Practice 4:

Terminology and Design Metrics

Requirements of a Digital Gate

Digital Gate – Analog vs. Digital

- The Analog World:
  - Continuous
  - Amplifies Noise
- A Digital Gate
  - Discrete (Boolean)
  - Suppresses Noise
- What is required to define something as "Digital"?
  - Distinctive *'1'* and *'0'* outputs.
  - Positive Noise Margins
  - Unidirectional
  - Regenerative Property

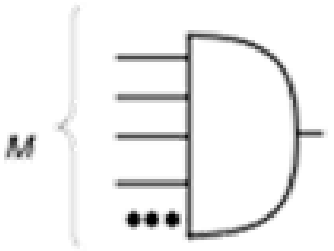
Digital Gate – Boolean, Unidirectional

- Boolean Functionality
  - A digital gate provides a single output resulting from a number of inputs.
  - The output is a discrete logical level – i.e. *'0'* or *'1'*.
  - We generally *map* these logic levels to the voltages *GND* and *VDD*.

- Unidirectional
  - A digital gate is *driven by* inputs and *drives* outputs.
  - Ideally, the outputs don't affect the inputs (i.e. there is no *feedback*)
  - A digital gate is ideally a *Buffer* that separates the circuit.

Digital Gate – Fan In, Fan Out

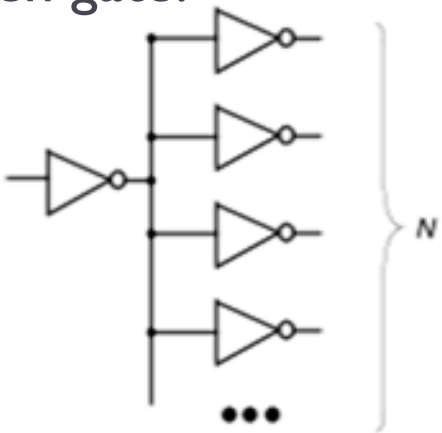
- Fan In
  - How many inputs drive the digital gate?
  - This is a direct result of the gate's Boolean function.
  - A gate with a high Fan In is known as a *Complex* gate.



(b) Fan-in *M*

- Fan Out
  - How many gates are *currently* being driven by a given gate.
  - Maximum Fan Out is how many gates can *theoretically* be driven by a given gate:

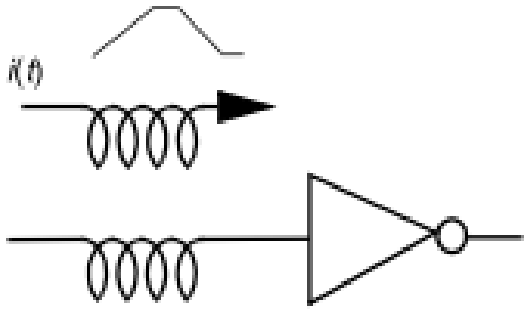
$$FO_{\max} = \frac{I_{out}(\max)}{I_{in}(gate)}$$



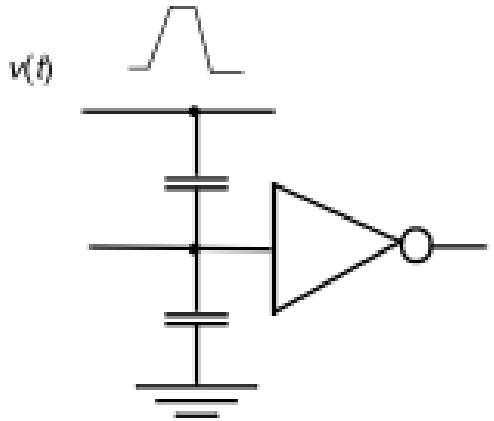
(a) Fan-out *N*

Digital Gate – Noise Suppression

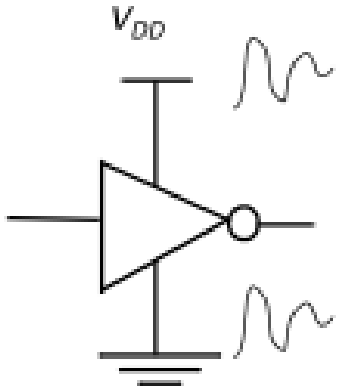
- We usually discuss four kinds of noise in digital circuit design:
  - Inductive Coupling
  - Capacitive Coupling
  - Supply (Power and Ground) Noise
  - External Charge Injection



(a) Inductive coupling



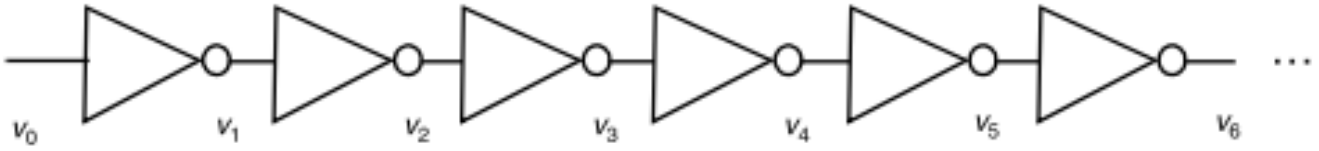
(b) Capacitive coupling



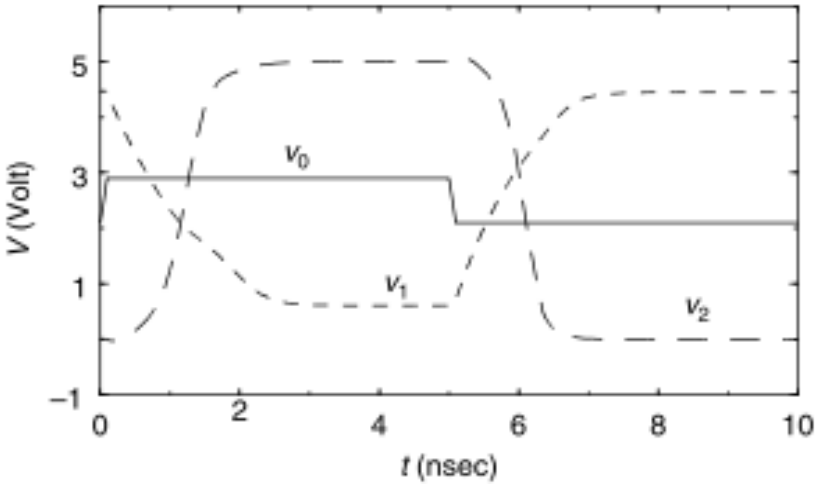
(c) Power and ground

Digital Gate – Noise Suppression

- In order to ensure Noise Suppression (rather than Noise Amplification) a digital gate must employ a *regenerative property*:



(a) A chain of inverters



(b) Simulated response of chain of MOS inverters

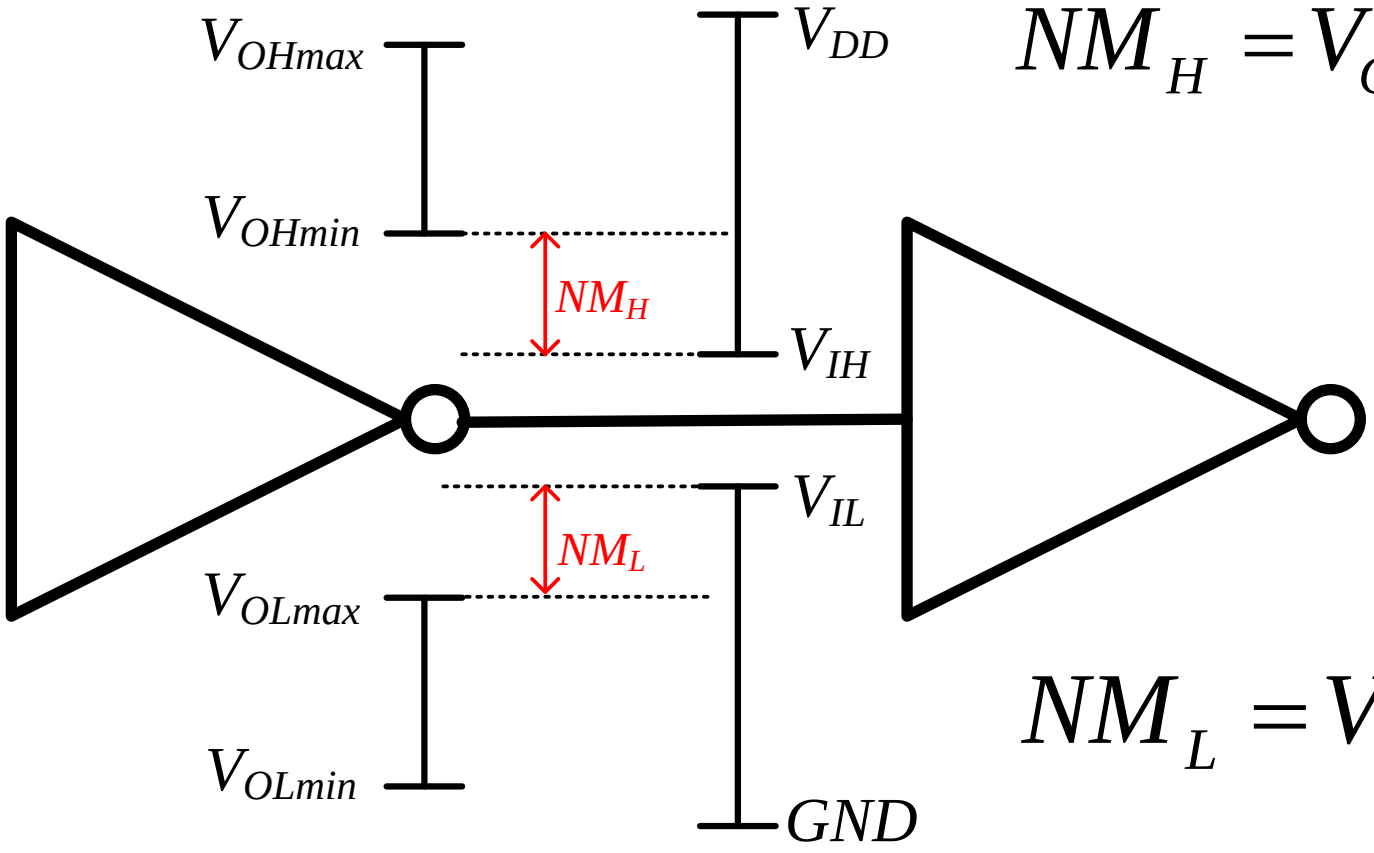
Noise Margins

Noise Margins – Definition

- A gate's noise margin is the amount of noise that can appear at an interim node without causing an error at a subsequent node.
- In order for a gate to function (digitally) it must have a positive noise margin.

- A digital gate generally has two noise margins:
  - NM_H: The noise margin for a node representing a '1'.
  - NM_L: The noise margin for a node representing a '0'.
- The gate's noise margin is the minimum of the two:
  - $NM=\min(NM_H, NM_L)$

Noise Margins – Definition



$$NM_H = V_{OH\,\min} - V_{IH}$$

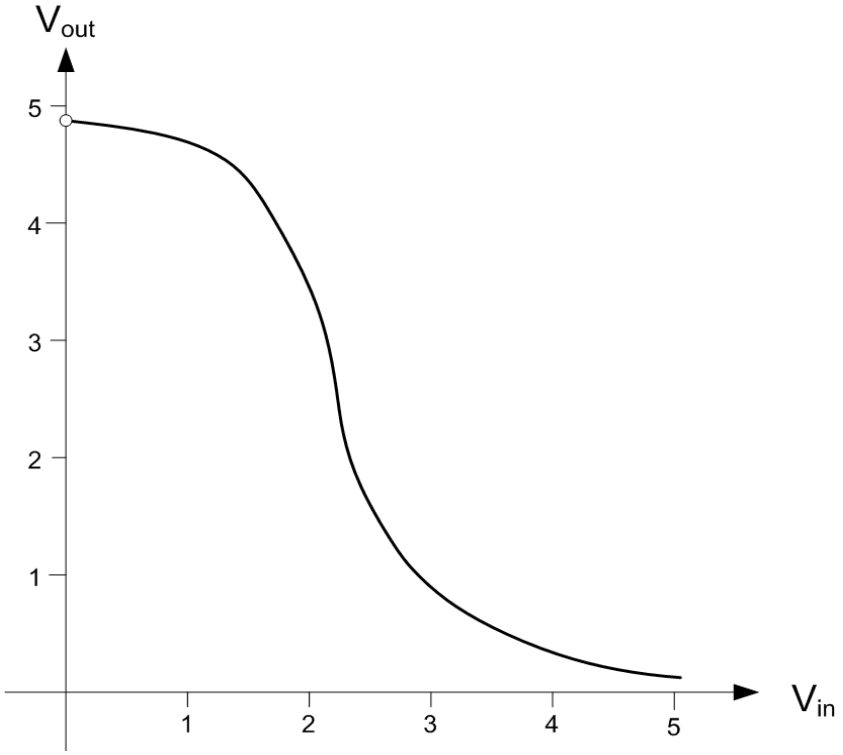
$$NM_L = V_{IL} - V_{OL\,\max}$$

Static Properties of a Digital Gate

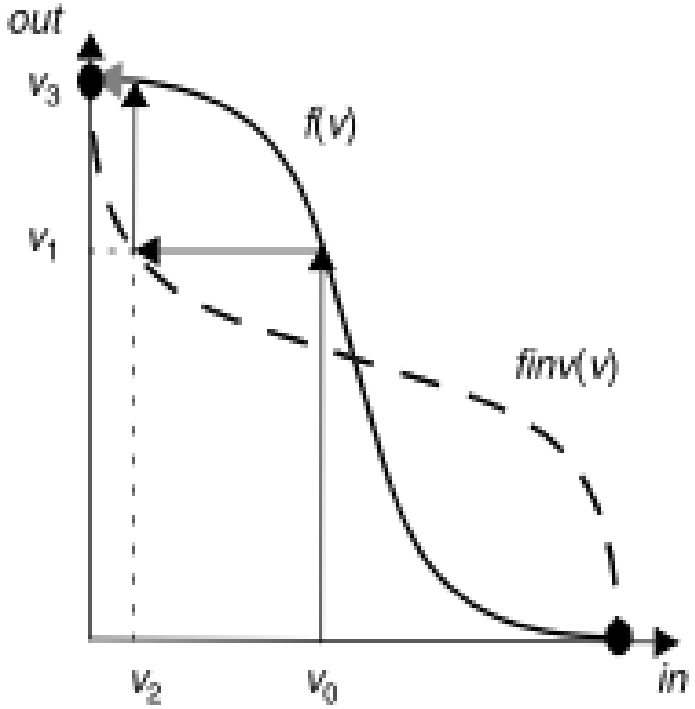
Voltage Transfer Characteristic

VTC – Properties

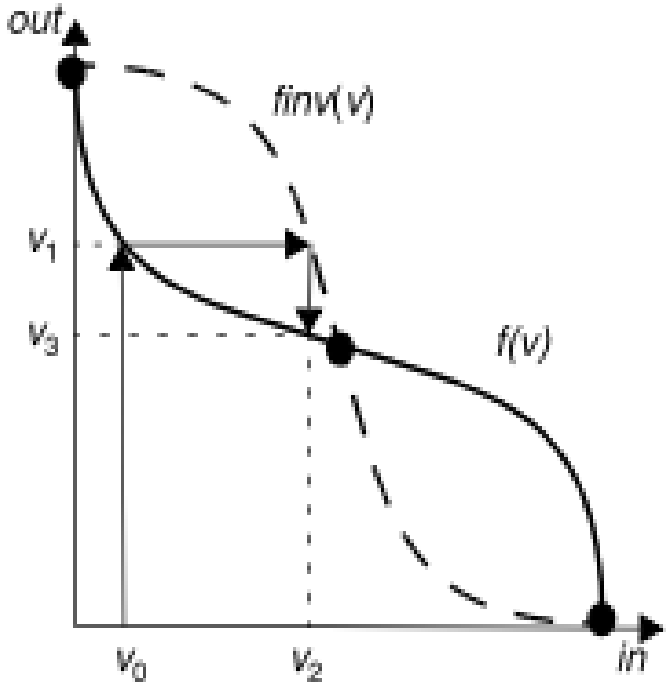
- A VTC shows us the static properties of a digital gate, such as:
  - Regenerative Property
  - Nominal Voltage Levels (VOH, VOL)
  - Switching Threshold (VM)
  - Gain
  - Noise Margins



VTC – Regenerative Property

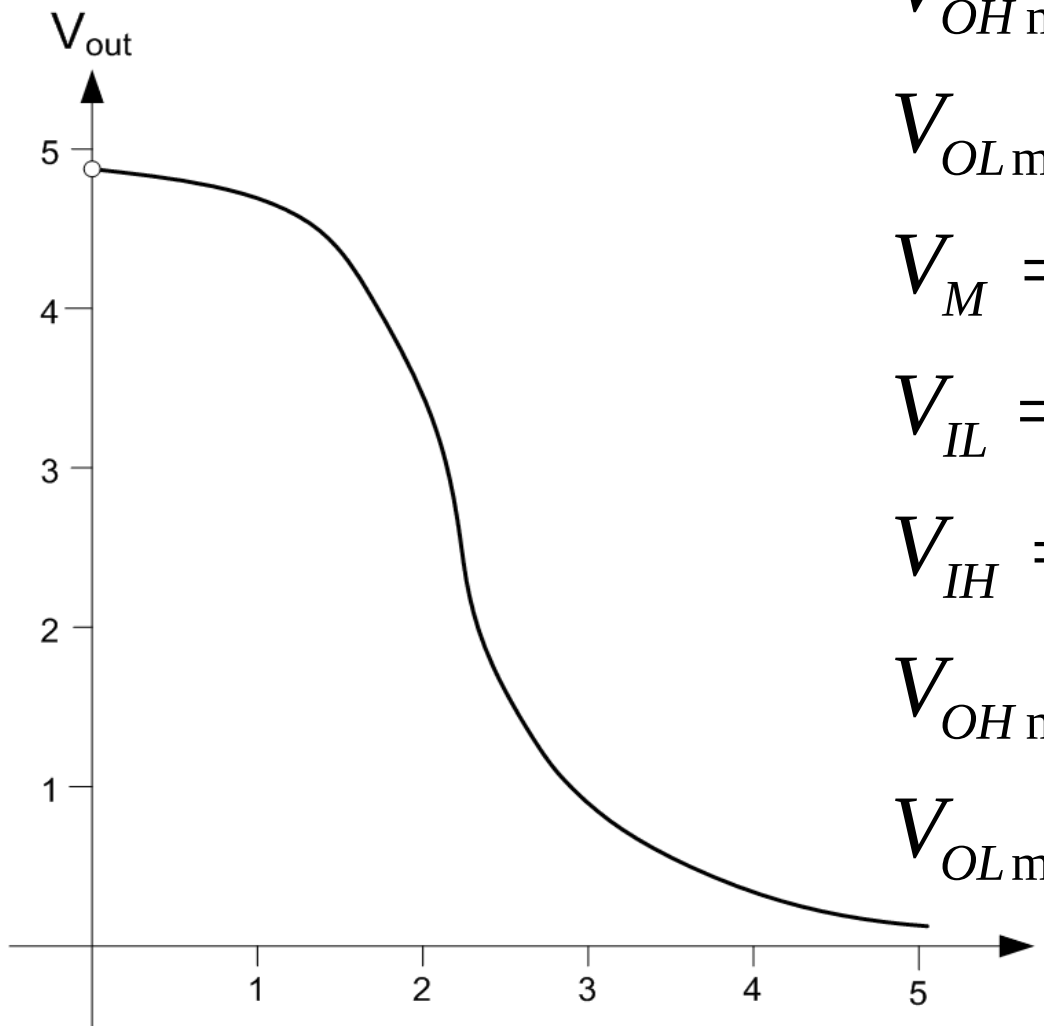


(a) Regenerative gate



(b) Nonregenerative gate

VTC – Nominal Voltage Levels



$$V_{OH\,\max} = 4.8V$$

$$V_{OL\,\min} = 0.2V$$

$$V_M = 2.25V$$

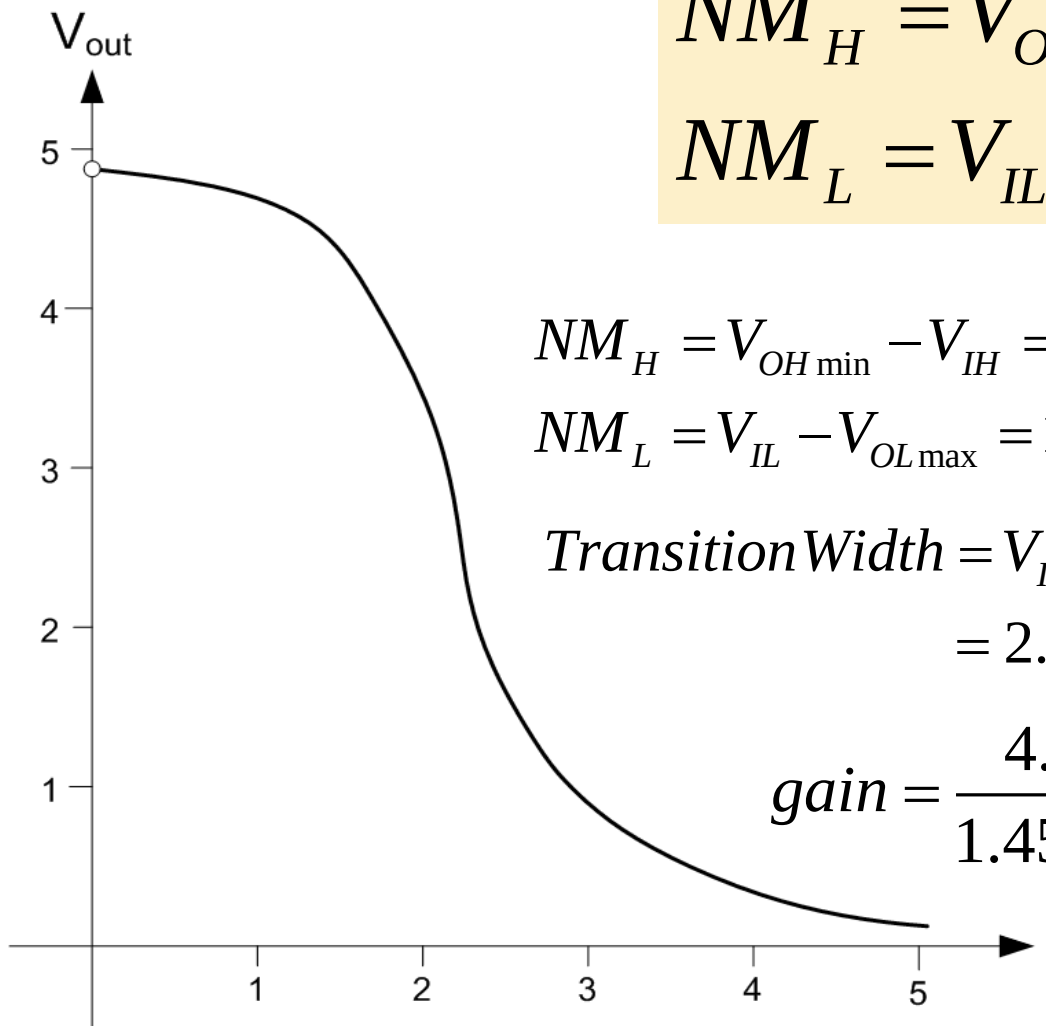
$$V_{IL} = 1.45V$$

$$V_{IH} = 1V$$

$$V_{OH\,\min} = 4.5V$$

$$V_{OL\,\max} = 1V$$

VTC – Noise Margins and Gain



$$NM_H = V_{OH\,\min} - V_{IH}$$

$$NM_L = V_{IL} - V_{OL\,\max}$$

$$NM_H = V_{OH\,\min} - V_{IH} = 4.5 - 2.9 = 1.6V$$

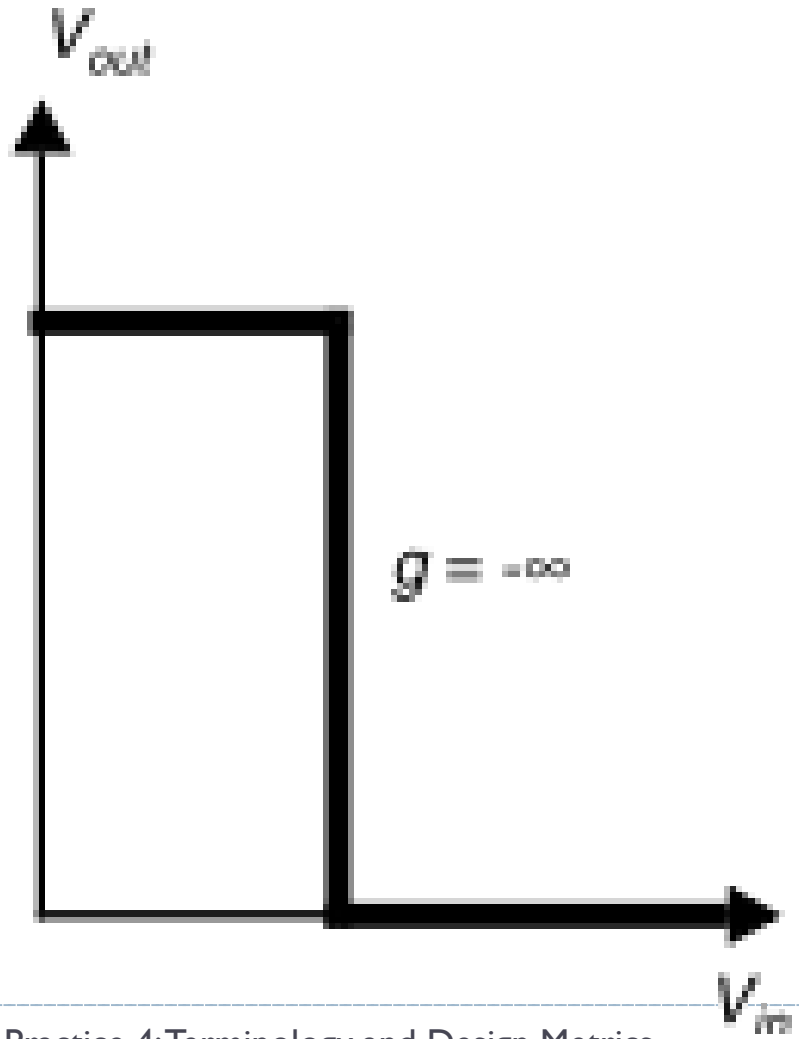
$$NM_L = V_{IL} - V_{OL\,\max} = 1.45 - 1 = 0.45V$$

$$Transition\,Width = V_{IH} - V_{IL} =$$

$$= 2.9 - 1.45 = 1.45V$$

$$gain = \frac{4.5 - 1}{1.45 - 2.9} = -2.4$$

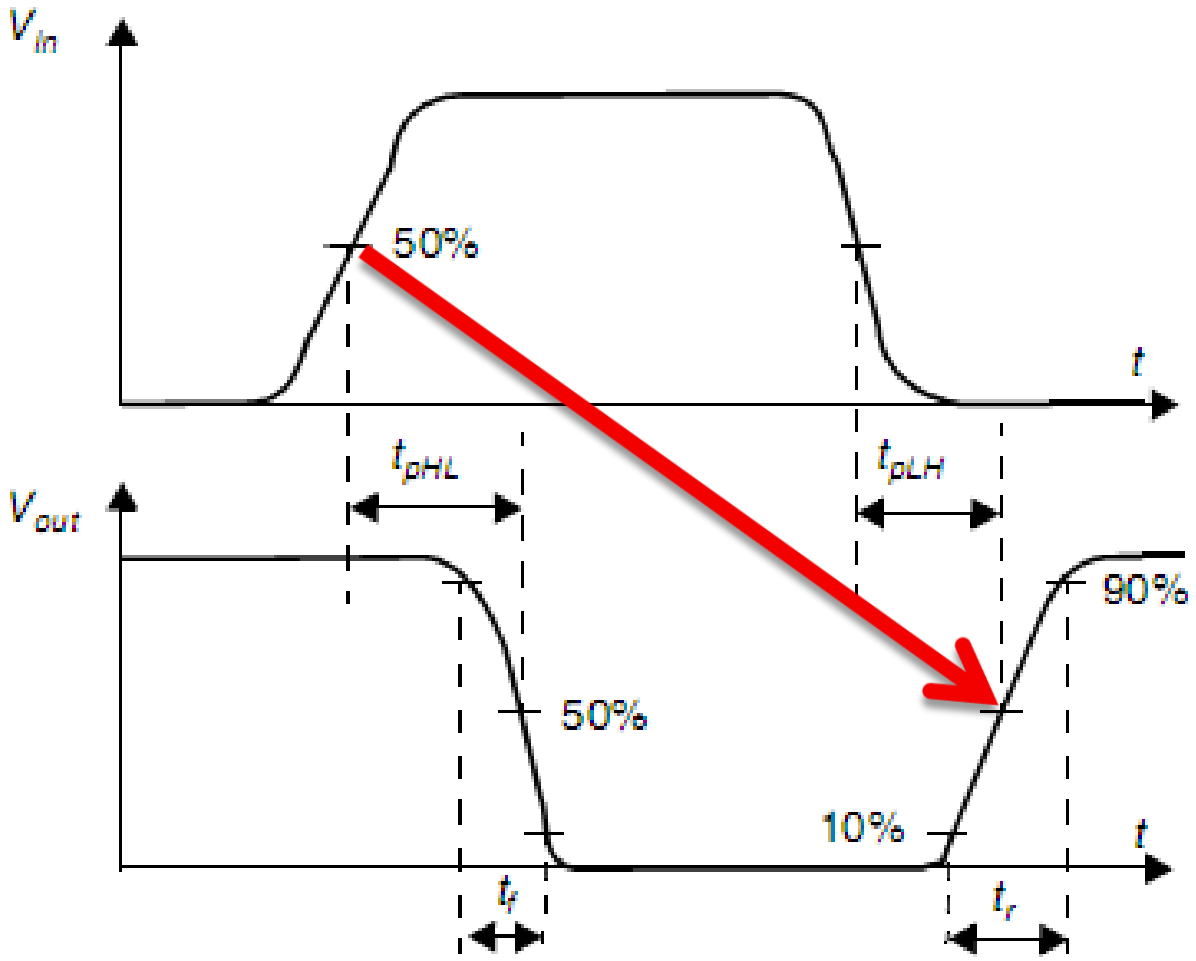
VTC – The Ideal Gate's VTC



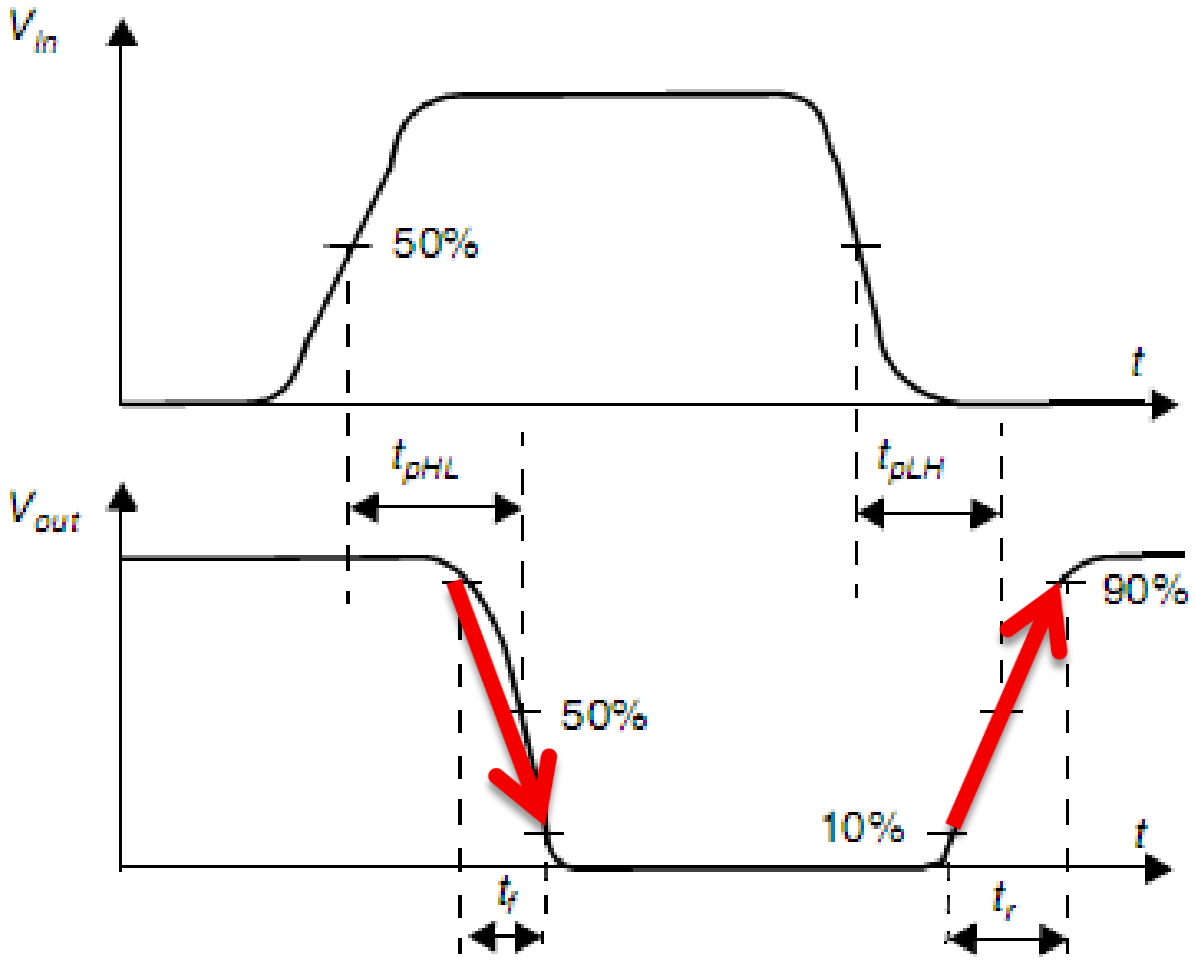
Dynamic Properties of a Digital Gate

Propagation Delay, Rise/Fall Time

Propagation Delay – Definition



Rise/Fall Time – Definition



Dynamic Properties - Example

- Given a simple RC network with a step input:
  - Find the Propagation Delay
  - Find the Rise Time of the Output

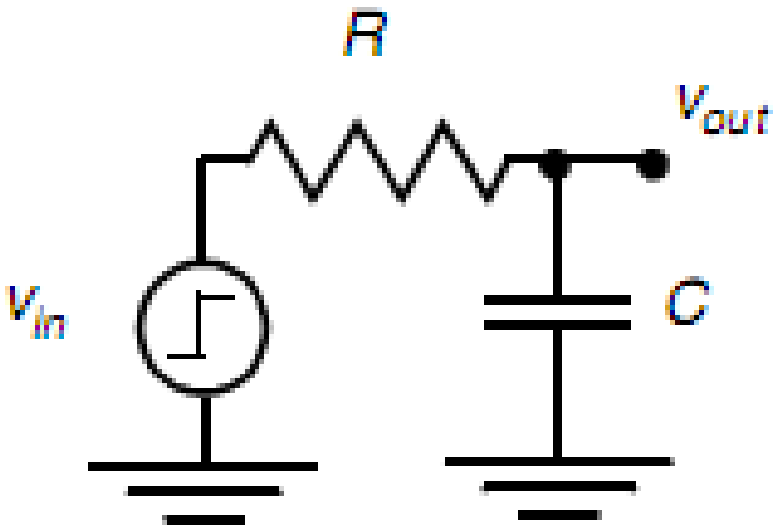
$$V_{in} = V_R + V_{out} = i_c R + V_{out} = RC\dot{V}_{out} + V_{out}$$

$$V_h = Ke^{-t/\tau} \quad \tau \triangleq RC \quad V_p = V_{in}$$

$$V_{out}(t) = Ke^{-t/\tau} + V_{in}$$

$$V_{out}(0) = 0 = Ke^{-0/\tau} + V_{in} \Rightarrow K = -V_{in}$$

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

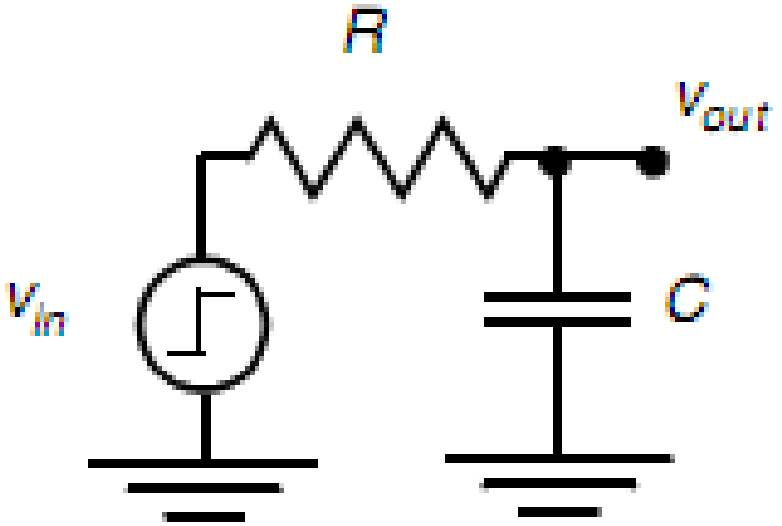


Dynamic Properties - Example

- Assuming a zero-time step input:

$$V_{out}\left(t_{pd}\right) = 0.5V_{in} = \left(1 - e^{-t_{pd}/\tau}\right)V_{in}$$

$$e^{-t_{pd}/\tau} = 0.5 \Rightarrow t_{pd} = -\tau \cdot \ln 0.5 = 0.69\tau$$



Dynamic Properties - Example

- Rise Time Calculation:

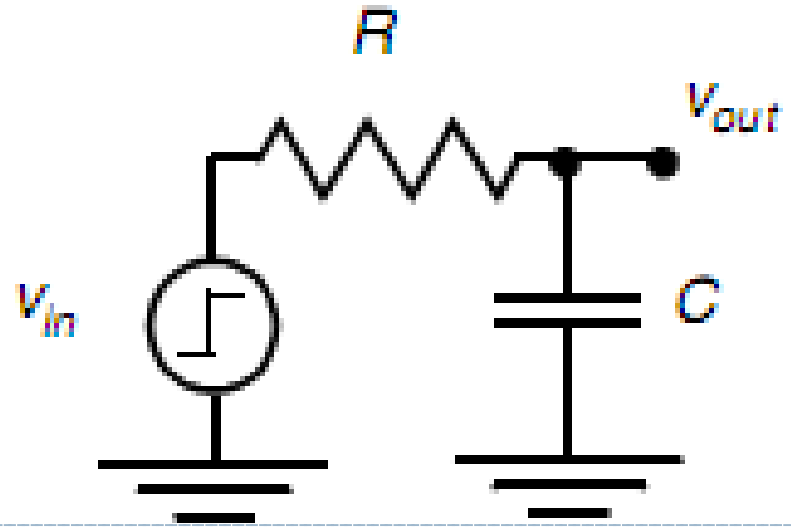
$$V_{out}\left(t_{pd}\right) = \left(1 - e^{-t_{pd}/\tau}\right) V_{in}$$

$$e^{-t_{pd}/\tau} = 1 - \frac{V_{out}}{V_{in}}$$

$$V_{out}\left(t_{10\%}\right) = 0.1V_{in} \quad \Rightarrow \quad t_{10\%} = -\tau \ln 0.9 = 0.1\tau$$

$$V_{out}\left(t_{90\%}\right) = 0.9V_{in} \quad \Rightarrow \quad t_{90\%} = -\tau \ln 0.1 = 2.3\tau$$

$$t_r = t_{90\%} - t_{10\%} = 2.2\tau$$



Power Dissipation

Dynamic Power, Static Power

Power Dissipation

- Power Components:

$$P_{total} = P_{dynamic} + P_{static}$$

- Dynamic Power:
  - The power consumed during a switching action.
  - Used to charge/discharge node capacitance.
  - Also includes *Short Circuit* power that is wasted during switching.
- Static Power:
  - The power consumed during steady state operation.
  - Usually considered leakage power.

Dynamic Power - Example

- Find the power dissipated by a first order RC network with a step input:
  - The energy needed to fully charge the capacitor:

$$E_{switch} = \int_0^{\infty} i_{in}(t) v_{in}(t) dt = V_{in} \int_0^{\infty} C \frac{dv_{out}}{dt} dt = CV_{in} \int_0^{V_{in}} dV_{out} = CV_{in}^2$$

  - The power is the amount of energy dissipated per second:

$$P_{dynamic} = fE_{switch} = fCV_{in}^2$$

  - Considering an ideal capacitor, there is no power dissipation in steady state: $P_{static} = 0$
  - Altogether we get: $P_{total} = P_{dynamic} + P_{static} = fCV_{in}^2$

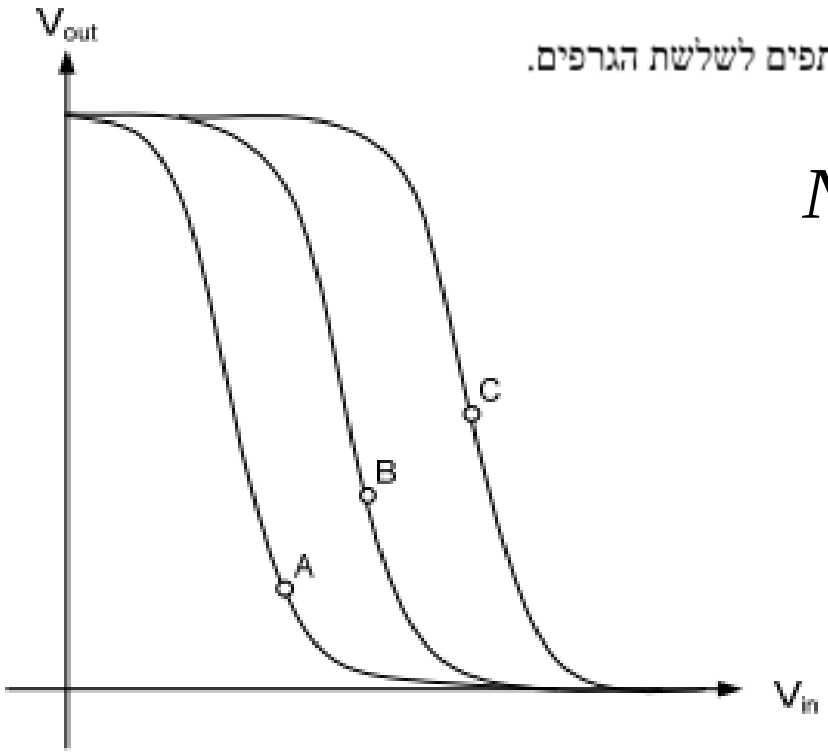
Questions from Tests

Questions from Tests

- Which gate has higher NM_H and NM_L ?

4.4 (4) נתונים שלשה מהפכים בעלי VTC כפי שמתואר באיור הבא:

הערה: V_{OLmax}, V_{OLmin}, V_{OHmax}, V_{OHmin} שותפים לשלשת הגרפים.

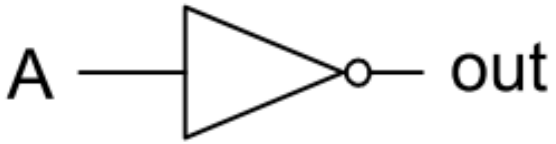


$$NM_H = V_{OH\min} - V_{IH}$$

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

Questions from Tests

- Which transition drains the battery more?



השאלה מתייחסת לצריכת האנרגיה (E) כוללת מהספק של המהפך בפרק זמן בין T1 ל-T2. נתונים 4 אפשרויות שונות של התנהגות הכניסה A כפונקציה של הזמן. האנרגיה Ea מתייחסת לאפשרות a, Eb לאפשרות b וכו'.