IIT Bombay

Makerspace (MS101)

2024 (Autumn)

EE-Lecture-10

Introduction to Transistors
Using Bipolar Junction Transistor (BJT) and
Metal Oxide Field Effect Transistor (MOSFET) as Switch

Transistors: Introduction

A transistor is a semiconductor device with three terminals, used in analog & digital applications. It can be modelled as a 'two-port network', with 'input-dependent output variable'.

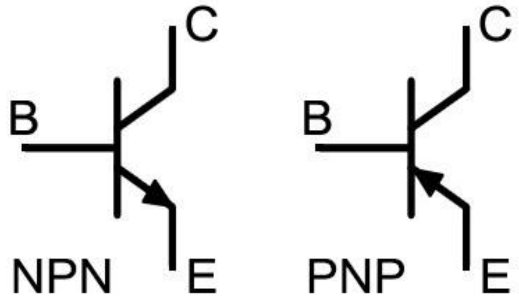
Commonly used transistors

(a) Bipolar Junction Transistor (BJT) **(b)** Metal Oxide Field Effect Transistor (MOSFET)

Circuit Symbol

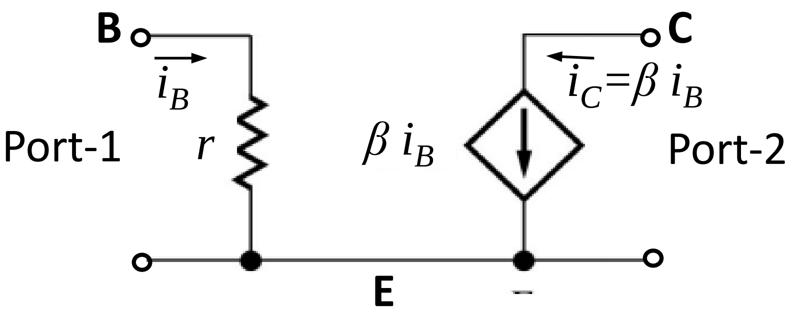
Simplified Small-Signal Model

Bipolar Junction Transistor

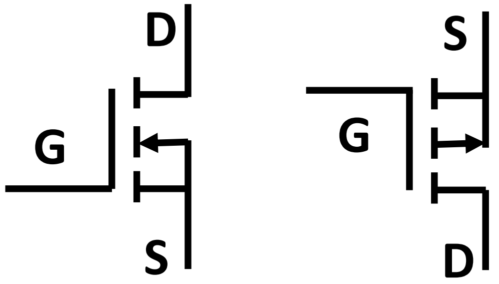


B: Base
C: Collector
E: Emitter

β: Current gain



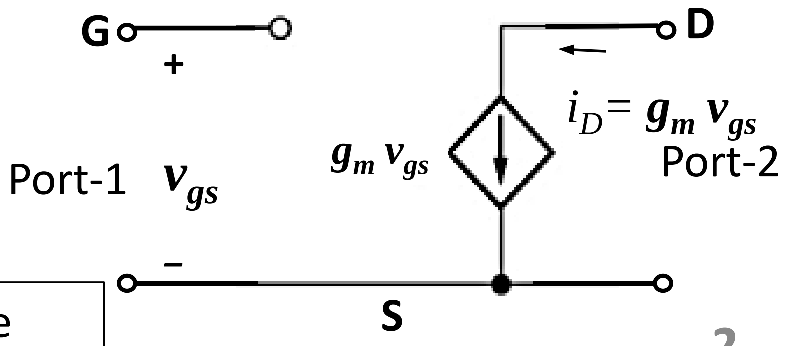
MOSFET (Enhancement mode)



N-Channel **P-Channel**

G: Gate
D: Drain
S: Source

g_m: trans-conductance

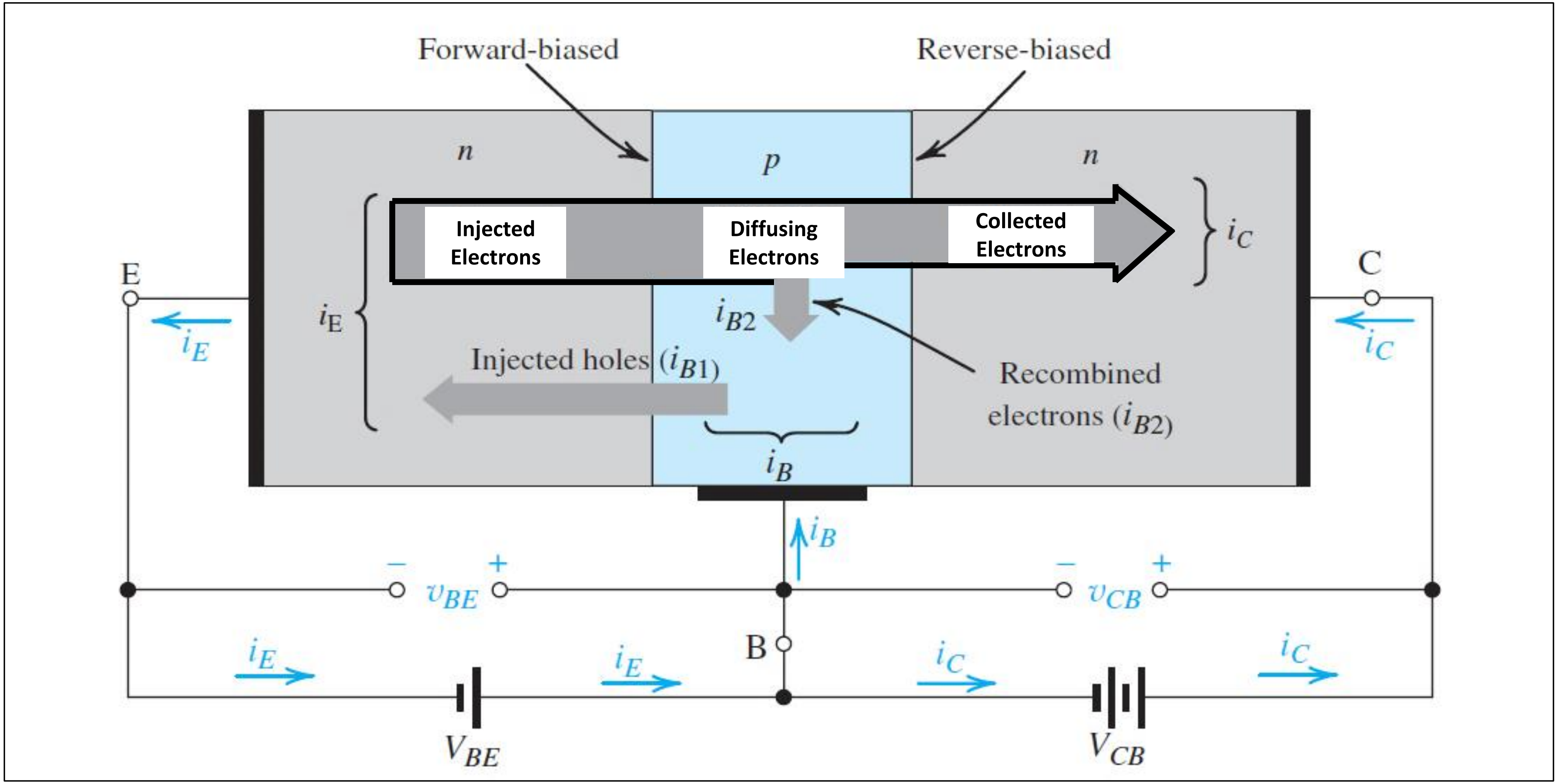


A transistor is operated with one terminal common to both input and output – Three modes of operations for both BJT (CE, CB, CC)) and MOSFET (CS, CG, CD)

Bipolar Junction Transistor (BJT)

Types	NPN, PNP
Terminals	emitter (E), base (B), collector (C)
Controlling quantity	Current-controlled current source: Base Current (I_B) controls Collector Current (I_C).
BJTs have lower input resistance (≈ 10 kΩ to 1 MΩ in common-emitter mode) and hence consume more power from the input signal source than MOSFETs.	

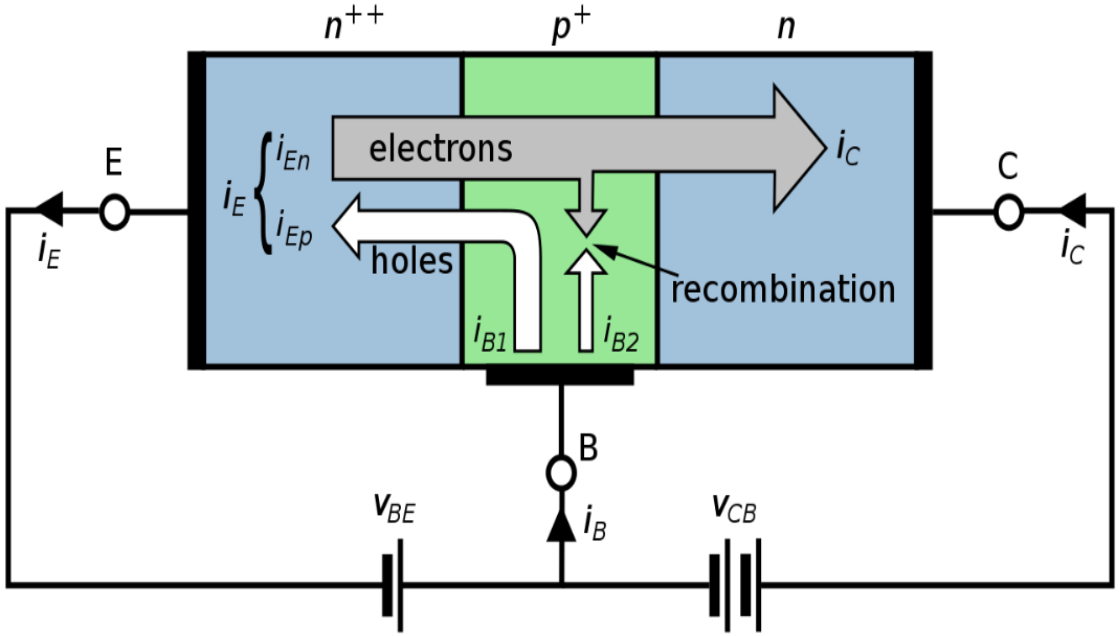
Bipolar Junction Transistor Operation



NPN transistor biased in active mode (BE junction: forward biased , BC junction: reversed biased)

Source: Fig 6.3:-Sedra A S, Smith K C, "Microelectronic Circuits", Oxford University Press, 7Ed. I**SBN: 9780199339136**

BJT Operation



Cricket analogy

- The emitter is the bowler who shoots balls (electrons) toward the base.
- The base is the batsman, a tail-ender who swings away but connects with only 1-2% of the incoming balls (electrons).
- Most of the balls (electrons) are collected by the wicketkeeper.

Current relations

KCL: $I_E = I_B + I_C$

Transistor action

$\Delta I_C = \alpha \Delta I_E$ ($\alpha \approx 0.90 - 0.99$)

$\Delta I_C = \beta \Delta I_B$

$I_C = \beta I_B$ is used as an approximate relation.

Relation between α & β

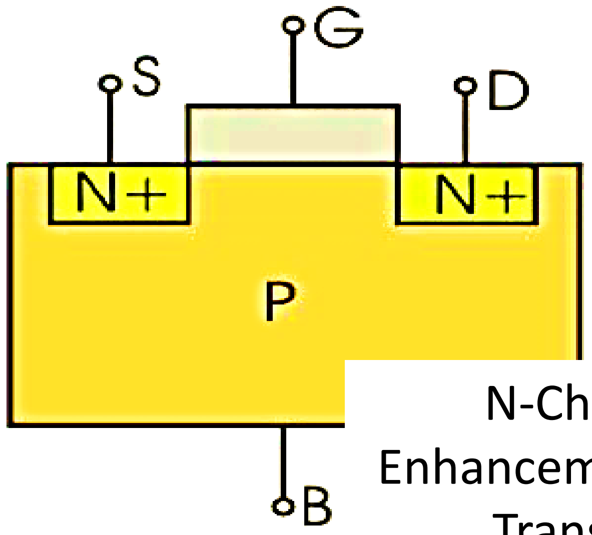
$\Delta I_E = \Delta I_B + \Delta I_C \Rightarrow \Delta I_B = \Delta I_E - \Delta I_C = (1/\alpha - 1)\,\Delta I_C$

$\Rightarrow \Delta I_C = \alpha/(1-\alpha)\,\Delta I_B = \beta \Delta I_B$

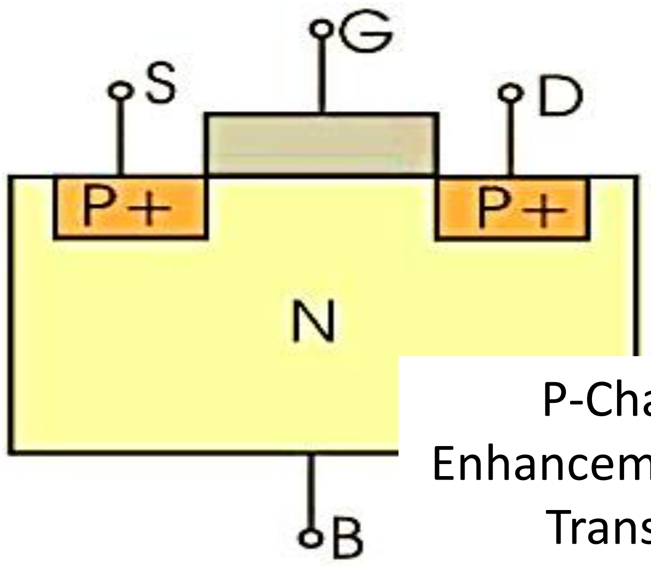
$\Rightarrow \beta = \alpha/(1-\alpha)$

Example: $\alpha = 0.98 \Rightarrow \beta = 0.98/0.02 = 49$

MOSFETs: Introduction



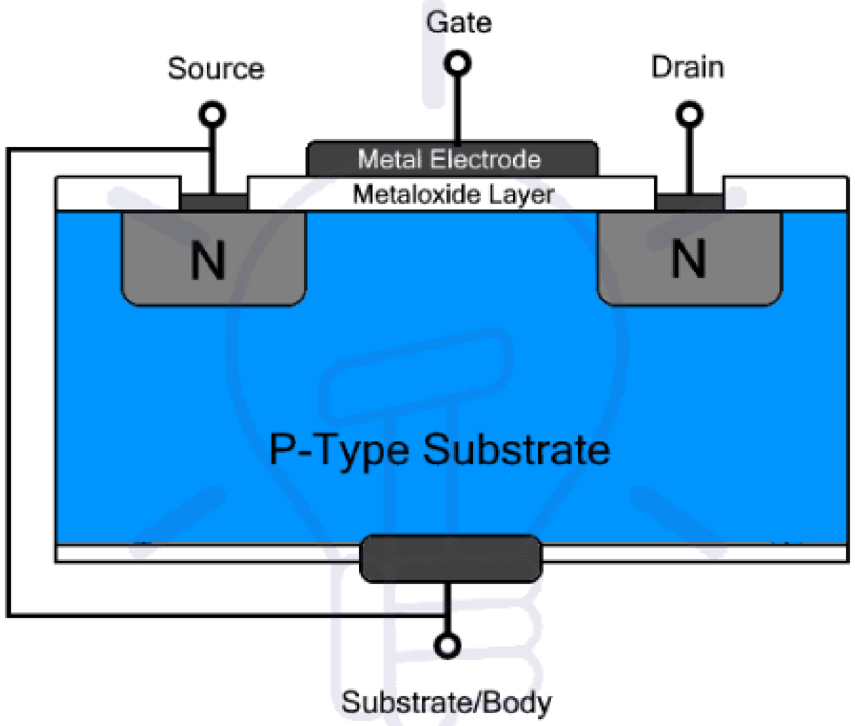
N-Channel Enhancement-mode Transistor

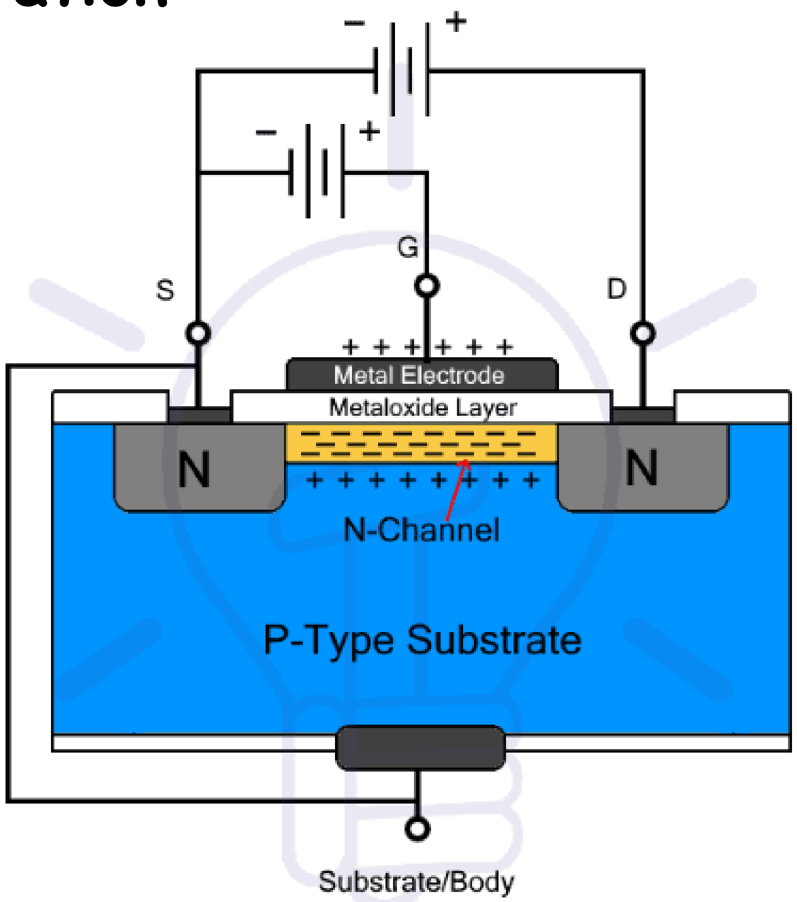


P-Channel Enhancement-mode Transistor

Types: N-channel & P-channel, fabricated in enhancement-mode for digital circuits	
Types	N-channel enhancement-mode P-channel enhancement-mode
Terminals	source (S), drain (D), gate (G), substrate or body or bulk.
Controlling quantity	Voltage-controlled current source device: Gate-Source voltage (V_{GS}) controls drain to source current (I_{DS})
MOSFETs have high input impedance (10 MΩ to 100 MΩ) and hence consume less power from the input signal source than BJTs.	

N-Channel Enhanement-mode MOSFET Operation





Device ON / OFF operation

ON: Low resistance for drain-source current flow.

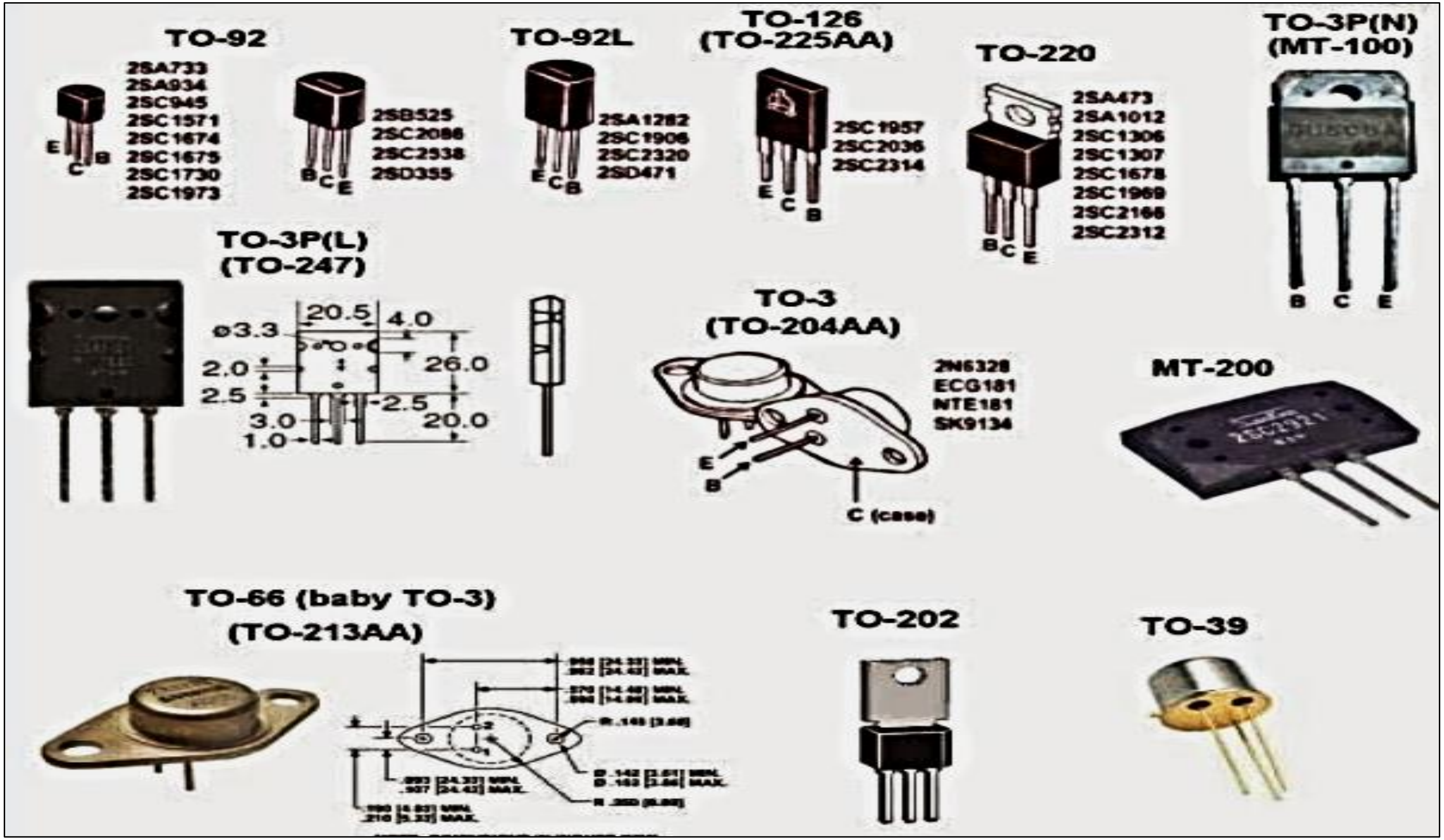
OFF: Very high resistance for drain-source current flow.

Enhancement mode: No channel is available at $V_{GS} = 0$. The channel is formed for V_{GS} above the threshold voltage V_T (+ve for N-channel).

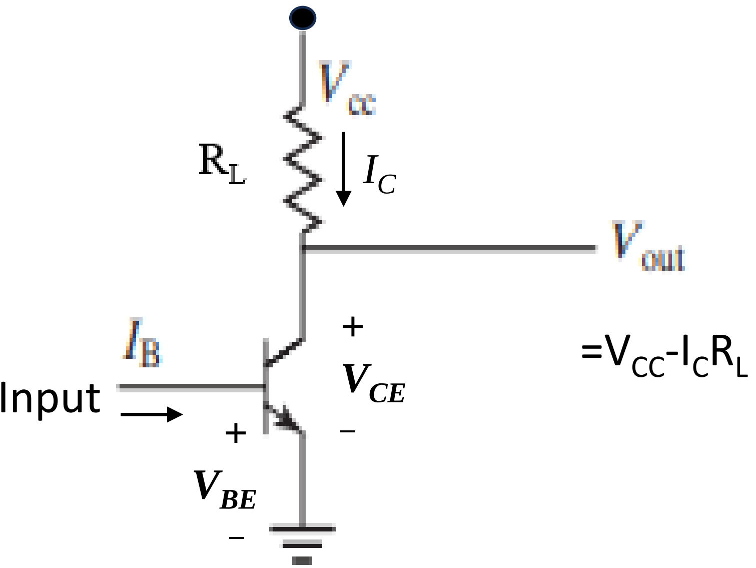
MOSFET Type	Condition for Switching
N-channel Enhancement	OFF for $V_{GS} < V_T$ (0.6 to 1 V)
P-channel Enhancement	OFF for $V_{GS} > V_T$ (—1.0 to 0.6 V)

Source: https://www.electricaltechnology.org/2021/06/mosfet.html

Commercially Available Transistor Packages



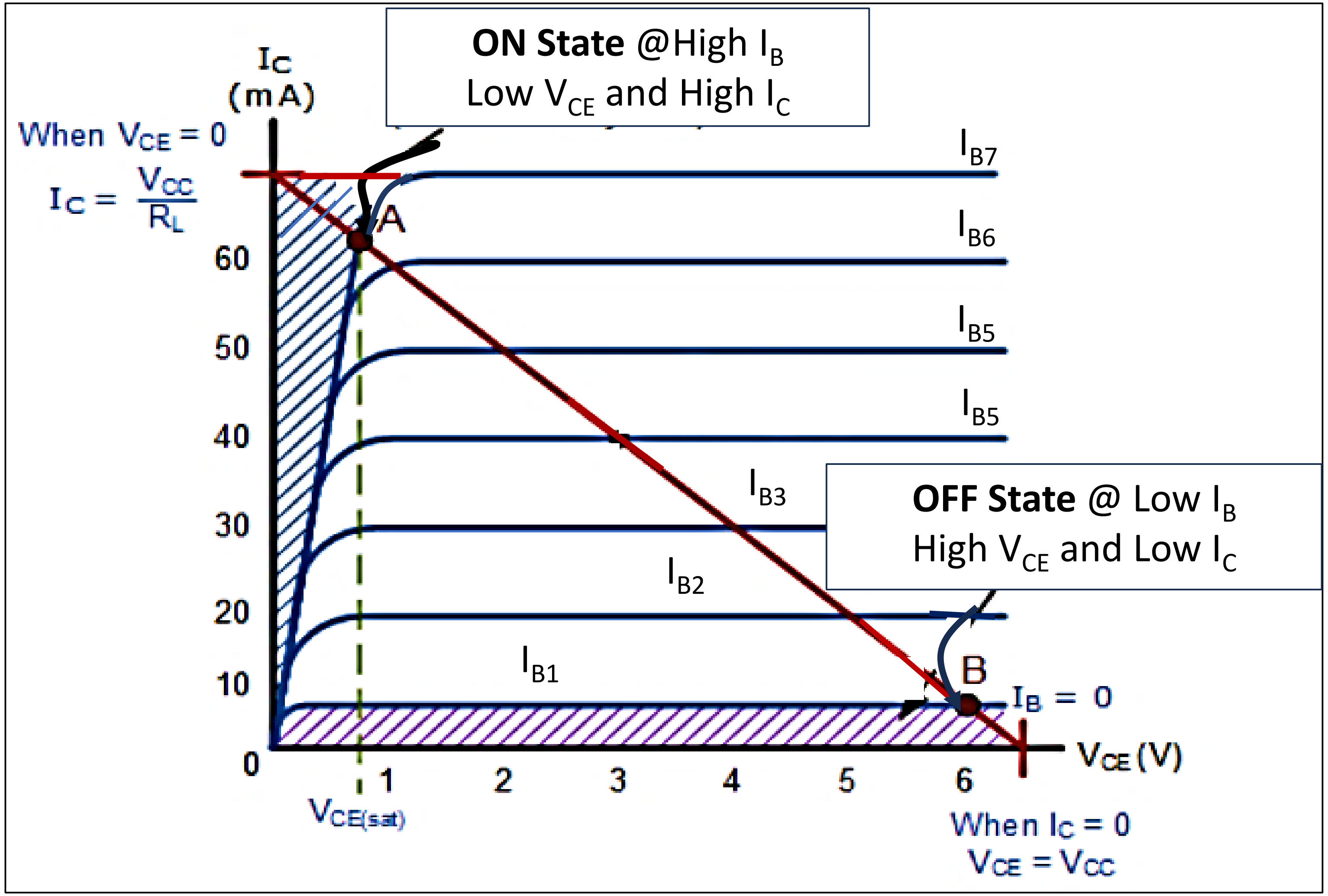
Switching Characteristics of BJT (on V_{CE}-I_C Plane)



BJT is switched ON / OFF by changing the base current I_B.

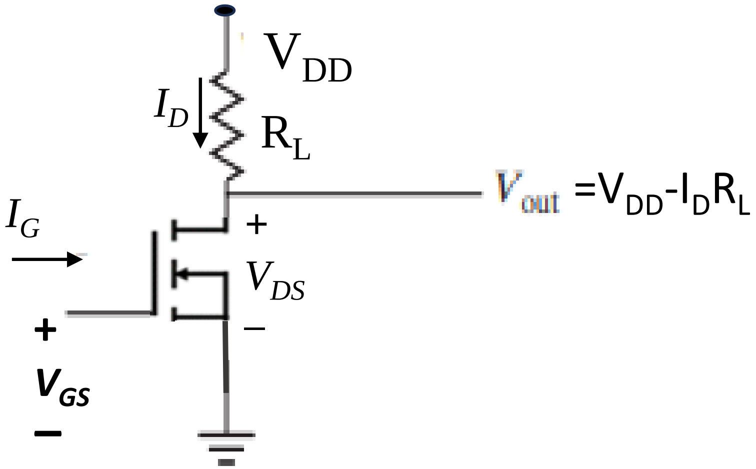
OFF: $V_{BE} < V_\gamma$. $(V_\gamma \approx 0.5$ V)
$I_B \approx 0$. $V_{CE} \approx V_{CC}$. $I_C \approx 0$.

Heavily ON: $I_B > I_C / \beta$.
$V_{BE} = V_{BES}$. $V_{CE} = V_{CES}$.
$I_C = (V_{CC} - V_{CES}) / R_L$
($V_{BES} \approx 0.8$ V. $V_{CES} \approx 0.2$ V)



Typical 'V_{CE} - I_C' characteristics for BJT (base currents: $I_{B1} < I_{B2} < I_{B3} < I_{B4} < I_{B5} < I_{B6} < I_{B7}$) . Operating points for switching action: A (on) & B (off).

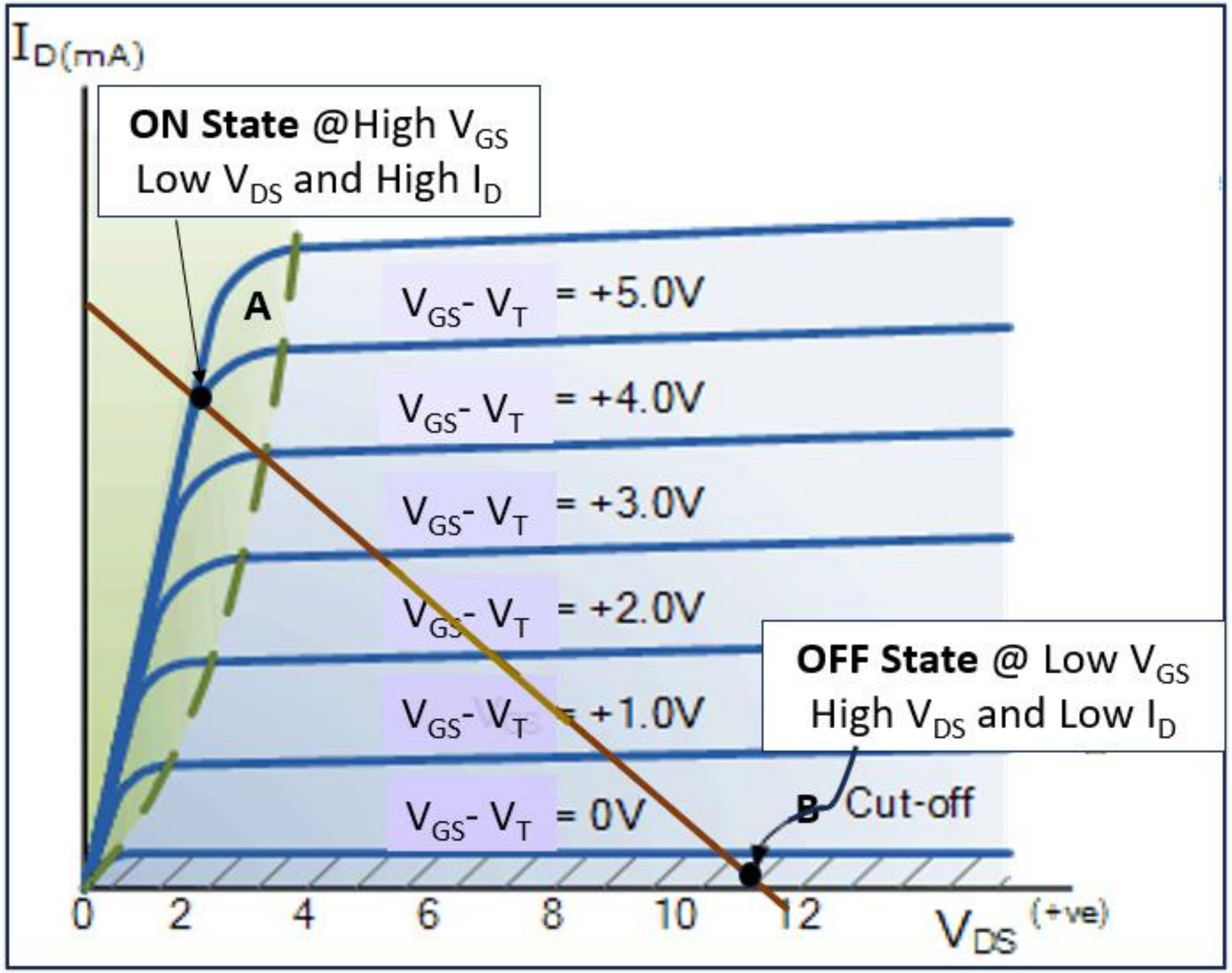
Switching Characteristics of N-Channel Enhancement-Mode MOSFET (on V_{DS}-I_D Plane)



- Enhancement MOSFET starts conducting when the drain-source channel is formed.
- N-Channel MOSFET: N-channel is formed.
- V_T is the minimum value of V_{GS} for the channel formation. $V_{GS} > V_T$ for MOSFET to be ON. Channel resistance decreases as V_{GS} increases further.

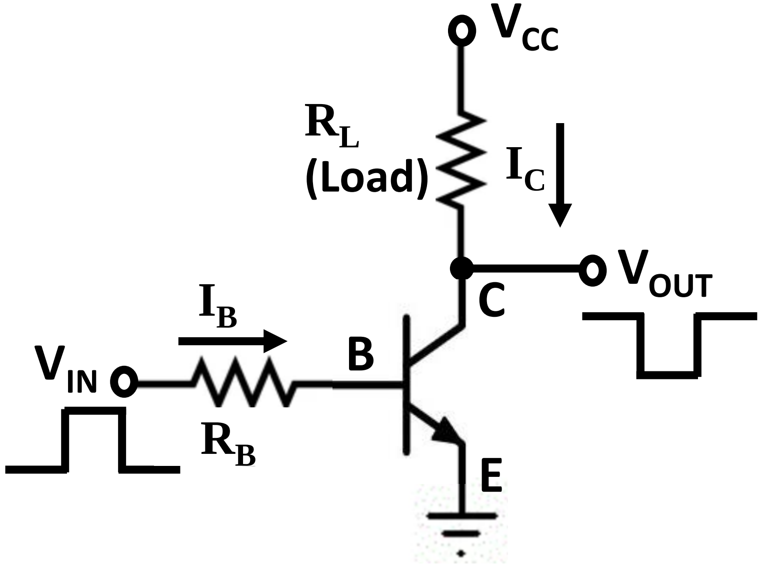
OFF: $V_{GS} < V_T$. $I_G \approx 0$. $I_D \approx 0$. $V_{DS} \approx V_{DD}$

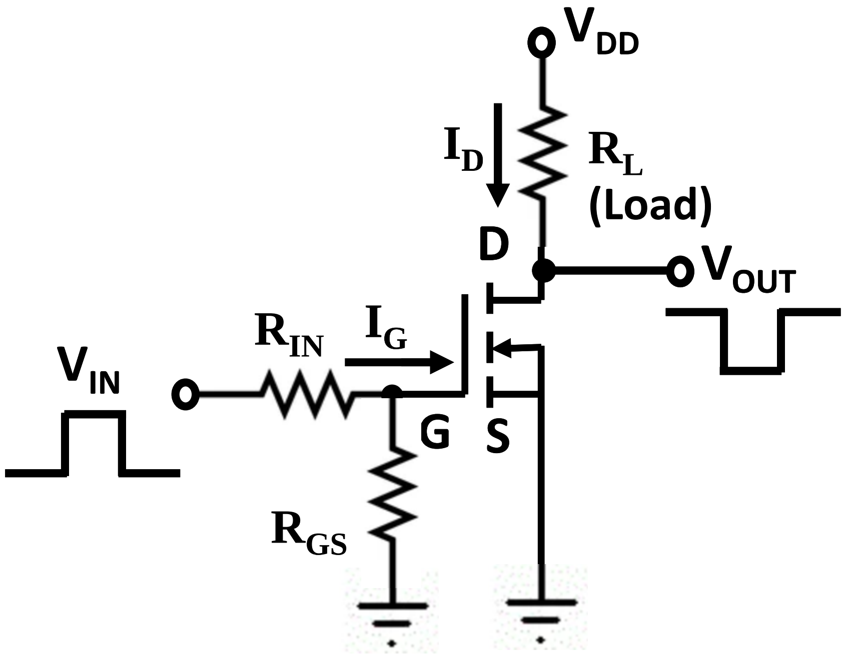
ON: $V_{GS} > V_T$ + a few V.
$I_G \approx 0$. $V_{DS} \approx 0$. $I_D \approx V_{DD} / R_L$.



Typical 'V_{DS}-I_D' characteristics for N channel Enhancement mode MOSFET
A & B: operating points for switching action

BJT & MOSFET Switching with Vin as Control Input





Switch circuit using NPN BJT & control input V_{in}.

R_B is for limiting I_B.

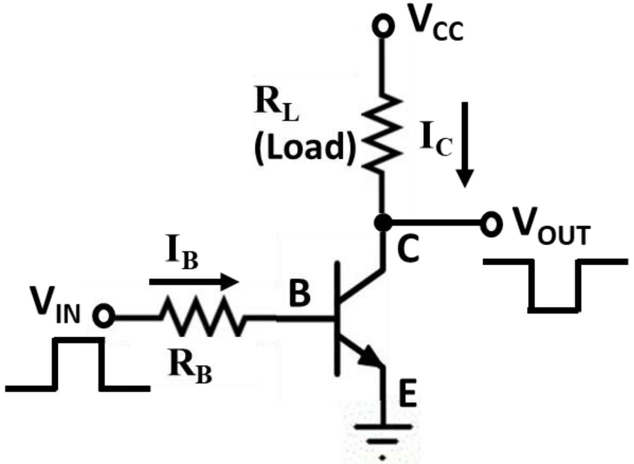
OFF: $I_B \approx 0$.
ON: $I_B > I_C/\beta$.

Switch circuit using N-Channel MOSFET & control input V_{in}.

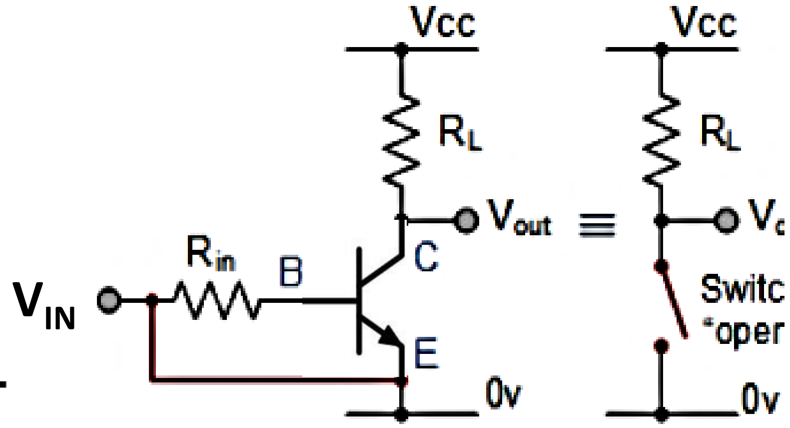
R_{in} and R_{GS} are for voltage attenuation, if V_{in}-peak is large.

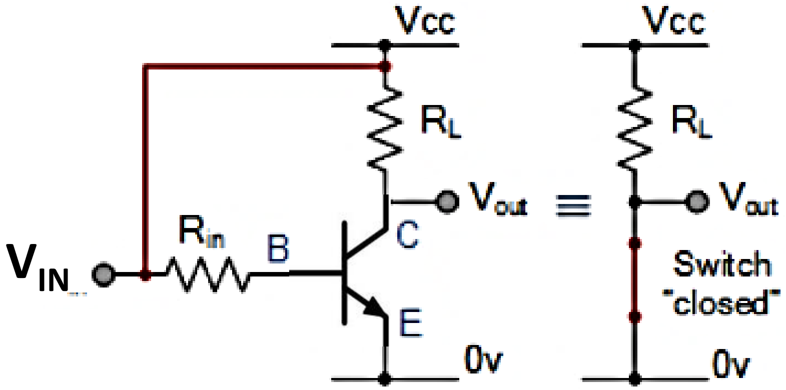
OFF: $V_{GS} < V_T$.
ON: $V_{GS} > V_T$ + a few V.

BJT Switching Operation



BJT (NPN) circuit with control input Vin (binary levels: 0, V_{CC}).





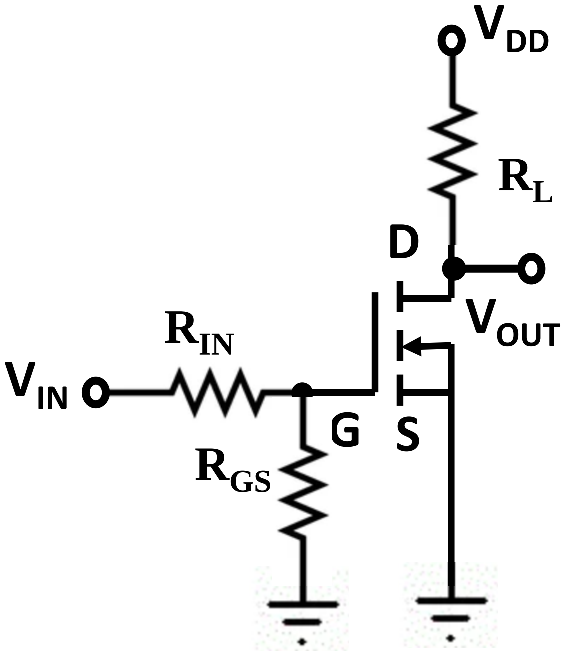
(a) $V_{IN} = 0$

- $V_{BE} = 0 < 0.5$ V .
- BJT operates as open switch.
  $I_B \approx 0$. $V_{CE} \approx V_{CC}$. $I_C \approx 0$.
- BE junction is not forward biased. BC junction is reverse biased.

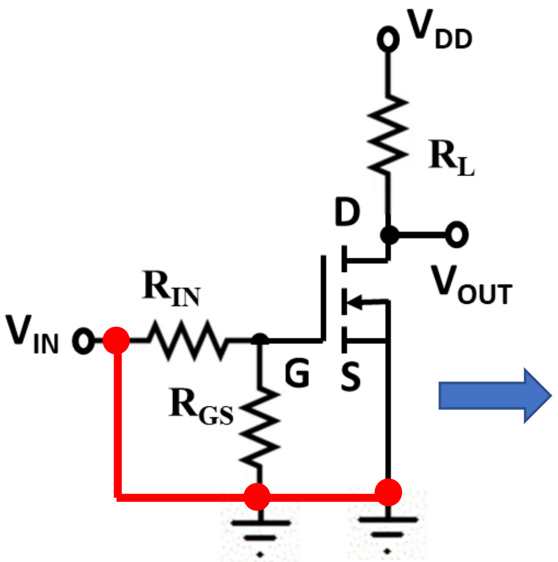
(b) $V_{IN} = V_{CC}$

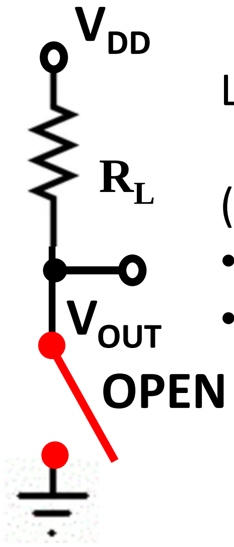
- BE junction is forward biased, with I_B limited by R_B , with V_{BE} reaching its saturation value V_{BES} (≈ 0.8 V). Collector voltage drops until BC junction gets forward biased with V_{BE} reaching its saturation value V_{CES} (≈ 0.2 V).
- BJT operates as closed switch.
- V_{BE} = 0.8 V. $V_{out} = V_{CES}$ = 0.2 V .
  $I_B = (V_{CC} - 0.8) / R_B$.
  $I_C = (V_{CC} - V_{CES}) / R_L$.

MOSFET Switching Operation



MOSFET (N-channel) circuit with control input V_{IN} (binary levels: 0, V_{DD}).
Usually R_{in} is short and R_{GS} is open



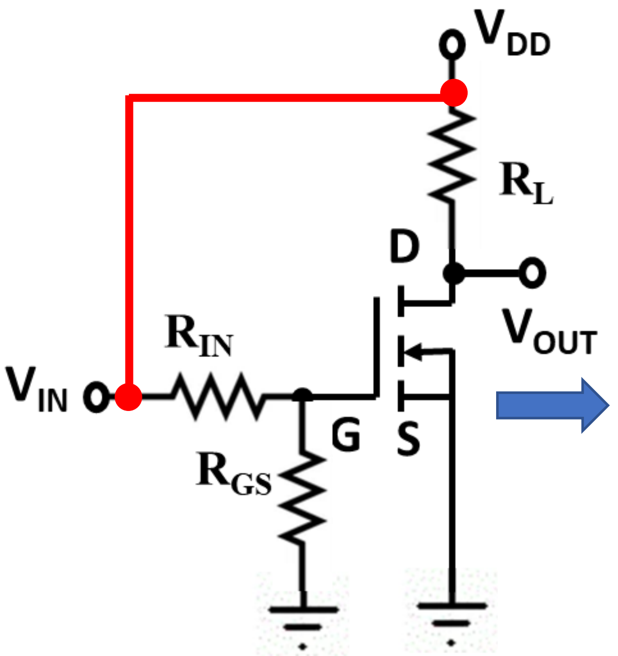


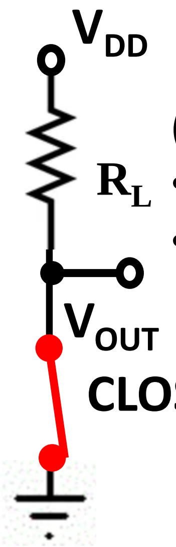
Let V_{DD} = 12 V, V_T = 2 V, R_{IN} = 0, $R_{GS} = \infty$.

(a) $V_{in} = 0$

- $V_{GS} = 0 < V_T$.
- MOSFET operates as open switch.

$I_G \approx 0$. $V_{DS} \approx V_{DD}$. $I_D \approx 0$.



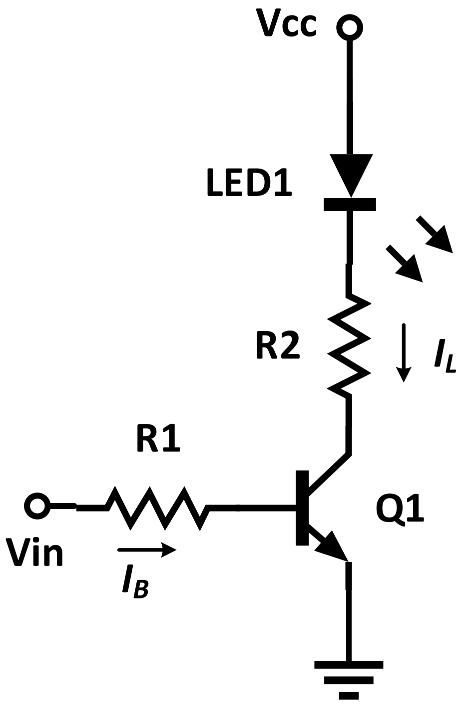


(b) $V_{in} = V_{DD}$

- V_{GS} = 12 V $> V_T$.
- MOSFET operates as closed switch.

$I_G \approx 0$. $V_{DS} \approx 0$. $I_D = V_{DD}/R_L$.

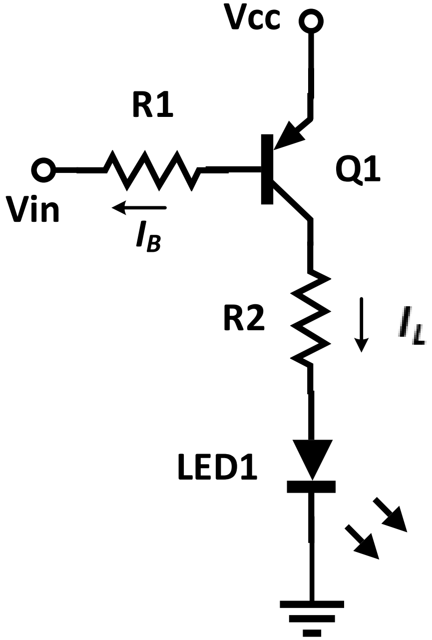
NPN Switch for Load Connected to +ve Supply End



$V_{cc} = 5$ V. V_{in}: 0 (LED off), 5 V (LED on). $\beta > 50$.
I_L for full brightness = 10 mA. LED drop = 2 V.

$I_L = [V_{CC} - V_{LED} - V_{CES}]/R_2 = [5 - 2 - 0.2]/R_2 > 10$ mA
$\Rightarrow R_2 < 2.8/10$ k$\Omega = 280\,\Omega$.
Let $R_2 = 270\,\Omega$. $\Rightarrow I_L = 10.3$ mA.
$I_B = [(V_{in})_{\text{high}} - V_{BES} - 0]/R_1 > I_L/\beta_{\text{min}}$
$\Rightarrow (5 - 0.8 - 0)/R_1 > 10.3/50 \;\Rightarrow\; R_1 < 20.38$ kΩ.
Let $R_1 = 18$ kΩ.

PNP Switch for Load Connected to –ve Supply End

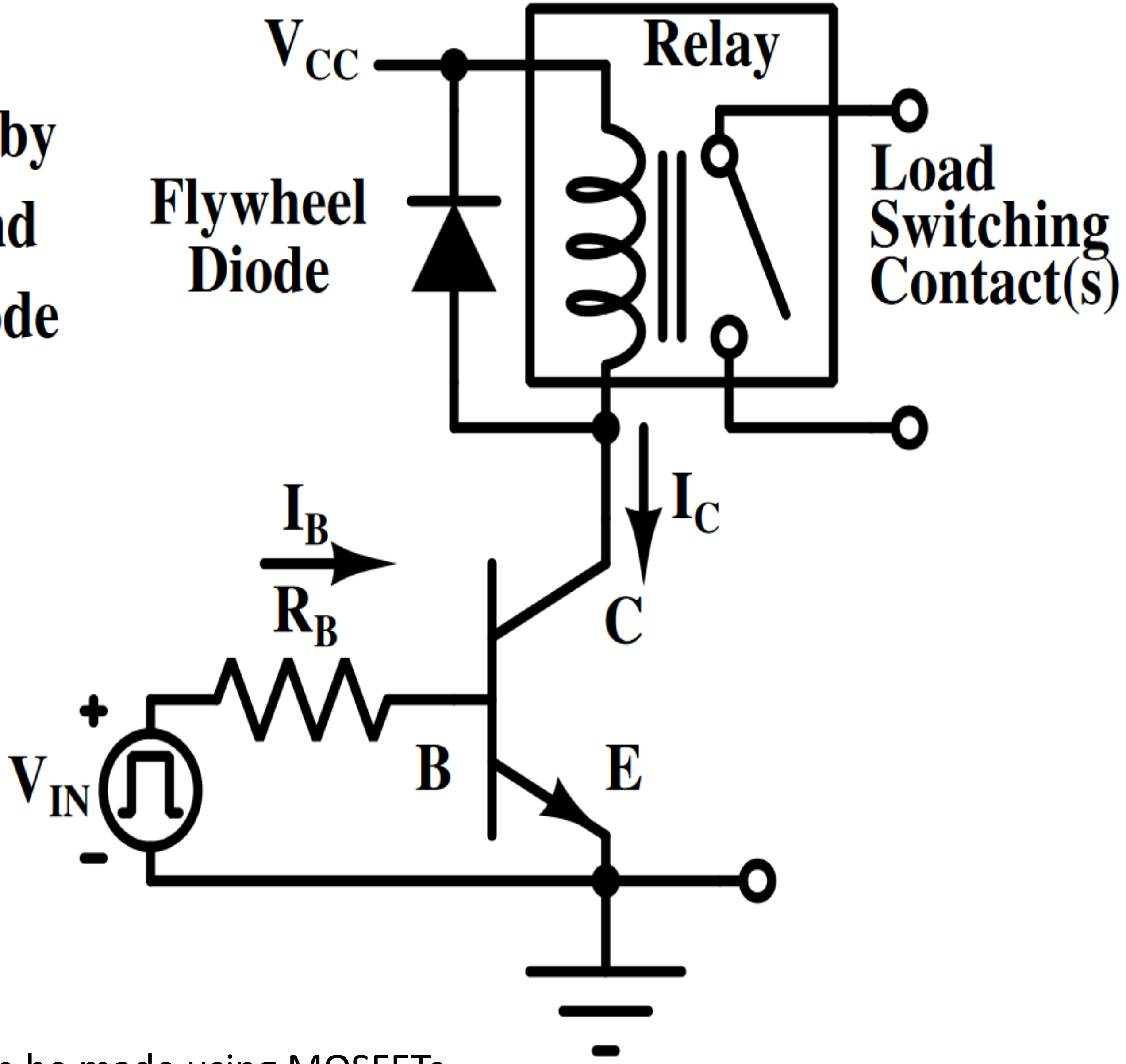


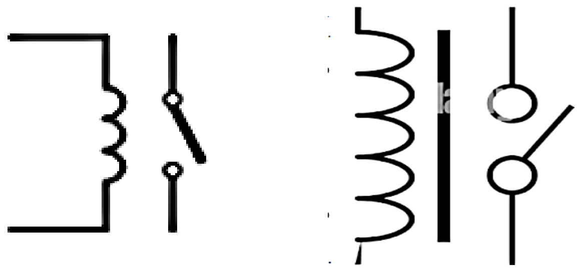
$V_{cc} = 5$ V. V_{in} : 0 (LED on), 5 V (LED off). $\beta > 50$.
I_L for full brightness = 10 mA. LED drop = 2 V.

$I_L = [V_{CC} - V_{ECS} - V_{LED}]/R_2 = [5 - 0.2 - 2]/R_2 > 10$ mA
$\Rightarrow R_2 < 2.8/10$ k$\Omega = 280\,\Omega$.
Let $R_2 = 270\,\Omega$, $\Rightarrow I_L = 10.3$ mA.
$I_B = [V_{CC} - V_{EBS} - (V_{in})_{\text{low}}]/R_1 > I_L/\beta_{\text{min}}$
$\Rightarrow (5 - 0.8 - 0)/R_1 > 10.3/50 \;\Rightarrow\; R_1 < 20.38$ kΩ .
Let $R_1 = 18$ kΩ.

Relay Operation Using a BJT Switch

R_L replaced by Relay coil and Flywheel diode



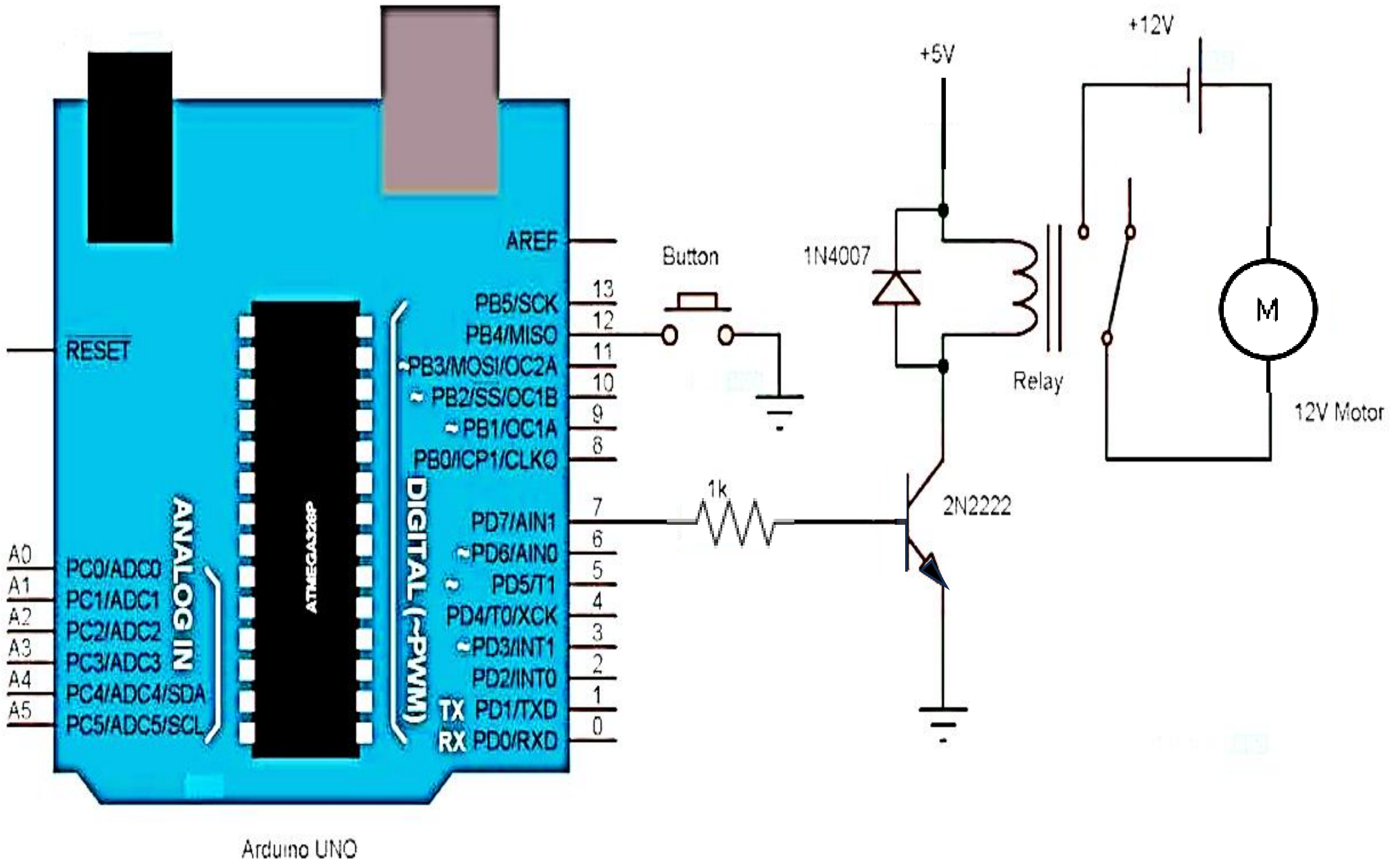


Circuit Symbols for a Relay

By controlling base current ($\boldsymbol{I_B}$) of BJT, high relay coil current (= $\boldsymbol{I_C}$) can be switched.
Current Gain: $\boldsymbol{\beta = I_C / I_B}$

A Similar circuit can be made using MOSFETs.

Relay Switching Using Micro-Controller (Arduino)



Arduino Relay Control Circuit Diagram

Source: https://www.electronicshub.org/arduino-relay-control/

Example

Control of a relay with 'Arduino' digital output pin (PD7) and NPN transistor (2N2222).

Relay coil current = 60 mA.
Transistor β_{min} = 30.

Set the pin PD7 to 'Hi'. It will put the transistor in ON state, allowing current to flow through the relay coil making the relay ON.
I_B > Relay current / β_{min} = 2 mA.

Diode connected in parallel with the relay avoids sudden change of current in the relay coil.

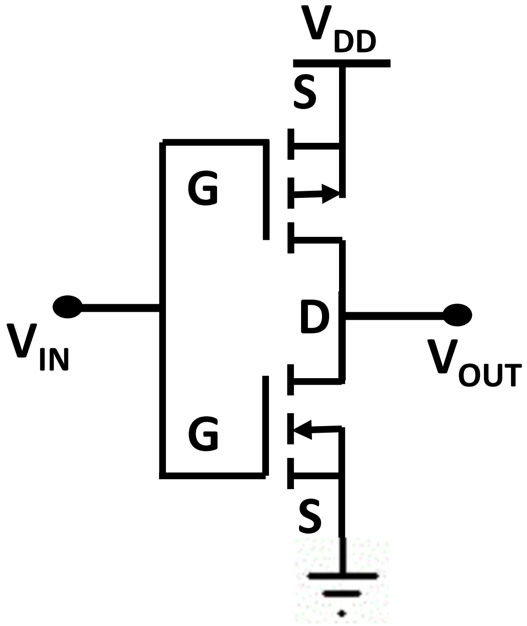
Some Logic Gates using MOSFETs

- CMOS Inverter
- CMOS NAND Gate – Universal gate
- CMOS NOR Gate – Universal Gate
- CMOS Tri-State Inverter

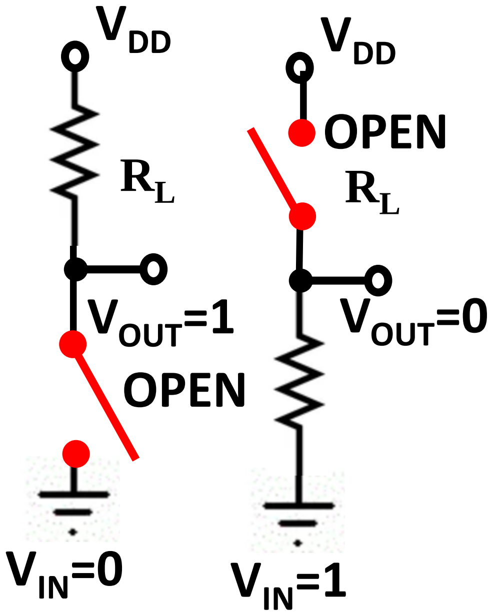
Complementary Metal Oxide Semiconductor Circuits

1. Combination of NMOS and PMOS Transistors
2. Usually same gate signal goes to NMOS and its complementary PMOS transistors for logic circuits
3. Negligible steady-state power consumption in CMOS digital circuits

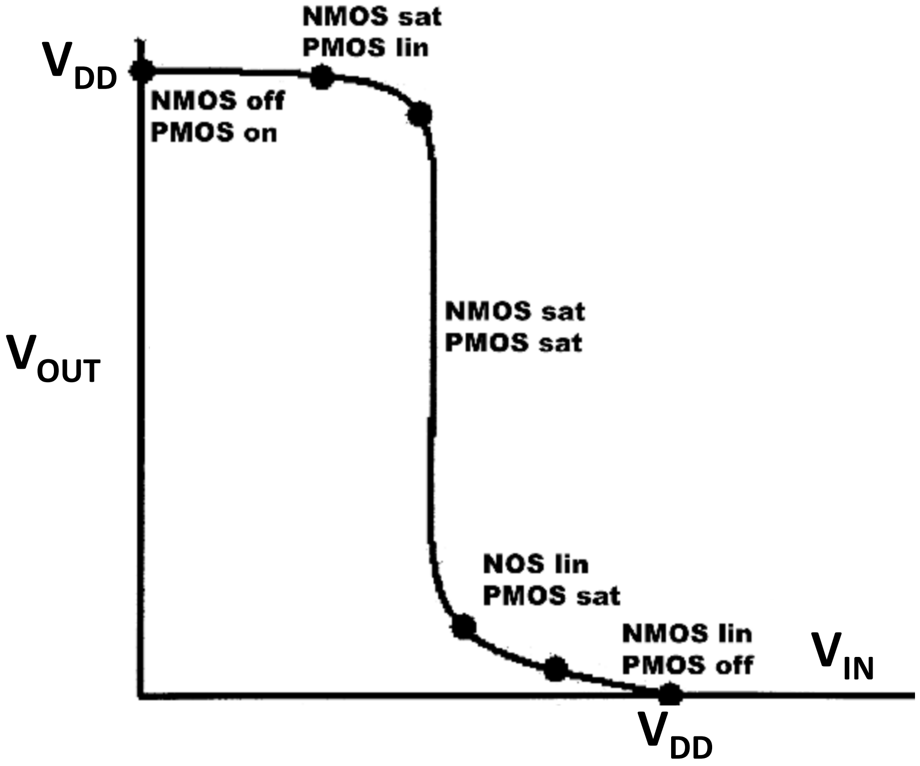
CMOS Inverter



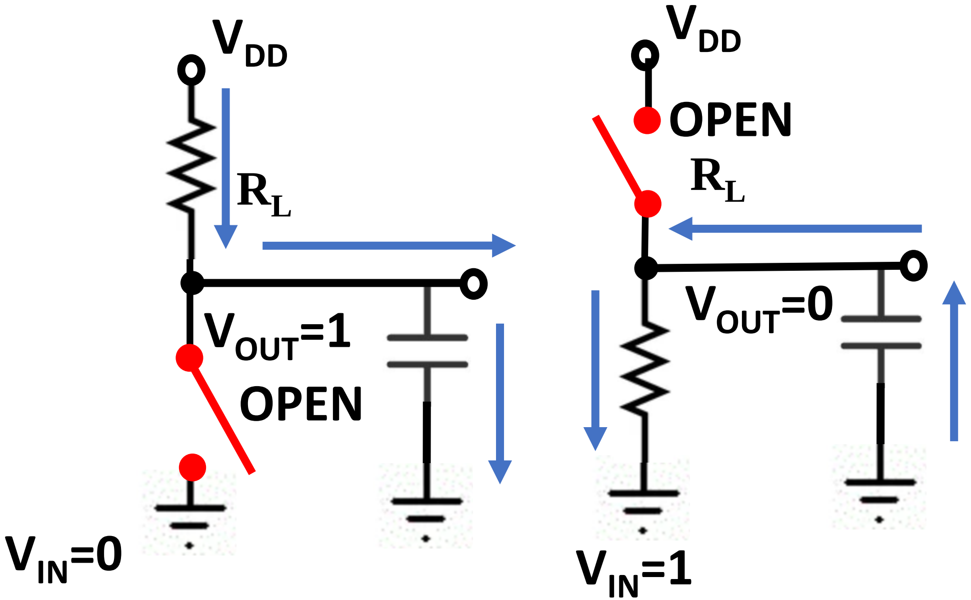
Schematic of a CMOS Inverter



Ideal Digital Operation



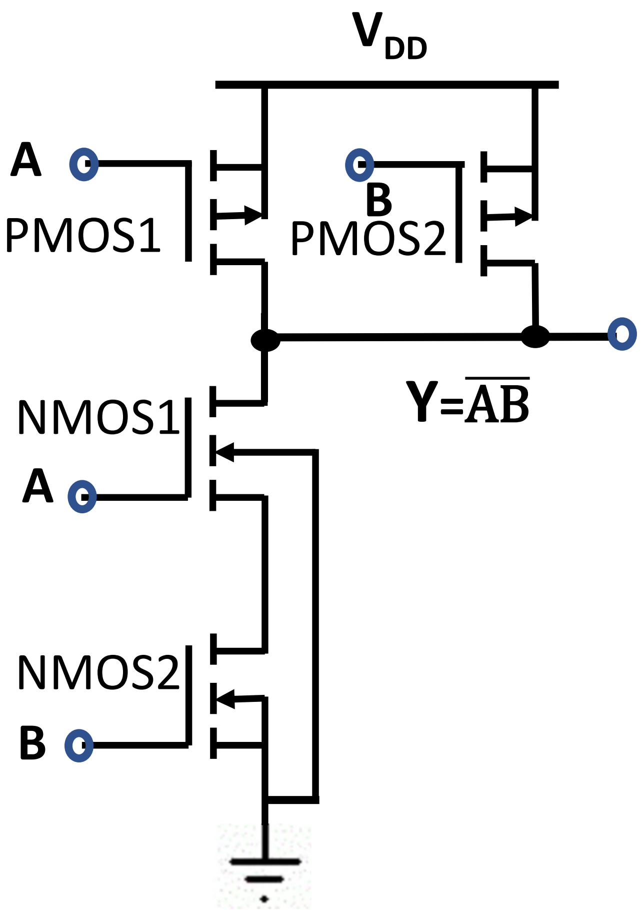
Practical Inverter Characteristics



Origin of delay in an inverter

1. Turn-ON delay – Output low to high
2. Turn-OFF delay – Output high to low

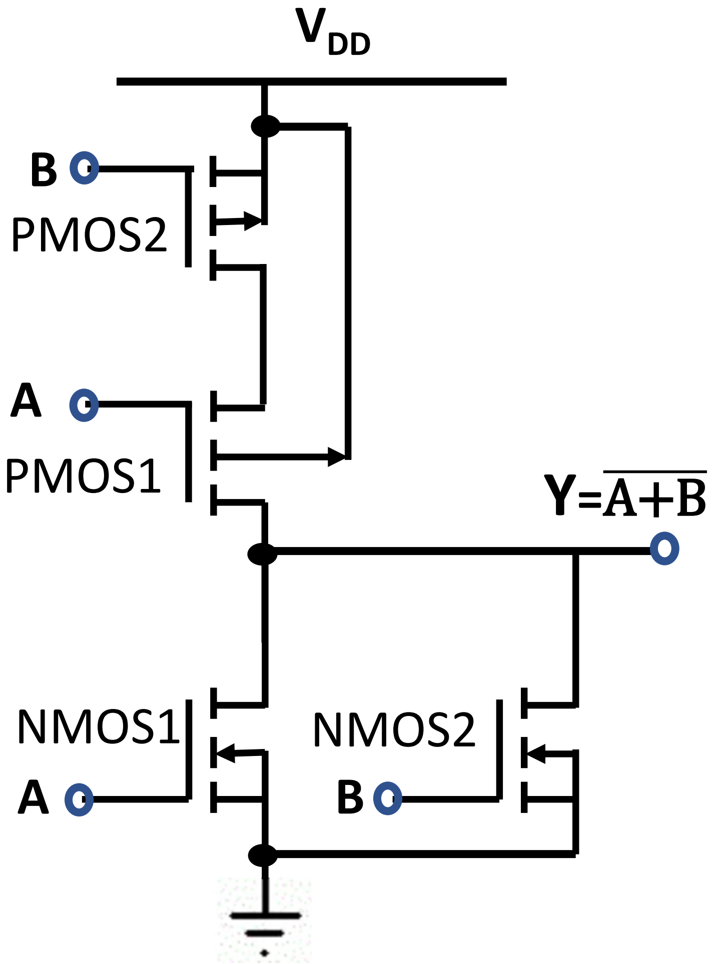
CMOS 2-INPUT NAND Gate



TRUTH TABLE / **STATE OF THE TRANSISTORS**

A	B	Y	NMOS1	PMOS1	NMOS2	PMOS2
0	0	1	OFF	ON	OFF	ON
0	1	1	OFF	ON	ON	OFF
1	0	1	ON	OFF	OFF	ON`
1	1	0	ON	OFF	ON	OFF

CMOS 2-INPUT NOR Gate



TRUTH TABLE / **STATE OF THE TRANSISTORS**

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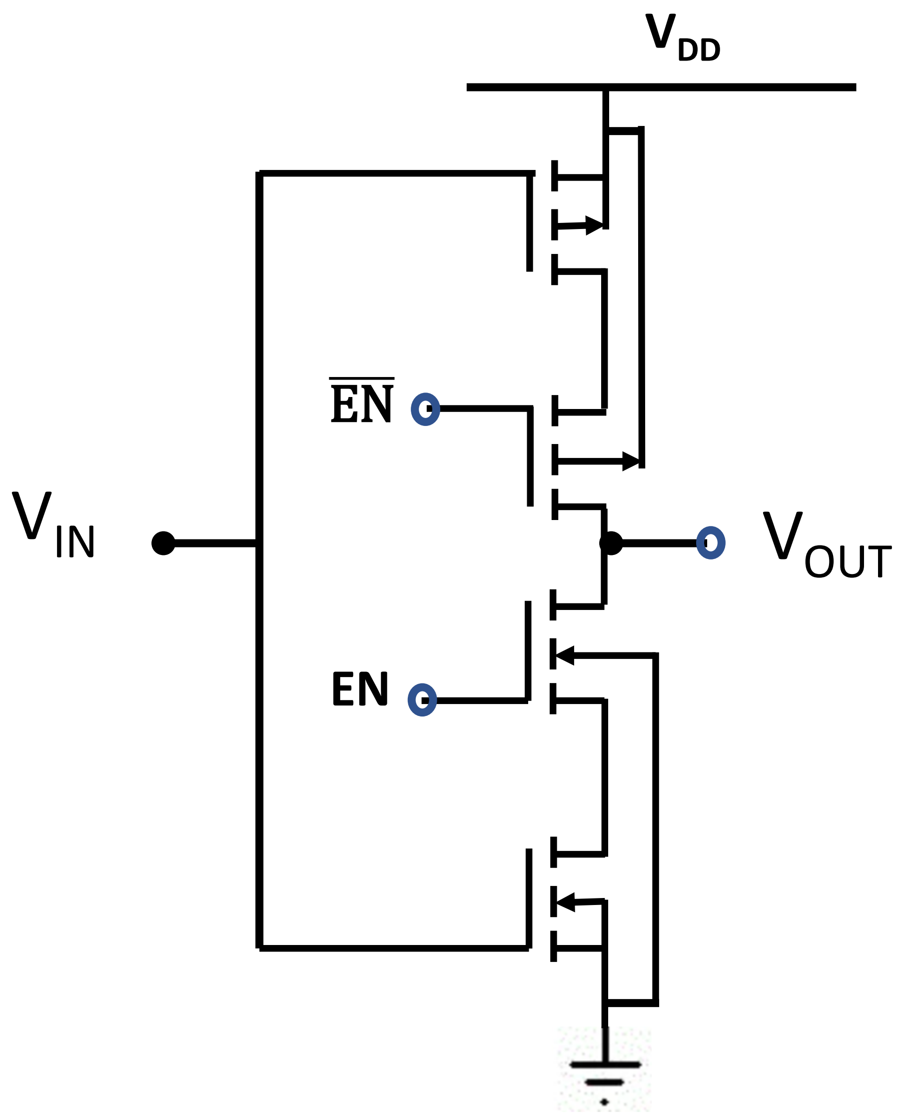
0	0	1	OFF	ON	OFF	ON
0	1	0	OFF	ON	ON	OFF
1	0	0	ON	OFF	OFF	ON
1	1	0	ON	OFF	ON	OFF

CMOS Tri-State Inverter



- When EN=1, $V_{OUT} = \overline{V_{IN}}$
- When EN=0, V_{OUT} is in the high impedance state

Questions and Discussions