INEL-6080
VLSI SYSTEMS DESIGN

Lecture 2

Characteristics of Digital ICs

CHARACTERISTICS OF DIGITAL ICs

Quality Metrics in IC Design

1. Cost
   - Resource investment to produce a batch of ICs
2. Functionality
   - IC ability to perform the function it was designed for
3. Performance
   - Circuit speed: delay, operating frequency, and processing capability
4. Robustness
   - Ability to withstand process variations and noise disturbances
5. Power and Energy Consumption
   - Energy consumed for IC operation and heat dissipation

CHARACTERISTICS OF DIGITAL ICs

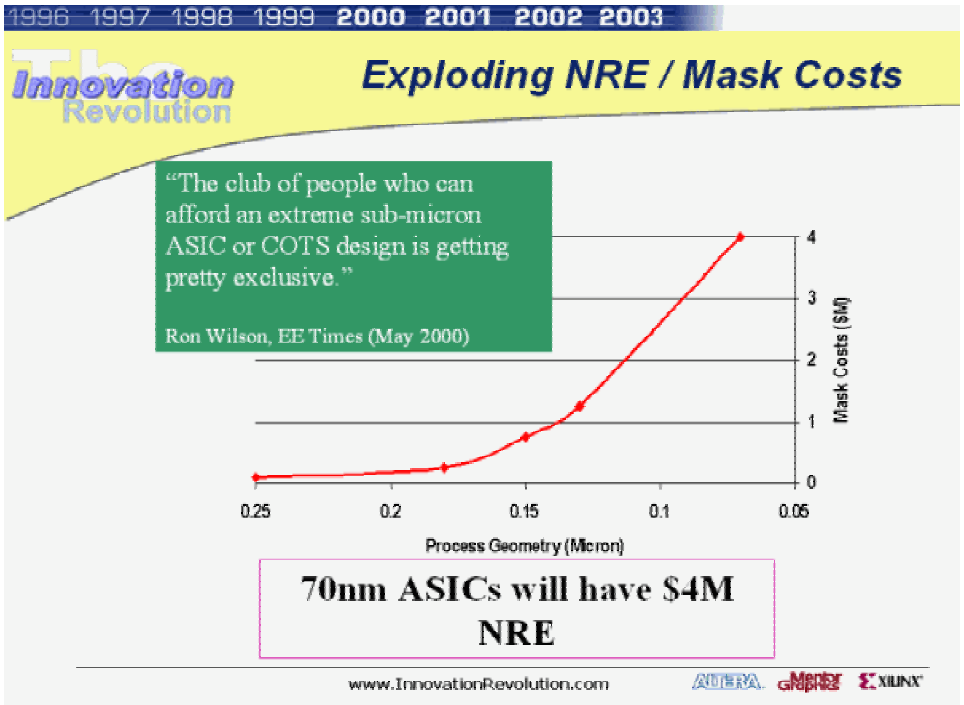
Cost of an Integrated Circuit

- Non-recurrent Engineering (NRE) Costs (Fixed)
  One-time cost factors. Independent from production volume
  - Design time and effort
  - Mask generation
  - Indirect costs: R&D, infrastructure, marketing, etc.
- Recurrent Costs (Variable)
  Cost directly attributable to a manufactured product. Proportional to chip area and product volume
  - Silicon processing
  - Die testing
  - IC packaging

$$\text{Cost per IC} = \text{Recurrent Cost per IC} + \left(\frac{\text{NRE Cost}}{\text{Volume}} \right)$$

CHARACTERISTICS OF DIGITAL ICs

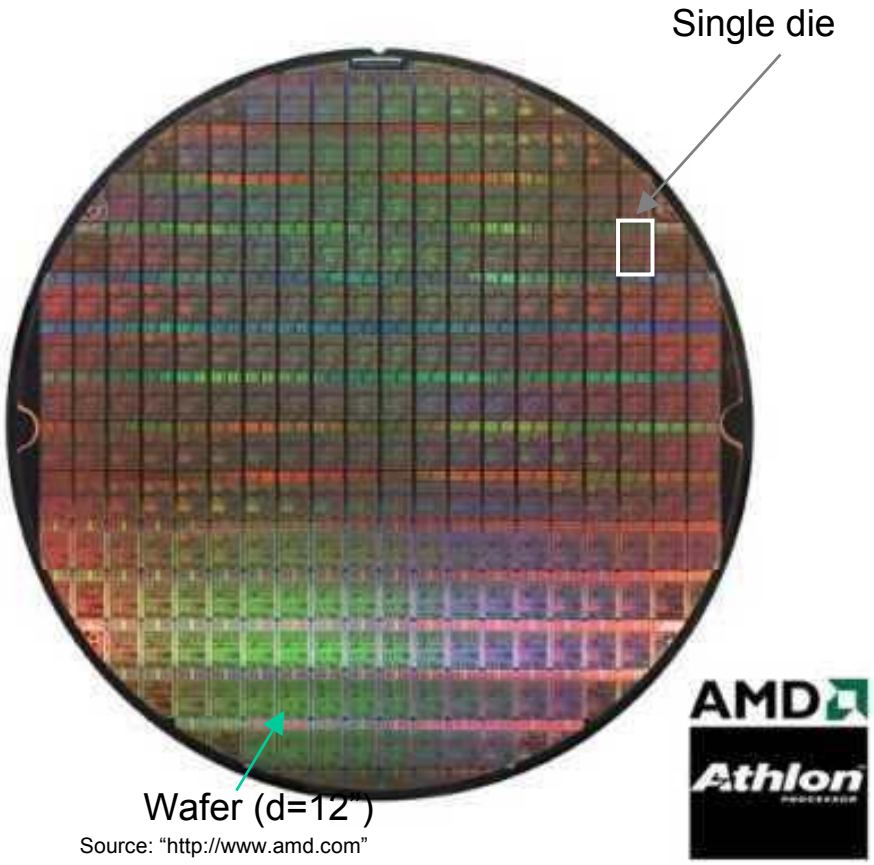
Fixed Costs



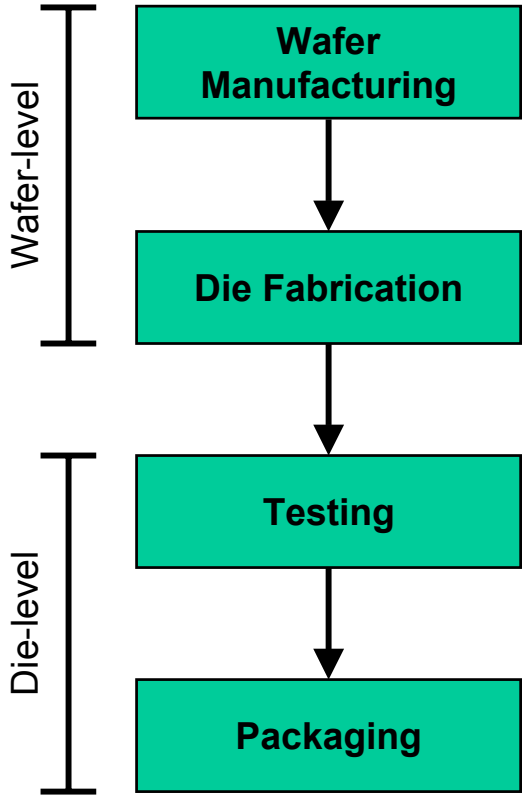
- Increase with:
  - Technology scale-down
  - Stringent design specifications
  - Chip complexity
- Decrease with:
  - Design automation level

CHARACTERISTICS OF DIGITAL ICs

Variable Costs

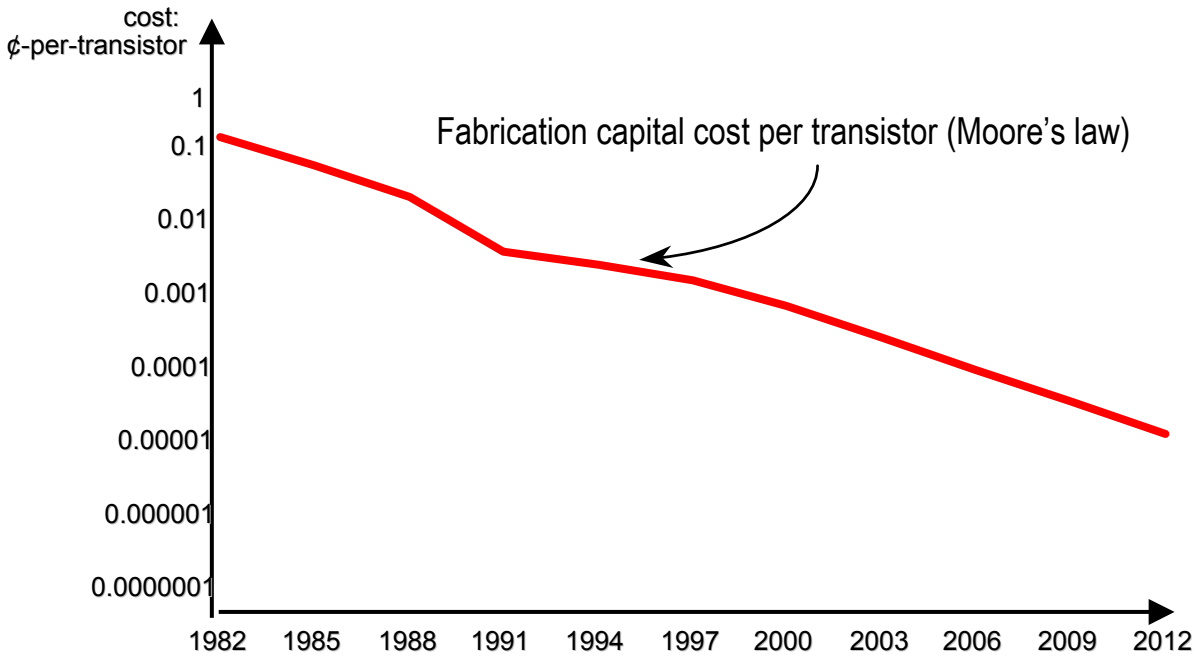


Source: "http://www.amd.com"



CHARACTERISTICS OF DIGITAL ICs

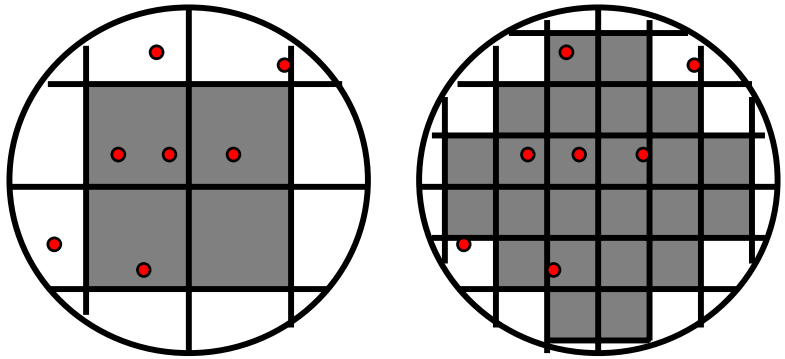
Variable Cost Computation



$$\text{Variable cost} = \frac{\text{Die cost} + \text{Testing cost} + \text{Packaging cost}}{\text{Test yield}}$$

CHARACTERISTICS OF DIGITAL ICs

Die Cost and Yield



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

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

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

Estimating Variable Costs

- Cost estimation during design phase
  - Based on process characterization information and design information

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

α is approximately 3

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

CHARACTERISTICS OF DIGITAL ICs

A Few Cost Examples

Based on production data back in 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

CHARACTERISTICS OF DIGITAL ICs

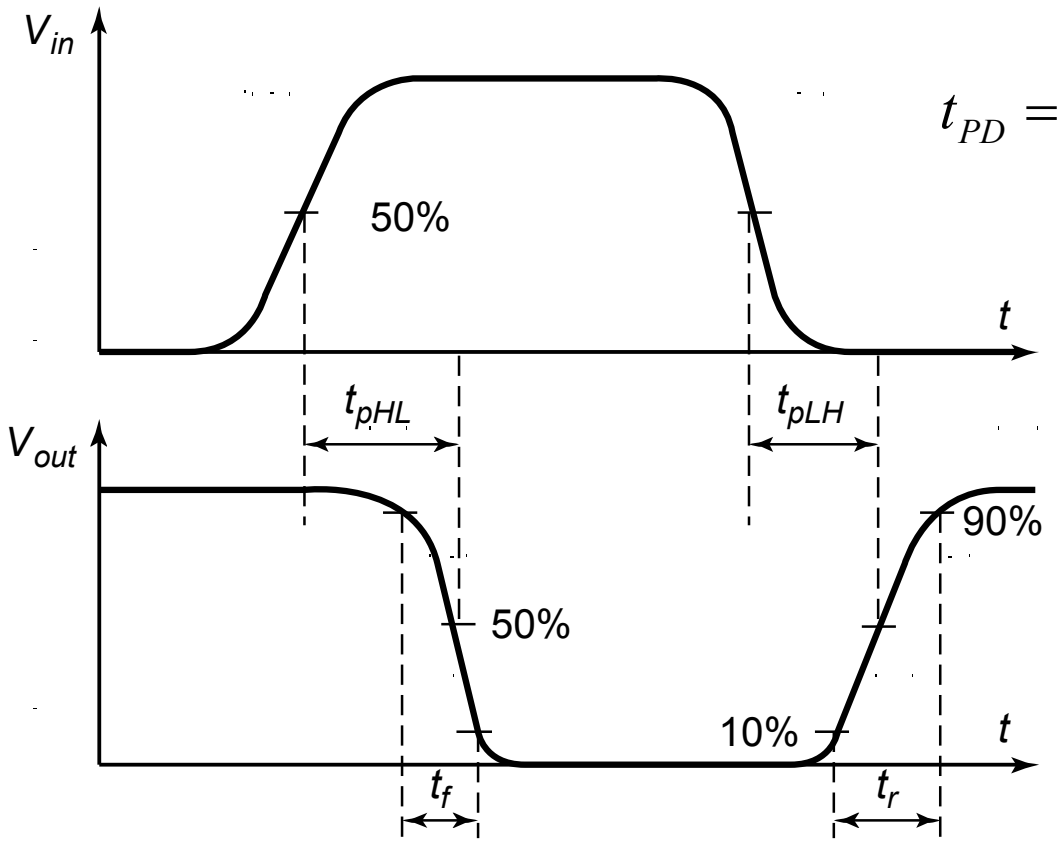
Performance

- Computational speed of a digital circuit:
  - Microprocessor: MIPS
  - Digital Gate: Propagation Delay

    Amount of time it takes an input stimulus to produce a change in the gate output
  - Parameters:
    - t_{PHL} = Low-high propagation delay
    - t_{PHL} = High-low propagation delay
    - t_{PD} = Average propagation delay
    - t_r = Rise time
    - t_f =*Fall time*

CHARACTERISTICS OF DIGITAL ICs

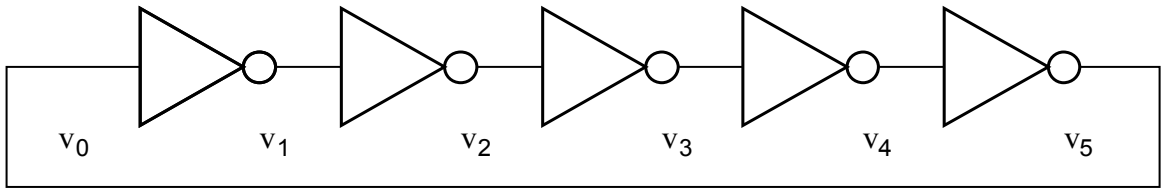
Delay Definitions

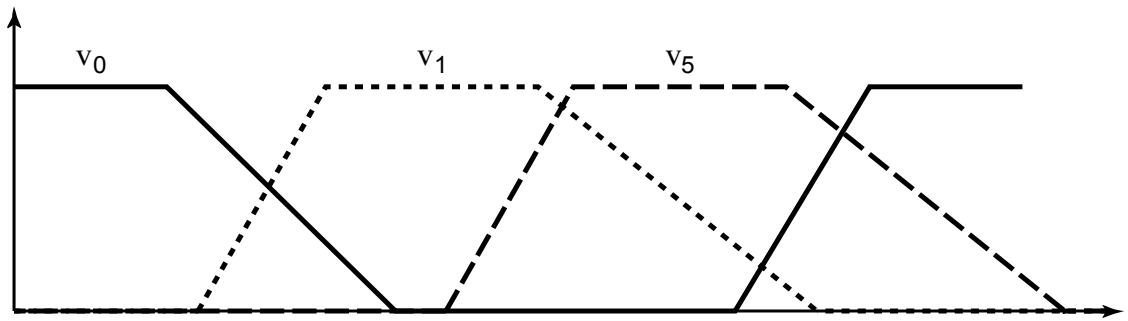


$$t_{PD} = \frac{1}{2}\left(t_{PLH} + t_{PHL}\right)$$

CHARACTERISTICS OF DIGITAL ICs

Ring Oscillator



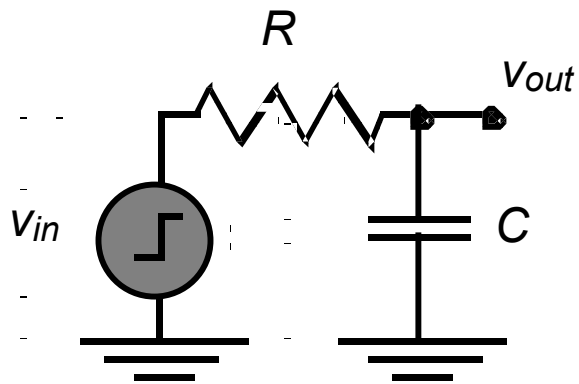


$$T = 2 \times t_{PD} \times N$$

N odd

$$T >> t_r + t_f$$

A First-Order RC Network



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

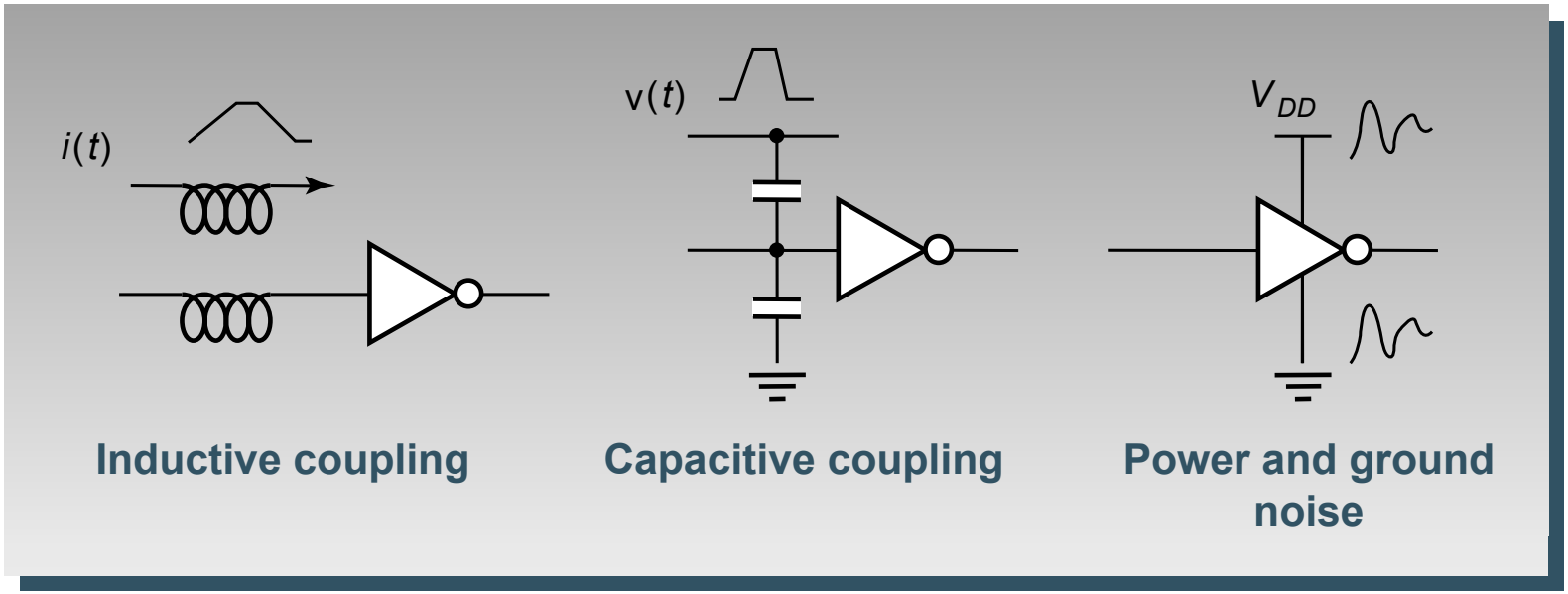
$t_p = \ln(2)\,\tau = 0.69\,RC$

Important model – matches delay of inverter

CHARACTERISTICS OF DIGITAL ICs

Functionality and Robustness

- Sources of Noise in Digital Ics:
  - Crosstalk (Inductive and capacitive coupling)
  - Reflections and ringing
  - Power Supply Noise

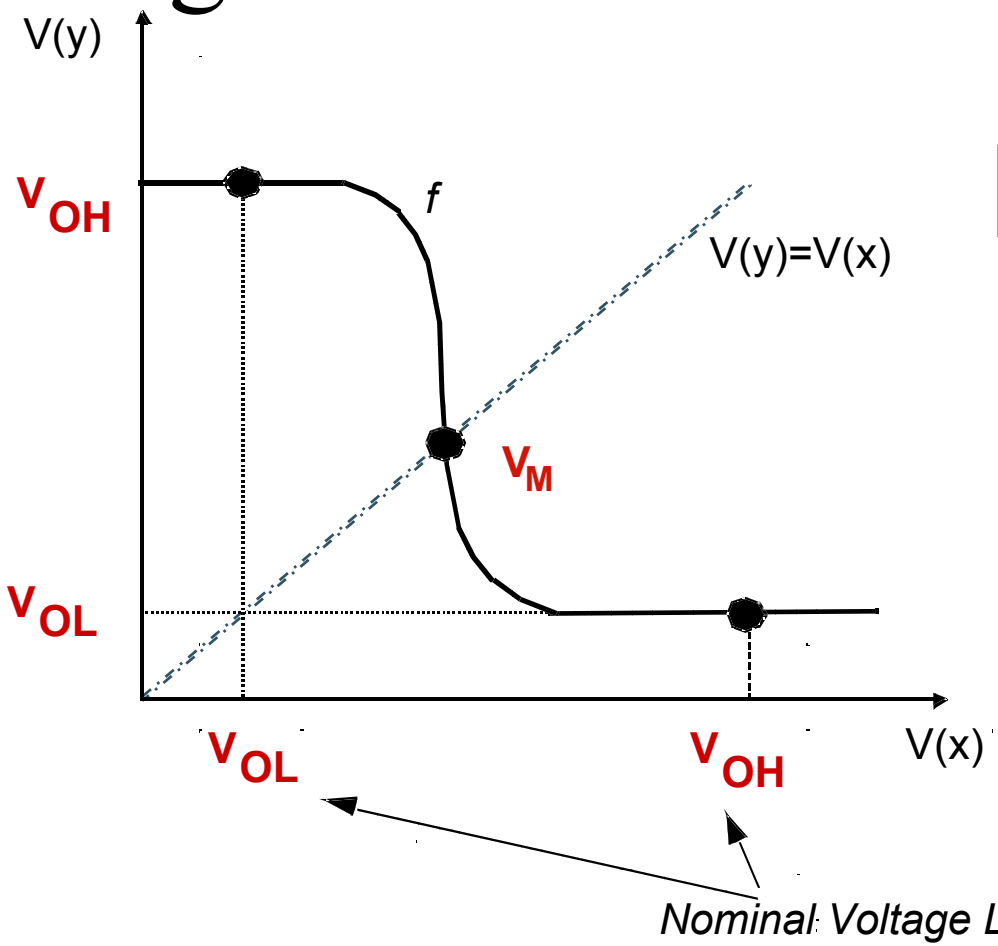


CHARACTERISTICS OF DIGITAL ICs

Robustness Parameters

- Voltage Transfer Characteristic
- Noise Immunity
- Regenerative Property
- Directivity
- Fan-in and Fan-out

Voltage Transfer Characteristic



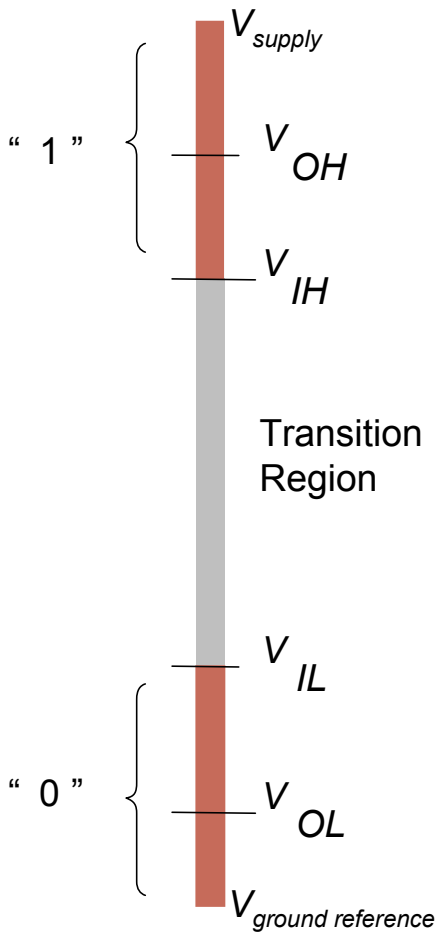
$$\text{VTC}: v_{out} = f(v_{in})$$

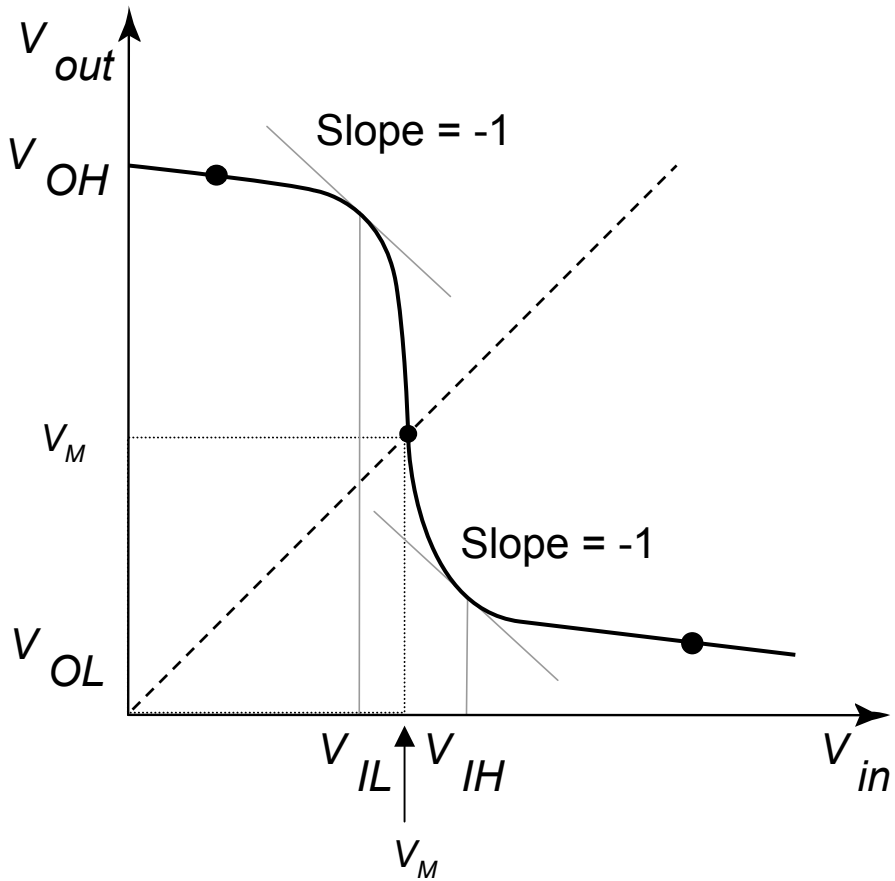
Inverting VTC

$V_{OH} = f(V_{OL})$
$V_{OL} = f(V_{OH})$
$V_M = f(V_M)$

CHARACTERISTICS OF DIGITAL ICs

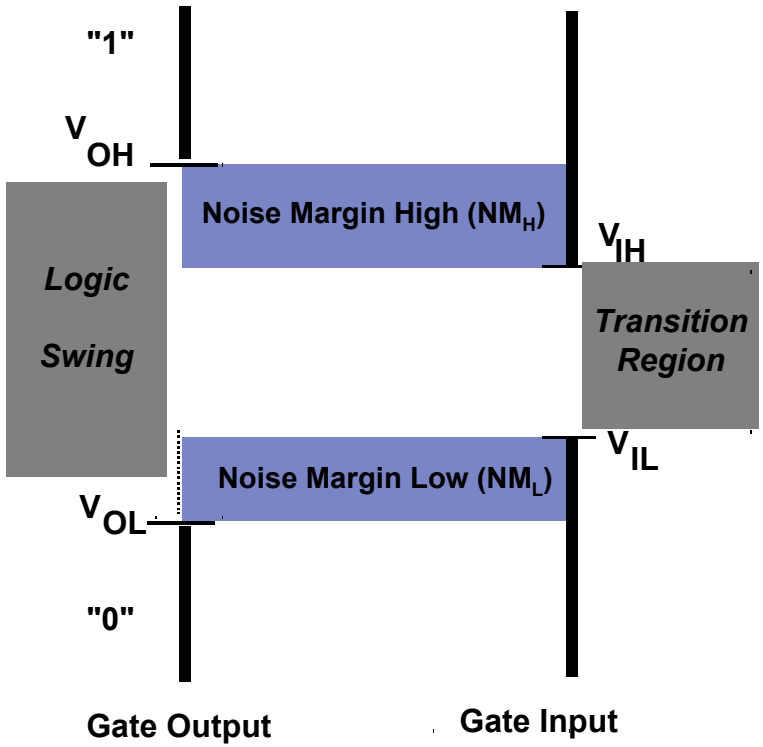
VTC Thresholds

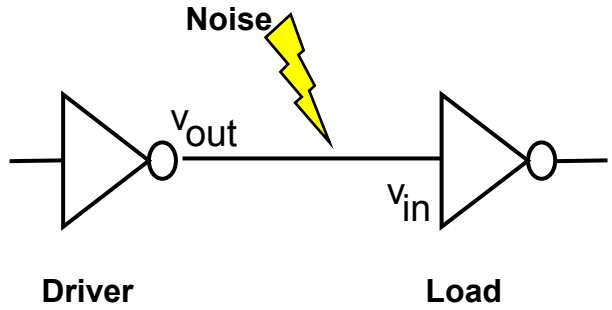




CHARACTERISTICS OF DIGITAL ICs

Noise Margins





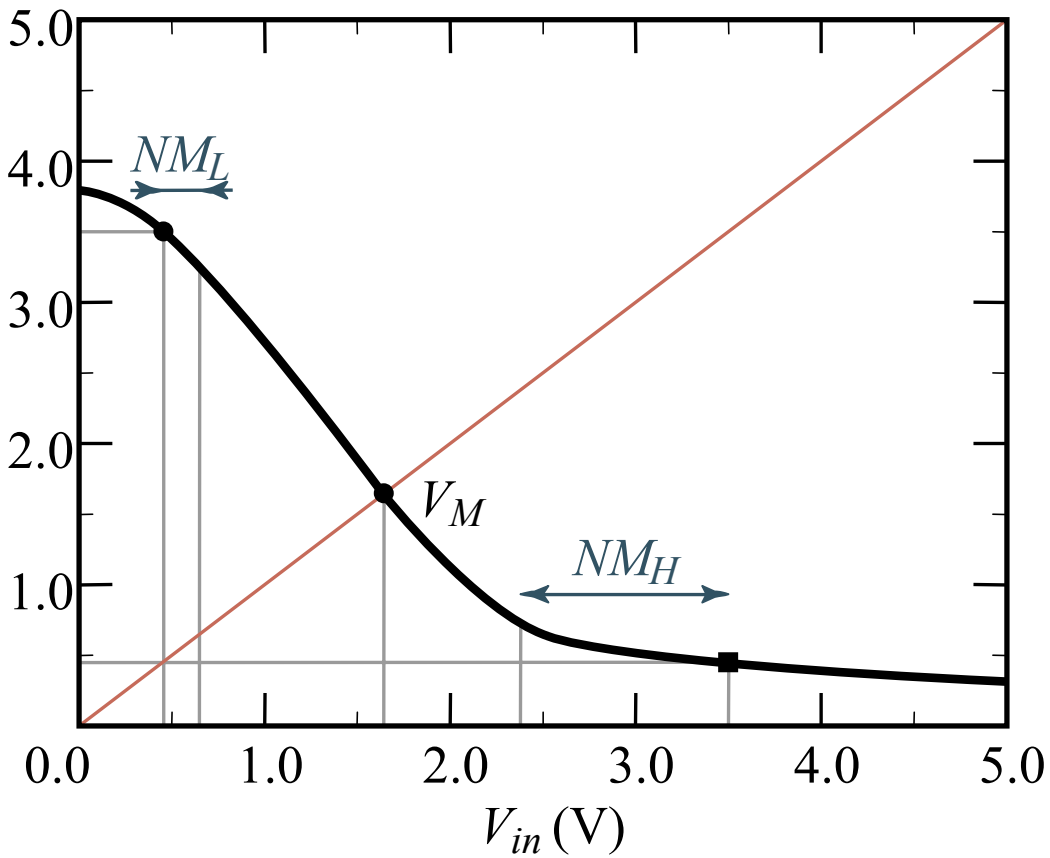
$$NM_L = V_{IL} - V_{OL}$$

$$NM_H = V_{OH} - V_{IH}$$

$$\text{Logic Swing} = V_{OH} - V_{OL}$$

$$\text{Transition Region : From } V_{IL} \text{ to } V_{IH}$$

Example: Inverting VTC



VOH = 3.5V

VOL = 0.45V

VM = 1.64V

VIH = 2.35V

VIL = 0.66V

MNL = 0.21V

NMH = 1.15V

LS = 3.05V

Transition region
0.66V to 2.35V