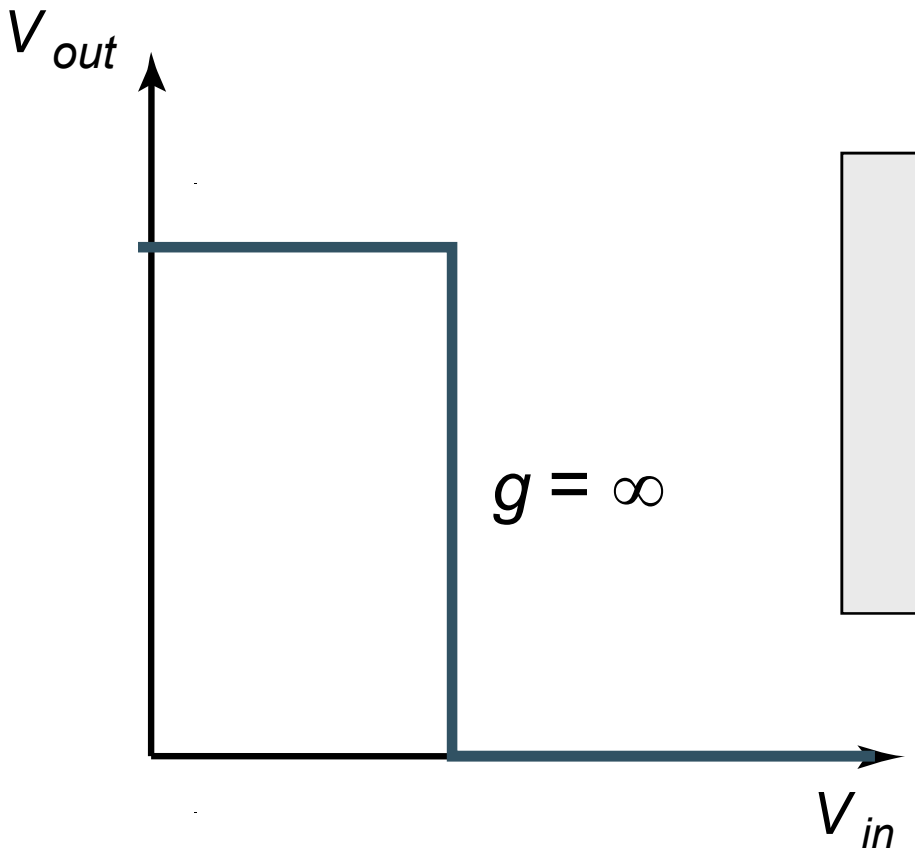


Fan-out *N*



Fan-in *M*

The Ideal Gate



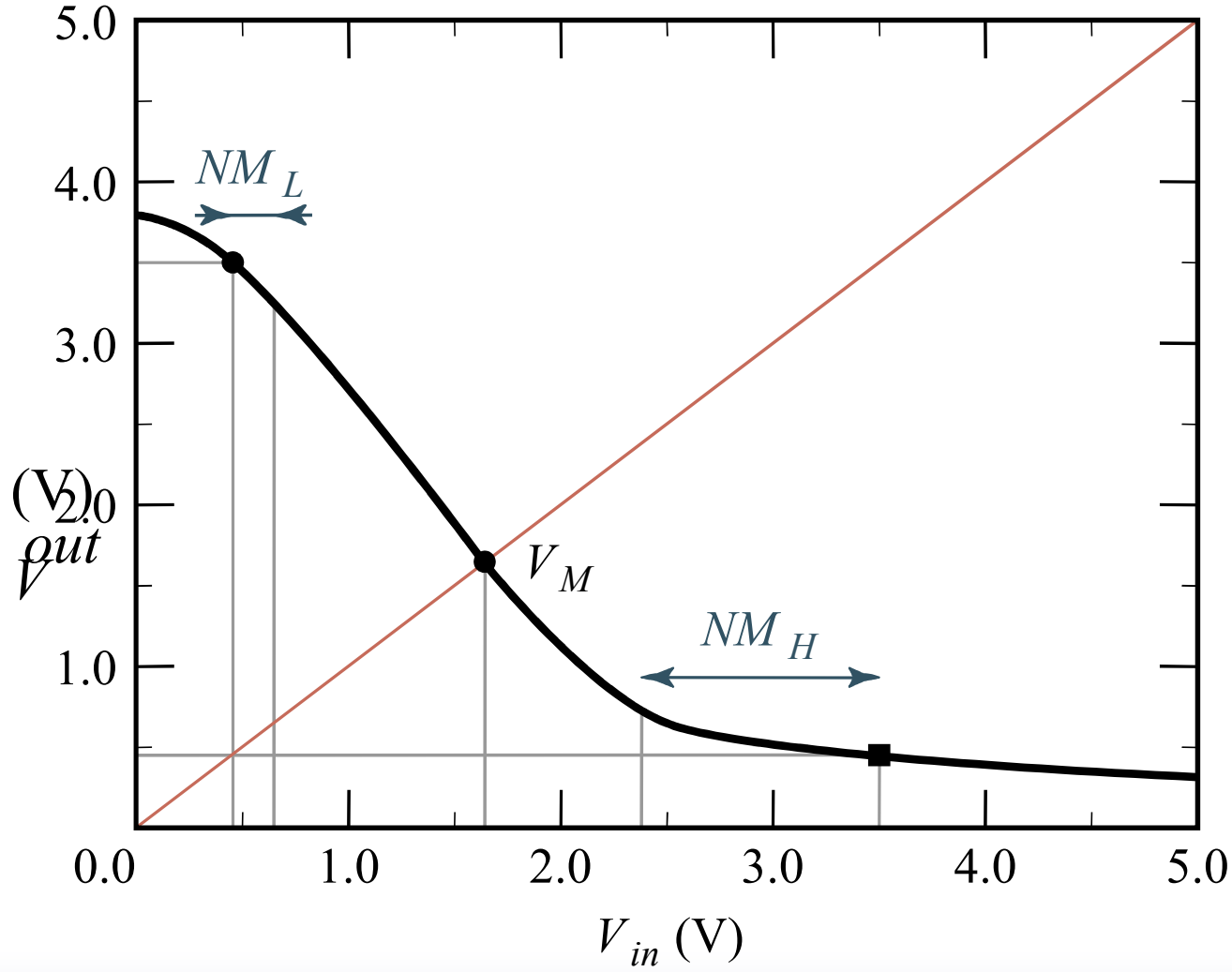
$R_i = \infty$

$R_o = 0$

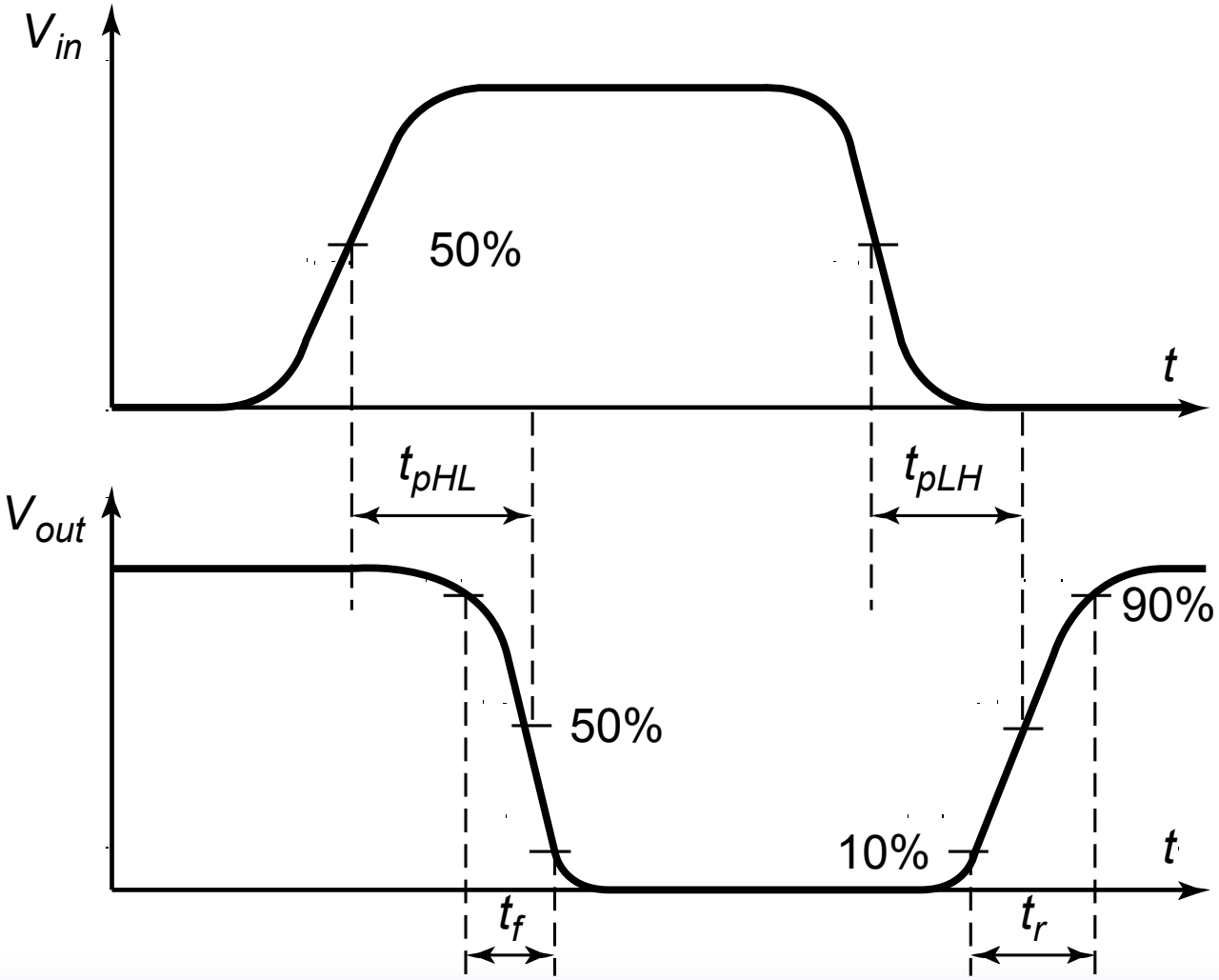
Fanout = ∞

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

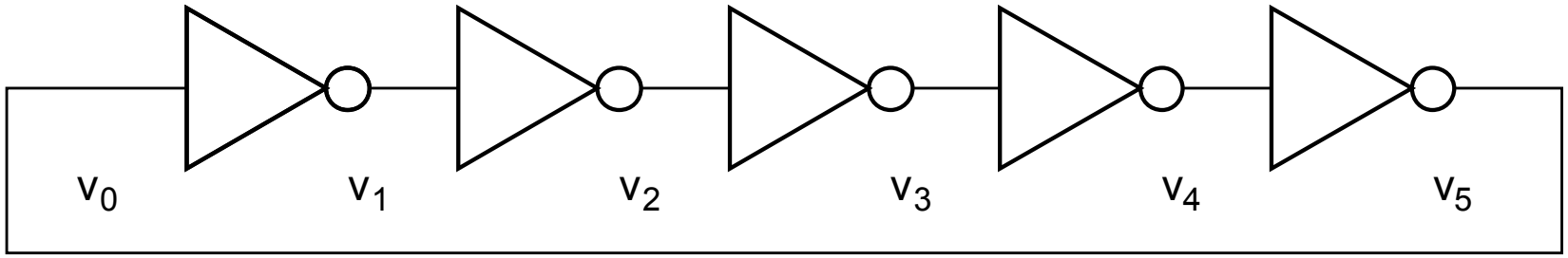
An Old-time Inverter

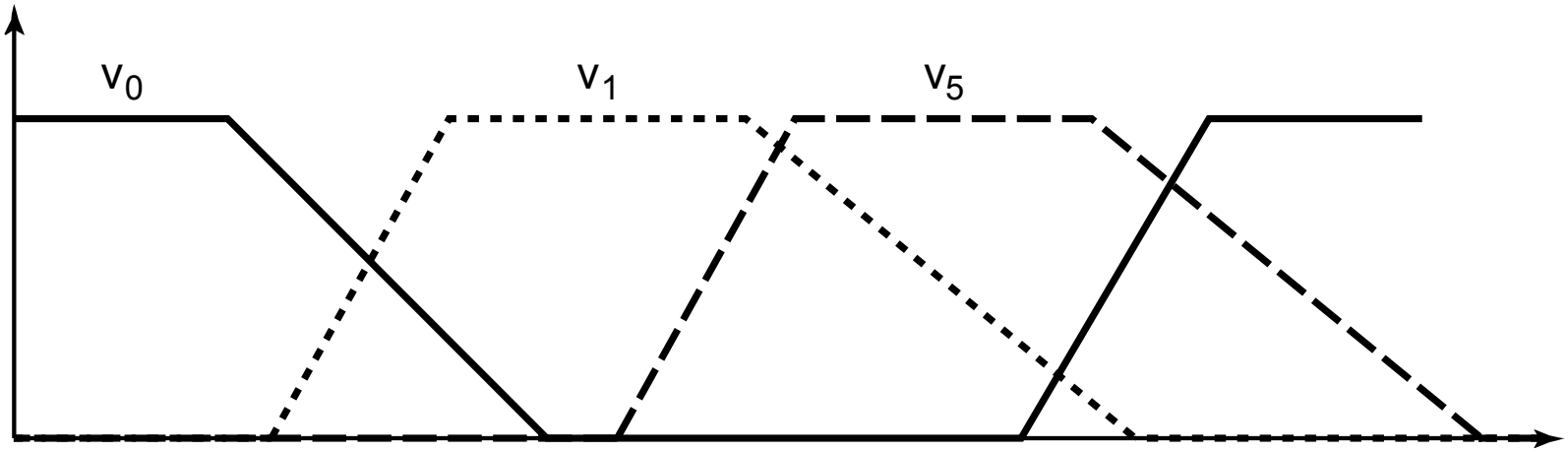


Delay Definitions



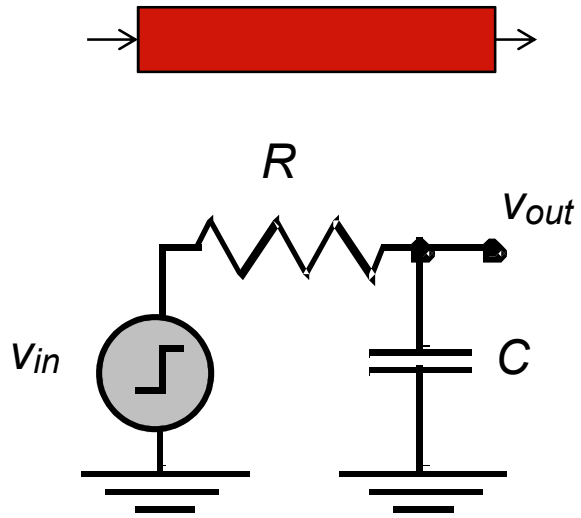
Ring Oscillator





$$T = 2 \times t_p \times N$$

A First-Order RC Network



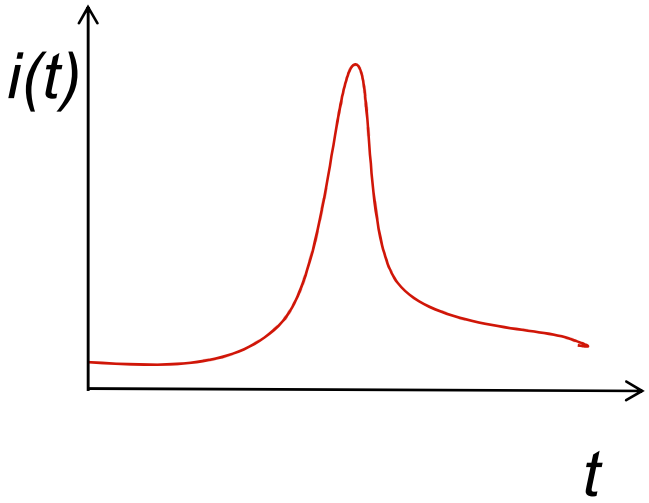
$$v_{out}(t) = (1 - e^{-t/\tau})\, V_{in}$$

Solving for the propagation delay, one gets

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

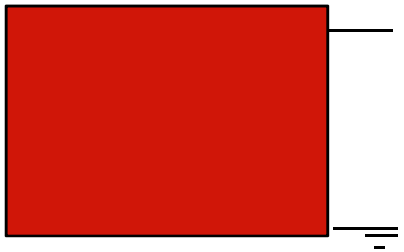
Important model – matches delay of inverter

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

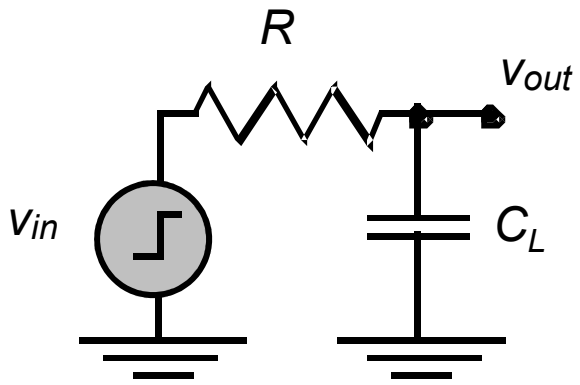
Power-Delay Product (PDP) =

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

Energy-Delay Product (EDP) =

quality metric of gate = $E \times t_p$

A First-Order RC Network



$$E_{0\to 1} = \int_0^T P(t)dt = V_{dd}\int_0^T i_{supply}(t)dt = V_{dd}\int_0^{Vdd} C_L dV_{out} = C_L \bullet V_{dd}^2$$

$$E_{cap} = \int_0^T P_{cap}(t)dt = \int_0^T V_{out} i_{cap}(t)dt = \int_0^{Vdd} C_L V_{out} dV_{out} = \frac{1}{2} C_L \bullet V_{dd}^2$$

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 Class
- Understanding the design metrics that govern digital design is crucial
  - Cost, reliability, speed, power and energy dissipation