Introduction to CMOS VLSI Design

Circuits Lecture A

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Based on material from
Prof. Jay Brockman, Joseph Nahas: University of Notre Dame
Prof. David Harris, Harvey Mudd College
http://www.cmosvlsi.com/coursematerials.html

Outline: Circuits

- ***Lecture A***
  - ***Physics 101***
  - ***Semiconductors for Dummies***
  - ***CMOS Transistors for logic designers***
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  - CMOS Inverter and NAND Gate Operation
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- Lecture C
  - Pass Transistors
  - Tri-states
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EE101

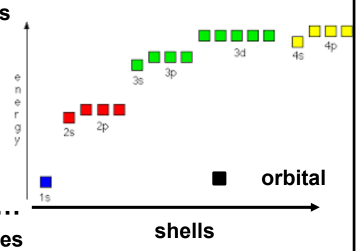
- **Charge (Q):** # of excess electrons beyond # of protons
  - Units of ***Coulombs***: 1 coulomb = 6.24151 × 10^{18} electrons
- ***Voltage (V)***: **electrical potential difference between two point in space**
  - **Point with lower potential called** *negative*
  - **Point with higher potential called** *positive*
- ***Current (I)***: **flow of electrons across a voltage potential**
  - **Electrons travel** ***from negative*** ***to positive***
  - **Units of** ***Amperes*** **(A), where 1 A = 1 coulomb moving in 1 sec**
- ***Resistance (R):*** **property of material controlling amount of current: I = V/R or R = V/O or V = IR**
- ***Capacitance (C):*** **property of material to store a charge & form a voltage potential**
  - **V = Q/C = potential when Q charge is stored in a capacitance C**
  - **Units of capacitance are** ***Farads,***
  - **where 1 volt = 1 Coulomb / 1 Farad**

Circuits-A **CMOS VLSI Design** **Slide 3**

Underlying Physics 101

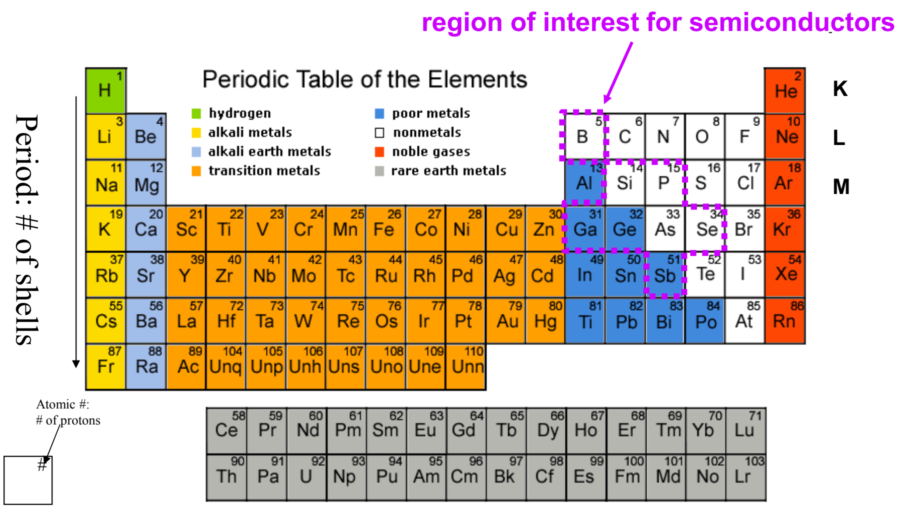
- **Atoms constructed from**
  - ***Protons***: **positively charged heavy particles**
  - ***Neutrons***: **heavy particles with no charge**
  - ***Electrons***: **very light negatively charged particles**
- **Protons & neutrons bind together in** ***nucleus***
- **In neutral atom, # protons = # electrons**
  - ***Ion***: **numbers not equal; atom is** ***charged***
- **Electrons circle nucleus in** ***orbitals***
  - **Energy of orbital higher the further from nucleus**
  - **Higher energy makes it easier to escape**
  - **Up to 2 electrons per orbital**
- **Orbitals group into** ***shells*** **(K, L, M, N, O, …)**
  - **# electrons in shell n = $2n^2$**
  - **Electrons fill lower shells first**
- **Each shell consists of** ***subshells*** **s, p, d, f,…**
  - **Different subshells have slightly different energies**

	Max electrons in subshells					
Shell	s	p	d	f	g	Total
K	2					2
L	2	6				8
M	2	6	10			18
N	2	6	10	14		32
O	2	6	10	14	18	50



Circuits-A **CMOS VLSI Design** **Slide 4**

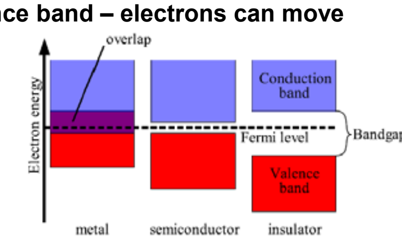
Periodic Table of Elements



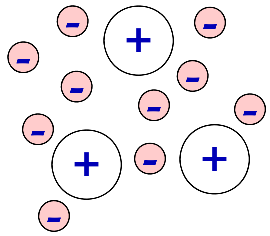
Same color is same "***group***" – elements with similar properties

Electronic Band Structure

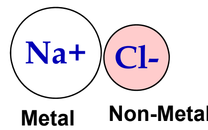
- ***Valence Shell:*** **outermost shell with electrons**
- ***Covalent bonds:*** **Atoms near each other with incomplete valence shell "share" electrons that fill valence shell**
- **Shells "above" valence shell**
  - **Have higher energies**
  - **Allow electrons to escape much easier**
- **In solids, differences between energy levels in neighboring orbitals becomes small (but non 0), and group into *BANDS***
  - ***Conduction Bands:*** **Those above valence**
  - **If conduction band overlaps valence band – electrons can move**
    - **I.E. "Current" can flow easily**



Metals and Insulators



Metal:
- typically valence shell only partially filled
- may readily lose electrons from valence
- atoms become positively charged “***holes***”
- surrounded by “sea of ***free electrons***”



Insulator (non-metal):
- valence shell is near full
- tough to pry out an electron
- when near a metal, loses an electron to form strong ***ionic bond***

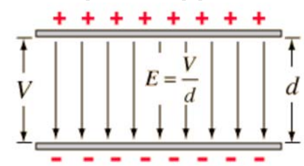
Some Materials

Element	Symbol	Atomic #	Valence Shell	Electrons in Valence	Electrons to fill valence
Aluminum	Al	13	M	3	15
Copper	Cu	29	N	1	31
Gold	Au	79	O	19	31
Boron	B	5	L	3	5
Phosphorus	P	15	M	5	13
Silicon	Si	14	M	4	14
Germanium	Ge	32	N	4	28

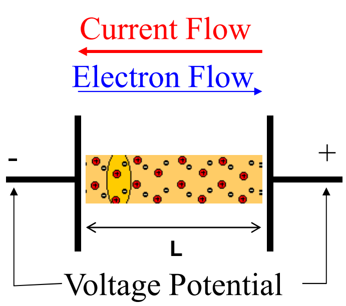
What Makes Electrons Move?

- **Coulomb's Law: Force between two separated charged particles**
  - **Force = $-q_i q_j/(4\pi\varepsilon r^2)$**
    - **q_i, q_j: charges of two particles in coulombs**
    - **r: distance between charges**
    - **ε ("episilon"): permittivity of material**
  - **If signs of q the same, force is repulsive**
  - **If signs different, force is attractive**
- **Mass of electron ~ 1/1836'th of proton**
- ***Electric field around charge* i at radius r: *E* = $q_i/(4\pi\varepsilon r^2)$**
  - **In units of *Volts*: "force per unit charge"**
  - **Force on particle j is thus Eq_j**
- ***Electric field between 2 parallel plates* with equal & opposite charges = V/d**

E = V/d
V = Q/C
E = Q/Cd



Resistance



1. Conduction electrons drawn from region nearest +
2. This leaves positive "holes"
3. Which attract electrons from next region
4. …
5. At "-" end, electrons are drawn from potential

Current flow is hole flow from + into material and out towards negative end. (OPPOSITE electrons)
How much flow depends on ***Voltage*** and ***Resistance***

Current = Voltage / Resistance or **Resistance = Voltage / Current**
Resistance in units of **ohms (Ω)**, or 1**Ω = 1 Volt / 1 Amp**

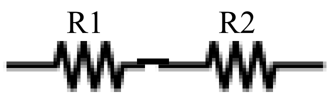
Resistance R = ρ L / A:
- A = Cross section **area**
- L = **Length** of material
- **ρ** (rho) = **Resistivity** of material (in units of ohm meter)

Material	Resistivity, ρ (ohm-meter)
Metals	10^{-8}
Semiconductors	variable
Electrolytes	variable
Insulators	10^{16}
Superconductors	0 (exactly)

10^{24}

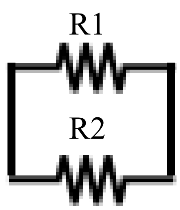
Kirchhoff's Laws

Resistance $R = \rho L / A$:
- A = cross section area
- L = length of material
- ρ = **resistivity** of material (in units of ohm meter)



$R = R1 + R2$

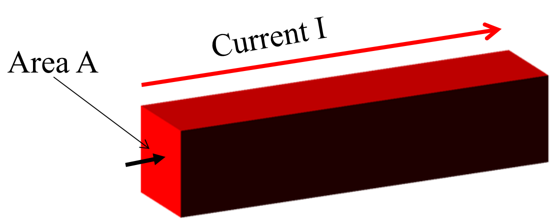
Why?



$R = 1/\,(1/R1 + 1/R2) = (R1 + R2)/(R1*R2)$

Why?

Current Density (J)

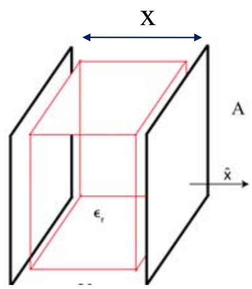


Current Density J = Current/Area = Amps/m^2 = $V/(\rho L)$

(J is a "vector" with direction along path of electrons)

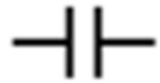
Why do we care? Too high a current density can cause:
- **Metal migration**
- **Burnout**
- **Skin effect**

Capacitors



Basic device:

- 2 conducting plates (of area A)
- Separated by a distance d
- With "***dielectric***" insulator material between
    - SiO_2 typical on chips



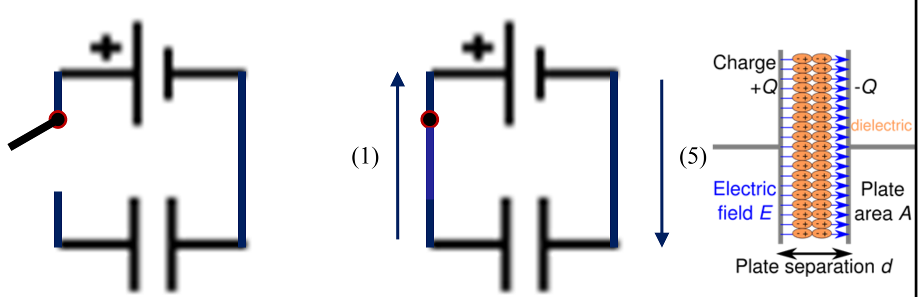
C (in units of ***Farads*** F: Coulombs / Volts) = ε A / d
where ε = "***permittivity***" of material, often written as $\varepsilon_r\varepsilon_0$

- ε_0 = permittivity of vacuum = 8.854×10^{-12} F m^{-1}
- ε_r = permittivity of material relative to vacuum
- 1 F = 1 Coulomb / 1 Volt

Material	Episilon[r]
Aluminium	-1.30E+17
Silver	-8.50E+13
Vacuum	1
Air	1.00058986
PTFE/Teflon	2.1
Polyethylene	2.25
Polyimide	3.4
Paper	3.5
Electroactive polymers	2–12
Silicon dioxide	3.9
Concrete	4.5
Pyrex (Glass)	4.7
Rubber	7
Diamond	5.5–10
Graphite	10–15
Silicon	11.68
Water	88
Titanium dioxide	86–173
Strontium titanate	310
Barium strontium titanate	500
Barium titanate	1250–10,000
(La,Nb):(Zr,Ti)PbO3	500–6000

What happens with large ε_r?

Capacitors in Action



(a) Both plates have no charge

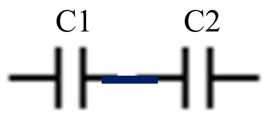
(b) Switch closes

1. Electrons attracted off of left plate into battery
2. Left plate becomes positively charged
3. Atoms in dielectric have electrons attracted to left
4. This pushes positive charge to right
5. Electrons on right plate attracted to leftmost side
6. Leaving positive charge in right wire
7. Which is neutralized by electrons from – battery
8. Current stops when charge Q = CV

Which Direction is Current Flow?

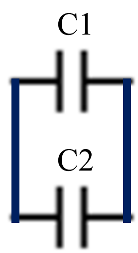
Capacitor Circuits

$C = \varepsilon A/d$



$C = 1/ (1/C1 + 1/C2)$
$= (C1*C2)/(C1 + C2)$

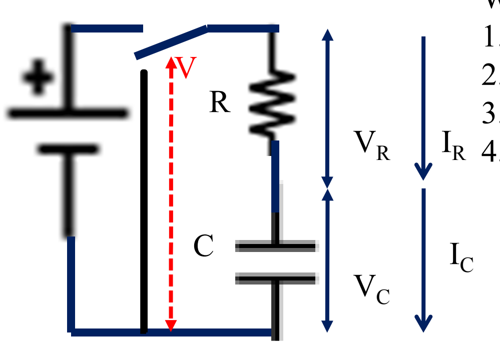
Why?



$C = C1 + C2$

Why?

RC Circuits

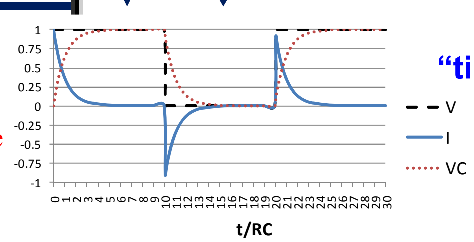


What do we know?

1. $I_R = I_C = I$
2. $V = V_C + V_R$ or $V_R = V - V_C$
3. $I_R = I = V_R / R$
4. $I_C = I = C\, dV_C/dt$
   or
   $V_C = V - RC\, dV_C/dt$
   or
   $\mathbf{V_C = V(1 - e^{-t/RC})}$

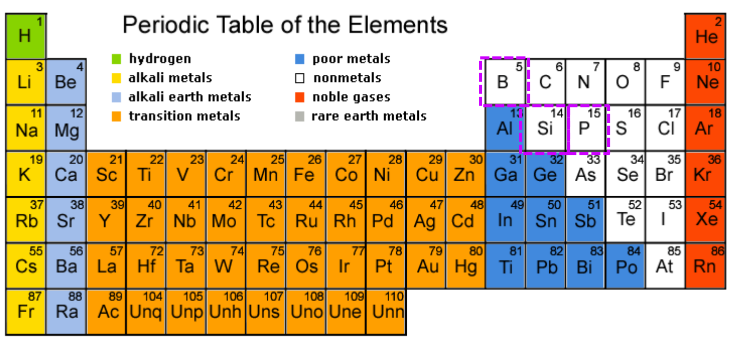
RC = "time constant"

What does a negative current flow mean?



Semiconductors

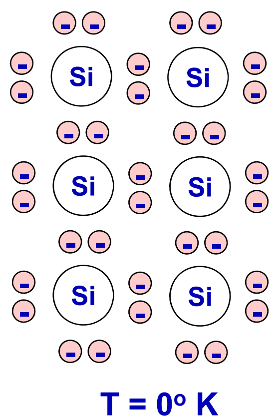
Key Materials: Si, B, P

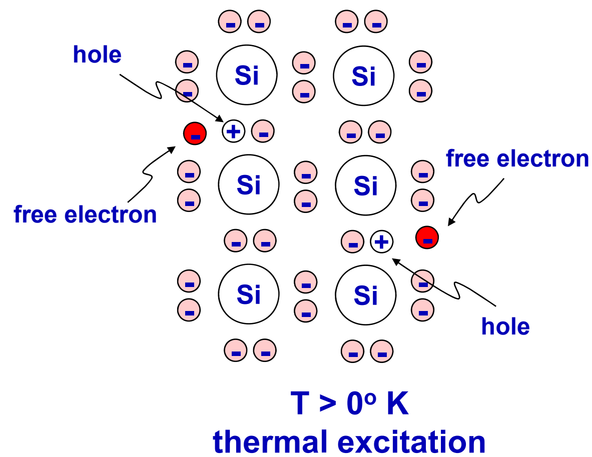


Material	Atomic #	Electrons per Shell
Silicon Si	14	2, 8, **4**
Boron B	5	2, **3**
Phosphorus	15	2, 8, **5**

Silicon

Si: silicon – has 4 electrons and space for 4 more in valence shell

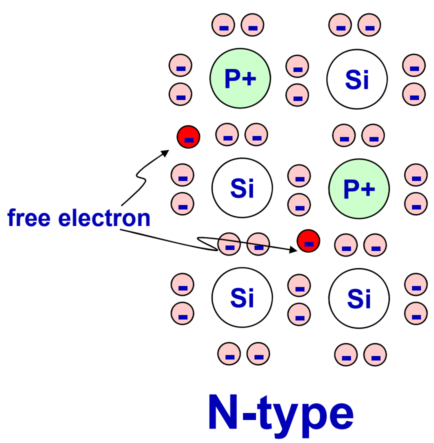


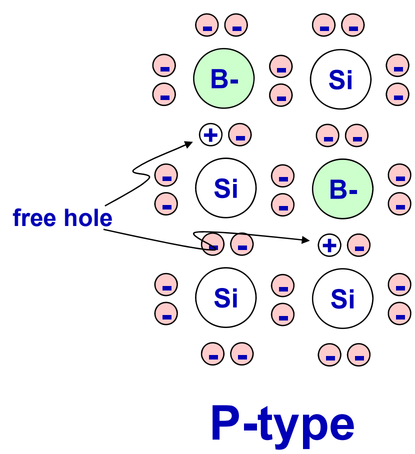


Doping: Mixing Into Pure Silicon

P or Phosphorus
•one more electron in valence than Si
•known as a ***donor*** atom

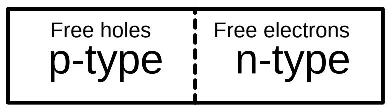
B or Boron
•one less electron in valence than Si
•known as a ***acceptor*** atom



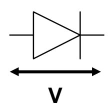


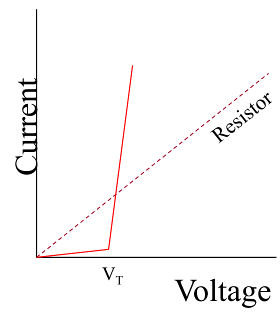
PN Junctions

- A junction between p-type and n-type semiconductor forms a *diode*.
- Current flows only in one direction



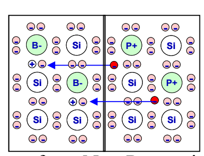
anode cathode



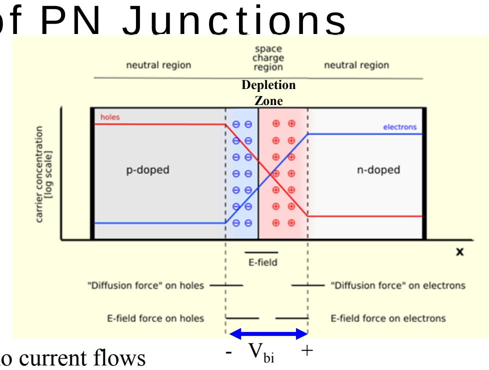


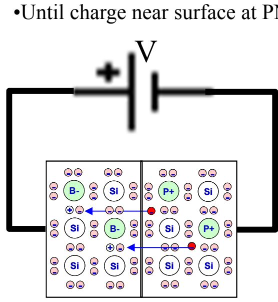
The "Why" of PN Junctions

P N

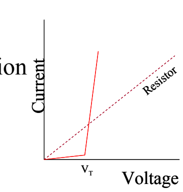


•Electrons move from N to P materials
•With holes that "move right"
•Until charge near surface at PN repels more



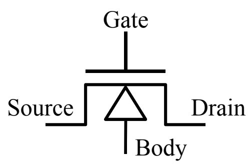


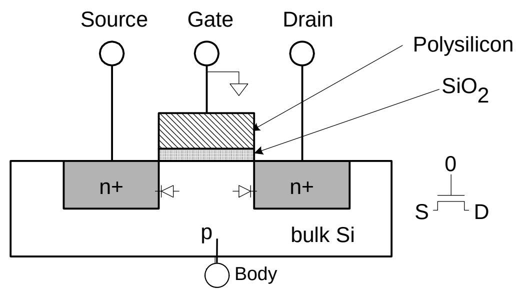
- If $V \le 0$, no current flows
  - V reinforces depletion zone
- If $0 < V < V_{bi}$
  - V cannot overcome attraction in junction
  - Depletion zone shrinks
  - No current flows
- If $V \ge V_{bi}$
  - Electrons pulled left from P-junction
  - Holes in N-type filled with electrons from V
  - Current flows



nMOS Transistor

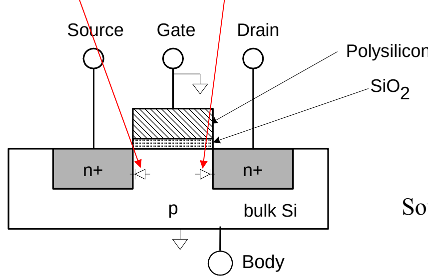
- Four terminals: ***gate, source, drain, body***
- Gate – oxide – body stack looks like a capacitor
  - Gate and body are conductors
  - SiO_2 (oxide) is a very good insulator
  - Called ***metal – oxide – semiconductor*** (***MOS***) capacitor
    - Even though gate is often not metal

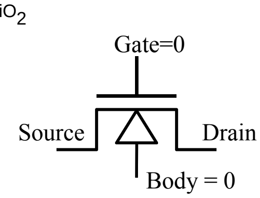




nMOS Operation

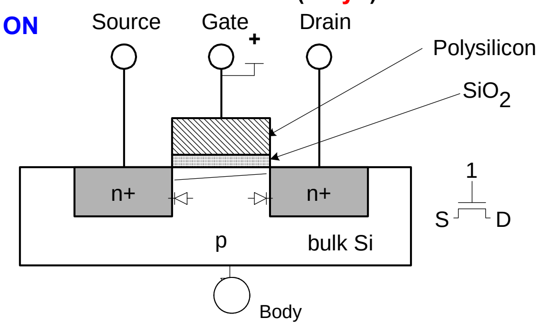
- Body is commonly tied to ground (0 V)
- When the gate is at a low voltage:
  - P-type body is at low voltage
  - ***Source-body*** and ***drain-body*** diodes are OFF
  - No current flows, transistor is OFF





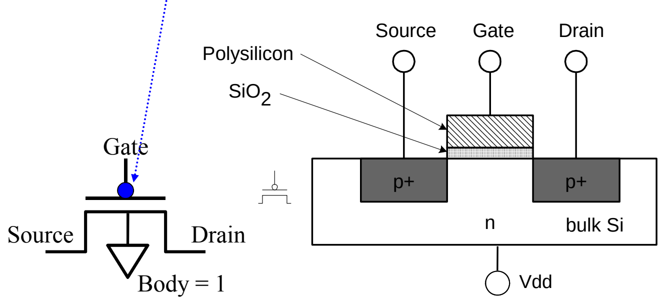
nMOS Operation Cont.

- When the gate is at a high voltage:
  - Positive charge on gate of MOS capacitor
  - Negative charge attracted to body
  - Inverts a channel under gate to n-type
  - Now electrons can flow through n-type silicon from source through channel to drain
  - Current flows from the drain to the source (Why?)
  - The transistor is ON

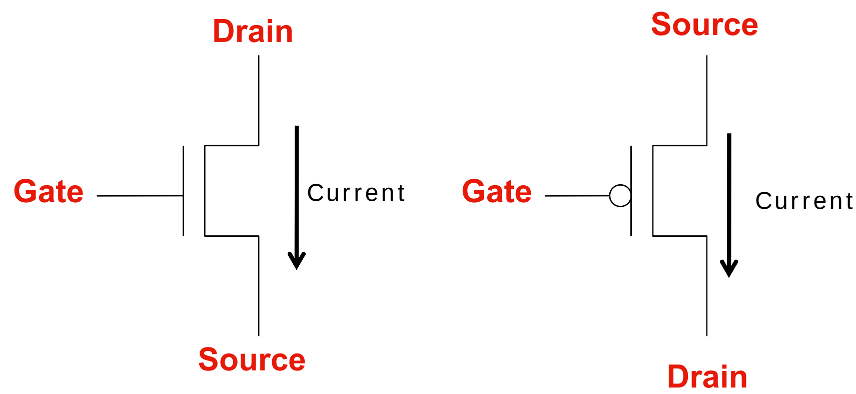


pMOS Transistor

- Similar, but doping and voltages reversed
  - Body tied to *high* voltage (V_{DD})
  - Gate low: transistor ON
  - Gate high: transistor OFF
  - "Bubble" on gate symbol indicates inverted behavior
  - Holes (and current) flow from the source to the drain

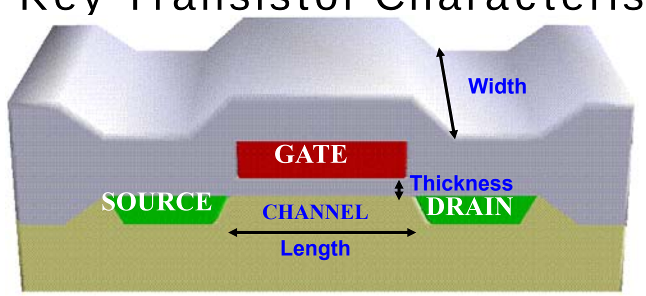


Circuit Symbols



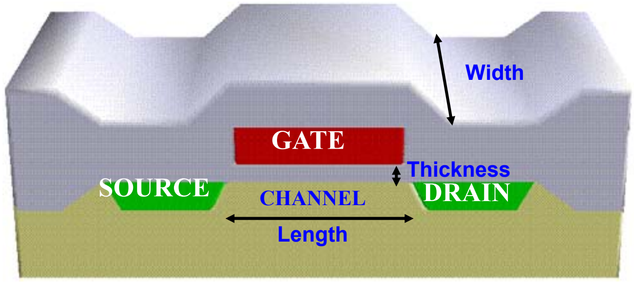
- When not shown, standard is:
  - NMOS Body is tied to V_{SS}, the logic negative voltage supply.
  - PMOS Body is tied to V_{DD}, the logic positive voltage supply.

Key Transistor Characteristics



- "*Threshold Voltage*" on gate that causes current to flow
- "*Resistance*" of channel that conducts current
- "*Capacitance*" of Gate
- Key Controlling Physical Parameters
  - Length (L) of channel
  - Width (W) of Channel
  - Thickness (t_{ox})of gate insulator

What is Your Intuition?



What Happens as We Make the Following Smaller?

	Length	Width	Thickness
Resistance			
Capacitance			
Threshold Voltage			

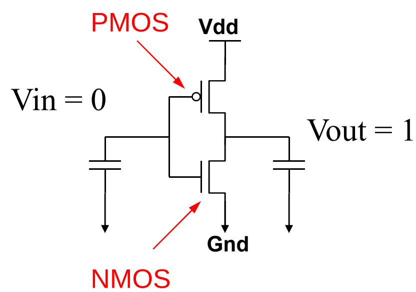
The “Water” Analog

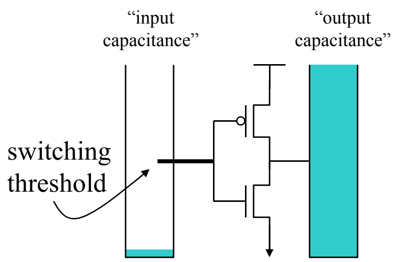
- **Think of electrons as “*drops of water*”**
- **Water flows from *high pressure* (high voltage) to *low pressure* (low voltage)**
- **Flow of water can *fill up* a container (capacitor)**
  - **“Height” of water = voltage**
- **How high a certain amount of water fills a container depends on area of container**
  - **Wider area = higher capacitance => more water flow needed to raise level**
- **Transistors like toilet “flapper valves”**
  - **Turn “on” when water level reaches *threshold***
  - **Assume threshold = 0.5 height in following**

CMOS Switching Circuits

- **Computing machines built from switches**
- **Encoding: voltage at points in circuit**
- **Operation: moving charge around**

A Simple Inverter



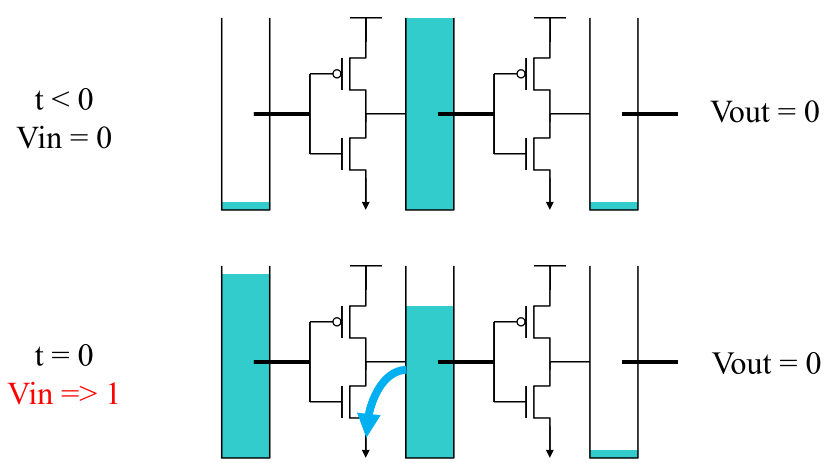


NMOS conducts when charge (water) level is above switching threshold

PMOS conducts when level below

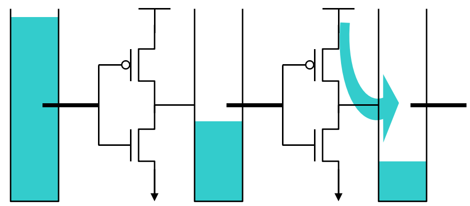
No conduction after output container is full

Signal Propagation (1)

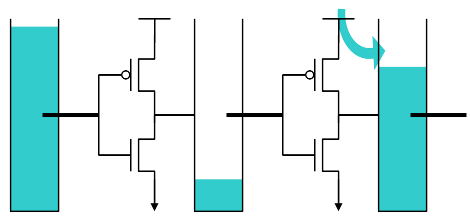


Signal Propagation (2)

t = 1
Vin = 1



t = 2
Vin = 1



Delay and Energy Definitions

- ***Propagation Delay***
  - time to fill output container to 50%
  - time to charge output capacitance to 50%
- ***Switching Energy***
  - weight x height of water moved
  - charge x voltage of charge transferred
  - $QxV = CVxV = CV^2$