IIT Bombay

Makerspace (MS101)

2024 (Spring)

EE-Lecture-10

Transistors as Switches

Kushal Tuckley, Joseph John, PC Pandey, Dinesh K Sharma
D Chakraborty, K Chatterjee, BG Fernandes, NS Shiradkar

Transistors: Introduction

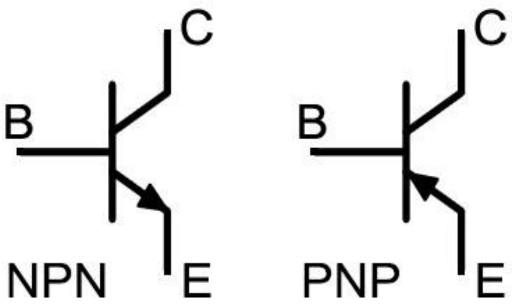
A transistor is a 3-terminal semiconductor device. It is used as a 2-port device with one terminal common between the input and output ports. It can be modelled as a 'dependent current source'.

Commonly used types of Transistors

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

Type | **Circuit Symbol** | **Simplified Signal Model**

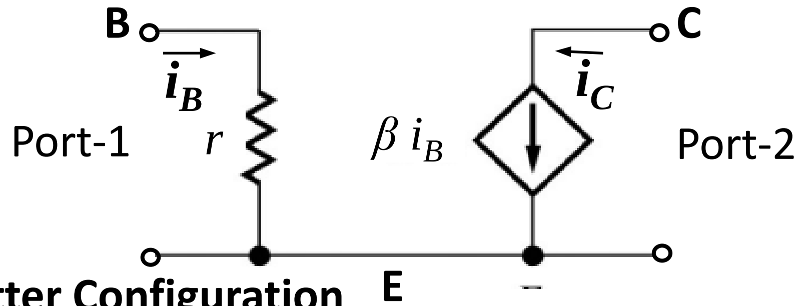
Bipolar Junction Transistor



B: Base

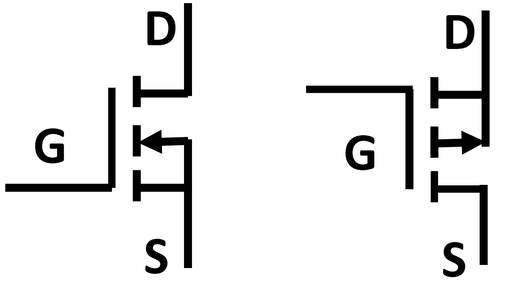
C: Collector

E: Emitter



Common Emitter Configuration

MOSFET (Enhancement mode)

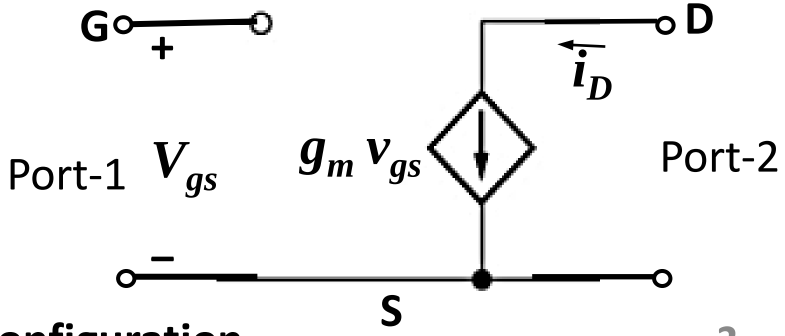


N Channel **P Channel**

G: Gate

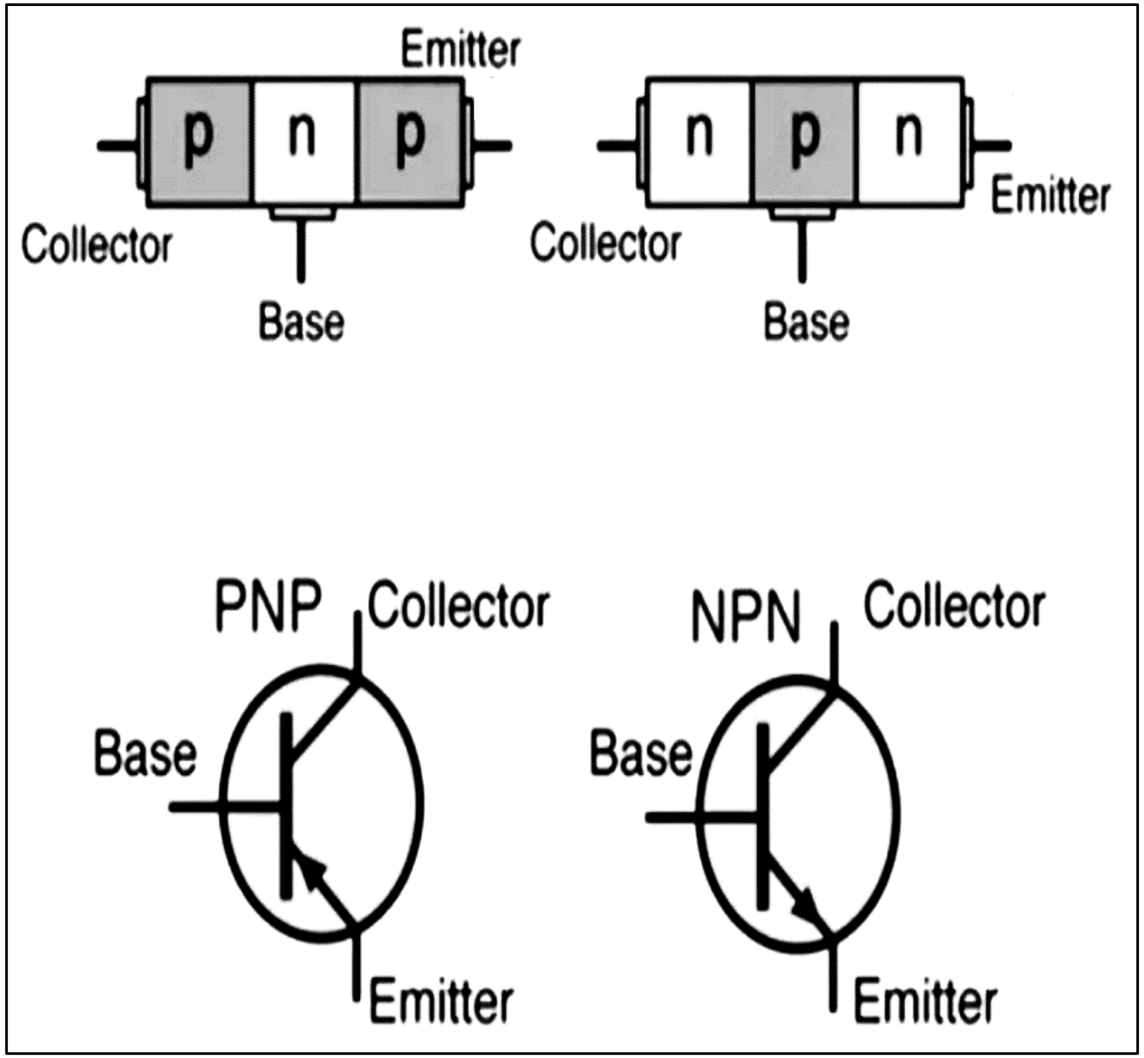
D: Drain

S: Source



Common Source Configuration

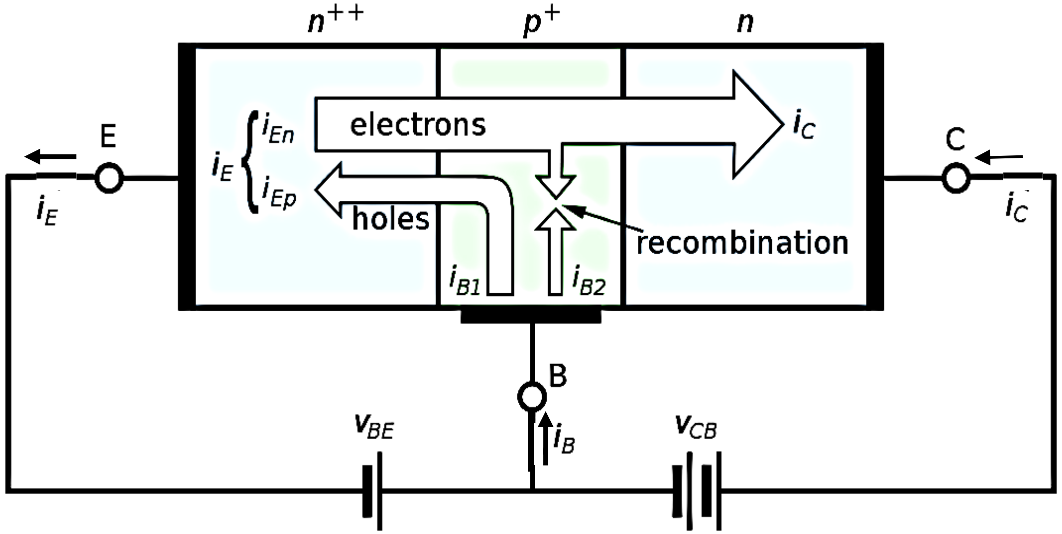
Bipolar Junction Transistor (BJT)



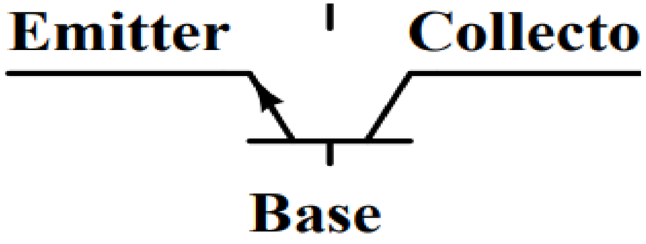
Types	NPN and PNP.
Terminals	Three terminals viz. emitter, base and collector.
Controlling quantity	BJT is a current controlled device Base current (I_B) controls the Collector Current (I_C).
Compared to MOSFETs, BJTs have lower input resistance (≈ 10 kΩ to 1 MΩ, in common emitter configuration) and hence consume more power from the input signal source.	

Input Resistance: BJTs < MOSFETs

BJT Operation: Cricket Analogy



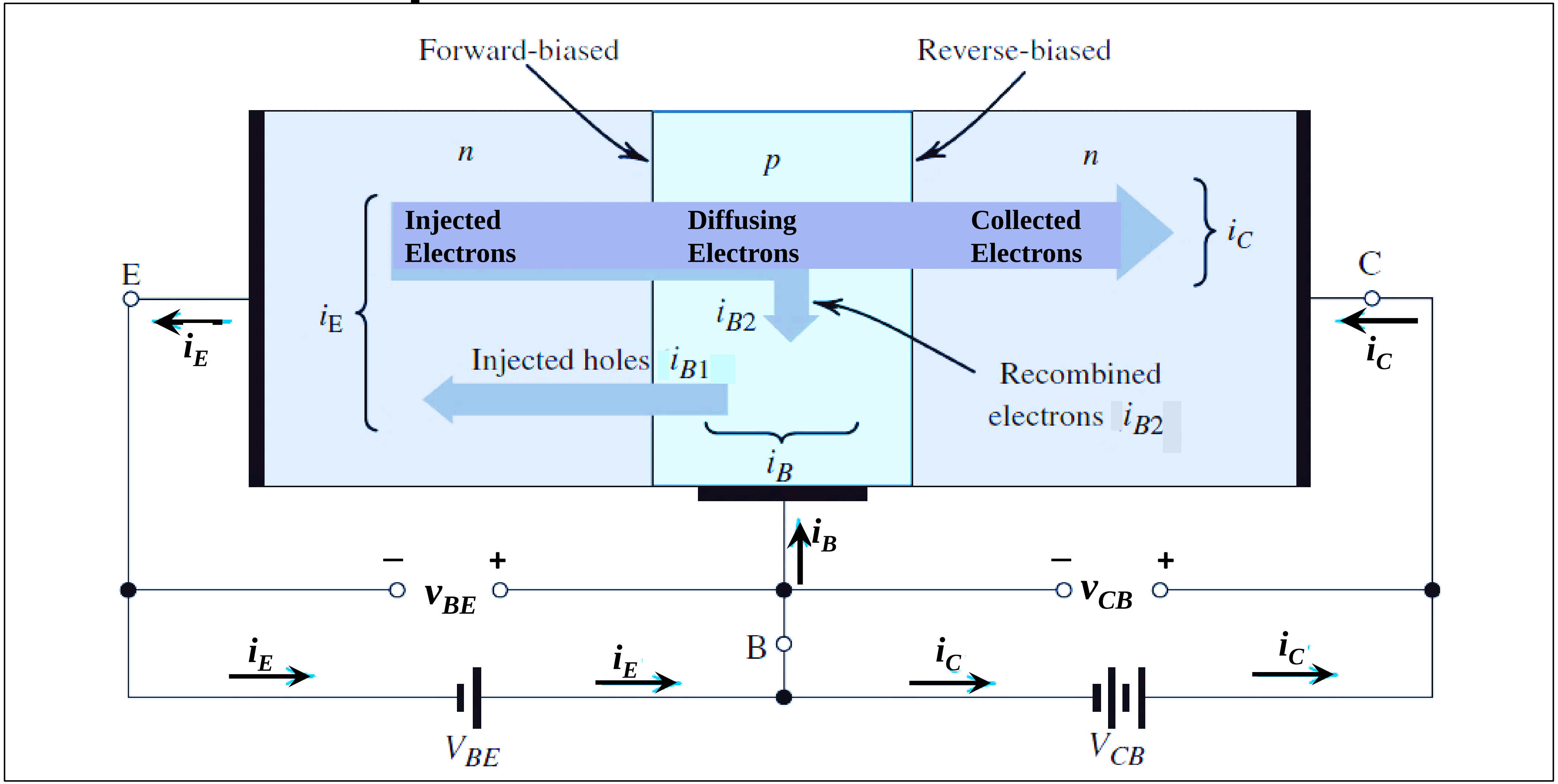
- The emitter is the bowler who shoots electrons into the base.
- The base is the batsman – a tail-ender who swings away, but connects with no more than 1 to 2% of the incoming balls (electrons).
- Most of the balls are collected by the wicket keeper – the collector.



- The base current (rare balls connected by the batsman) is a fraction of the emitter current and the collector current is almost equal to the emitter current.
- Thus the collector current is 50 to 100 times the base current. Ratio of collector current to the base current is the current gain of the transistor.

Ratio of the collector to the base current is current gain.

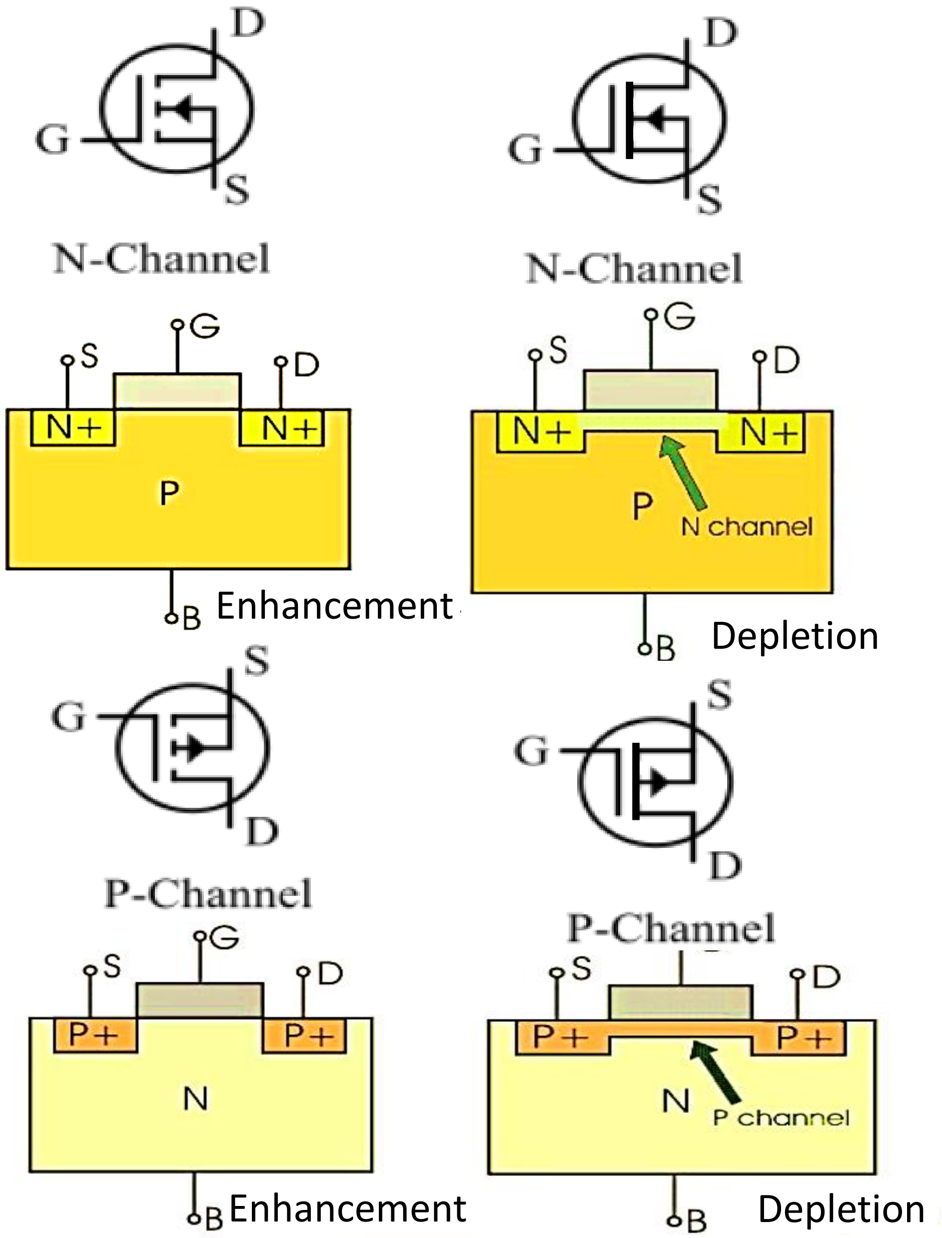
BJT Operation: Current Flow



Current flow in an NPN transistor biased in active mode (forward biased BE junction and reversed biased BC junction)

Source: Fig 6.3:-Sedra A S, Smith K C, “Microelectronic Circuits”, Oxford University Press, 7Ed. **ISBN: 9780199339136**

Metal Oxide Field Effect Transistor (MOSFET)



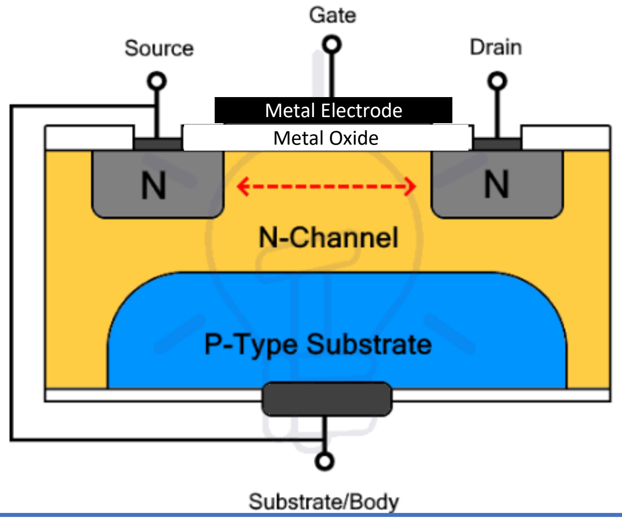
MOSFETs are available in two Types → N-Channel and P-Channel.
They are fabricated in two modes: Enhancement and Depletion.

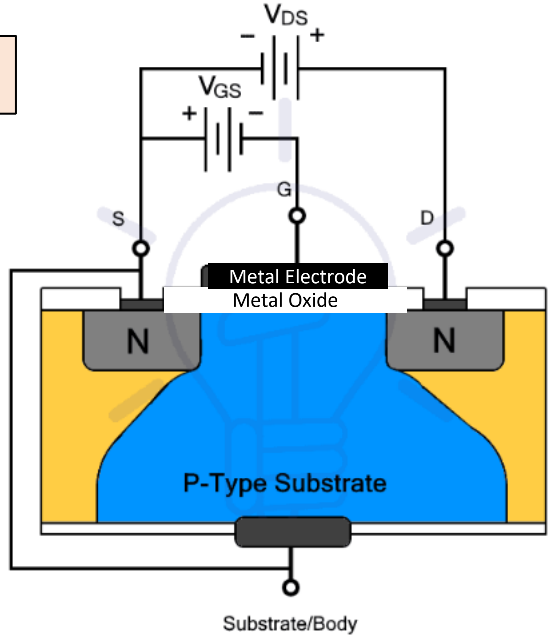
MOSFET	
Types (4)	P-channel enhancement, P-chaneel depletion, N-channel enhancement, N-channel depletion.
Terminals (4)	Source (S), Drain (D), Gate (G), Substrate or body (B). B is often connected to S.
Controlling quantity	MOSFET is a voltage-controlled device. Gate-to-source voltage (V_{GS}) controls drain-to-source current (I_{DS}).
MOSFETs have high input resistance (10 MΩ to 100 MΩ, depending on configuration and circuit) and hence consume less power from the input signal source, compared to BJTs.	

jiska channel uska terminal.

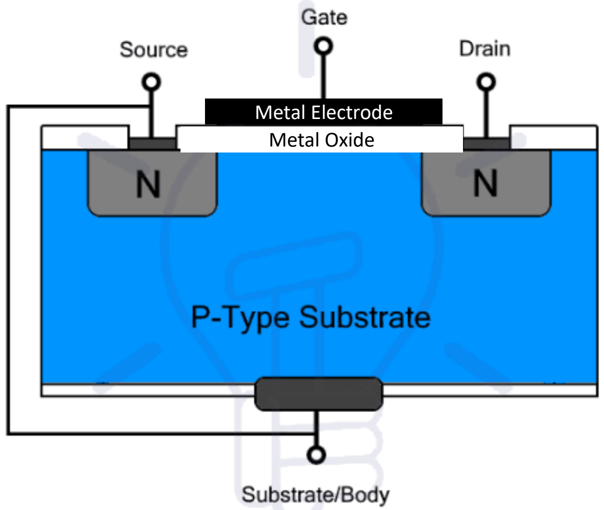
MOSFET Operation

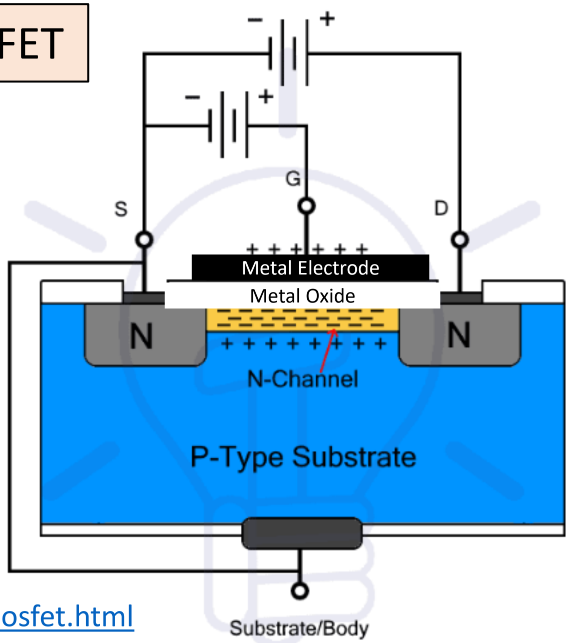
N- Channel Depletion mode MOSFET





N- Channel Enhancement mode MOSFET





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

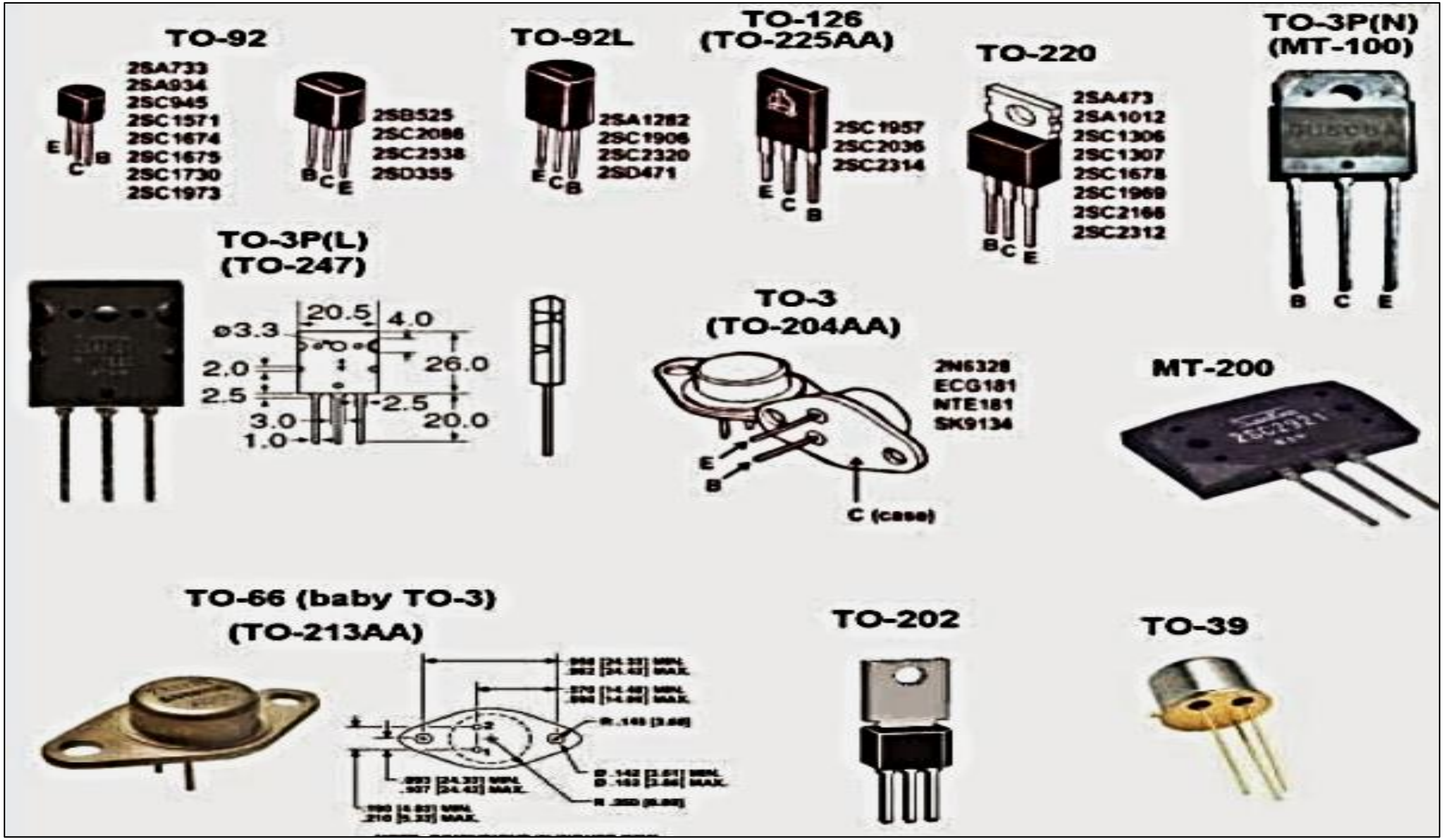
The MOSFET is said to be ON when current flows between Drain and Source

Depletion mode: Channel for drain-source current flow is available at V_{GS} = 0. The channel gets depleted for negative V_{GS}, and it is totally depleted for V_{GS} below the threshold voltage, V_{TH} (-ve for N-channel).

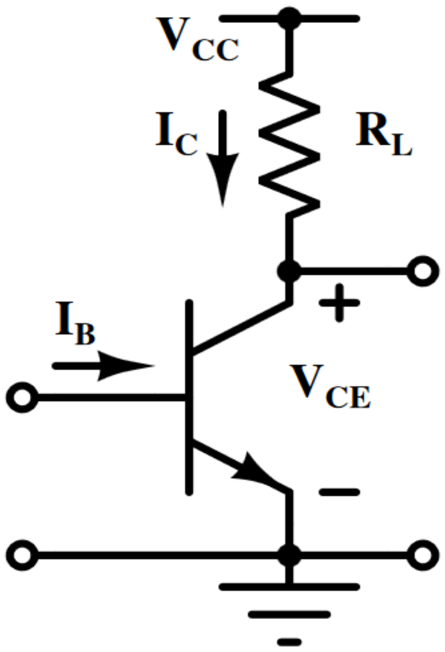
Enhancement mode: No channel is available at V_{GS}= 0
The channel for drain-source current flow is formed for V_{GS} above the threshold voltage, V_{TH} (+ve for N-channel).

MOSFET Type	Condition for Switching
N – Channel Enhancement	**OFF for $V_{GS} < V_{TH}$ (0.6 to 1 V)**
N - Channel Depletion	**OFF for $V_{GS} < V_{TH}$ (– 1.3 to – 0.0 V)**
P - Channel Enhancement	**OFF for $V_{GS} > V_{TH}$ (– 1.0 to – 0.6 V)**
P - Channel Depletion	**OFF for $V_{GS} > V_{TH}$ (0.0 to 1.3 V)**

Commercially Available Transistor Packages

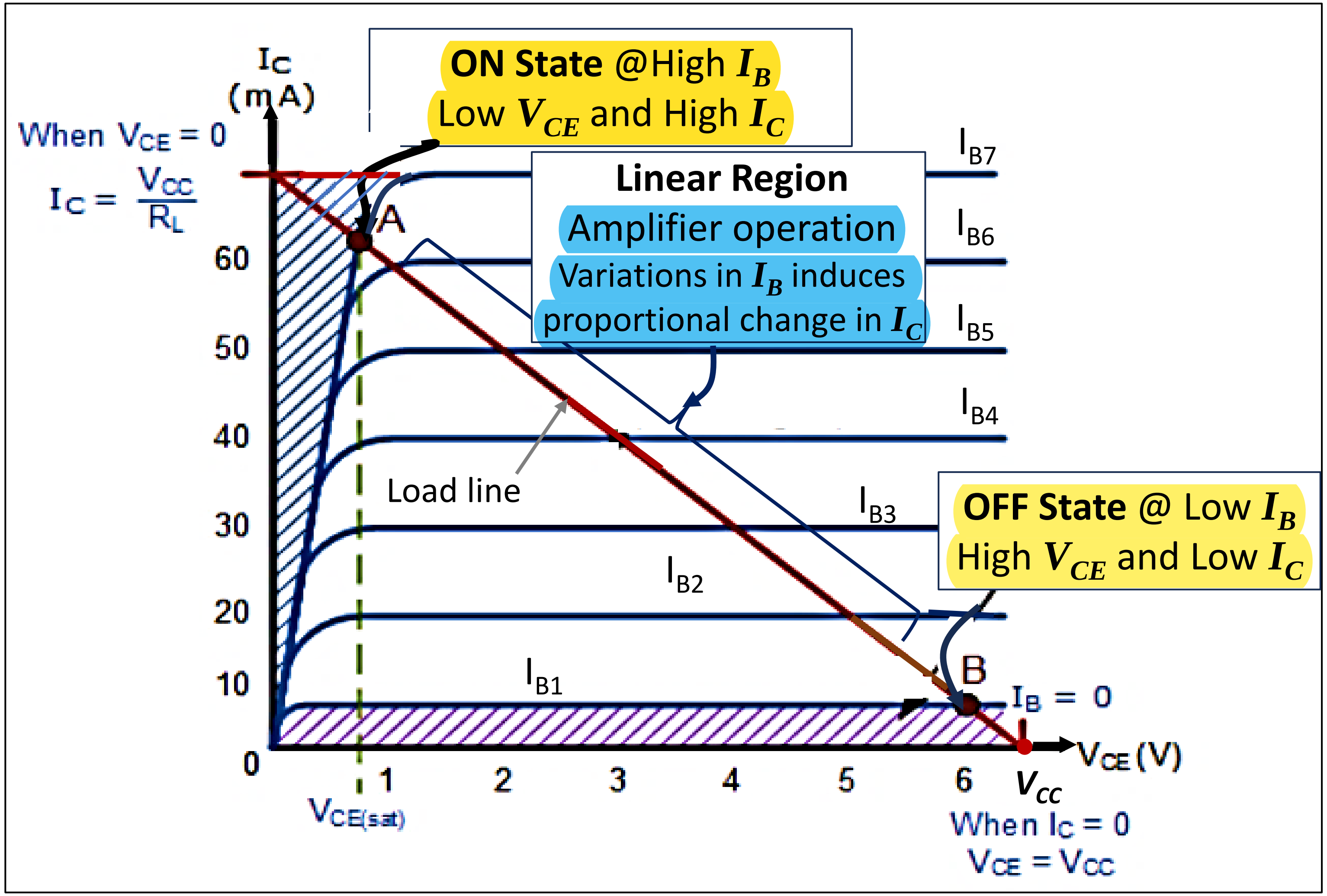


Switching Characteristics of BJT Presented on V_{CE}-I_C Plane



BJT is switched ON or OFF by

changing the base current (I_B)

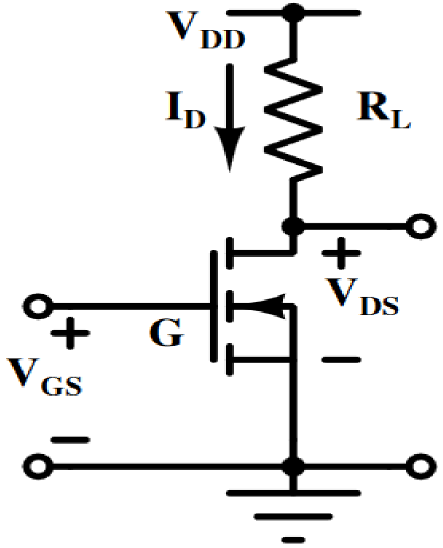


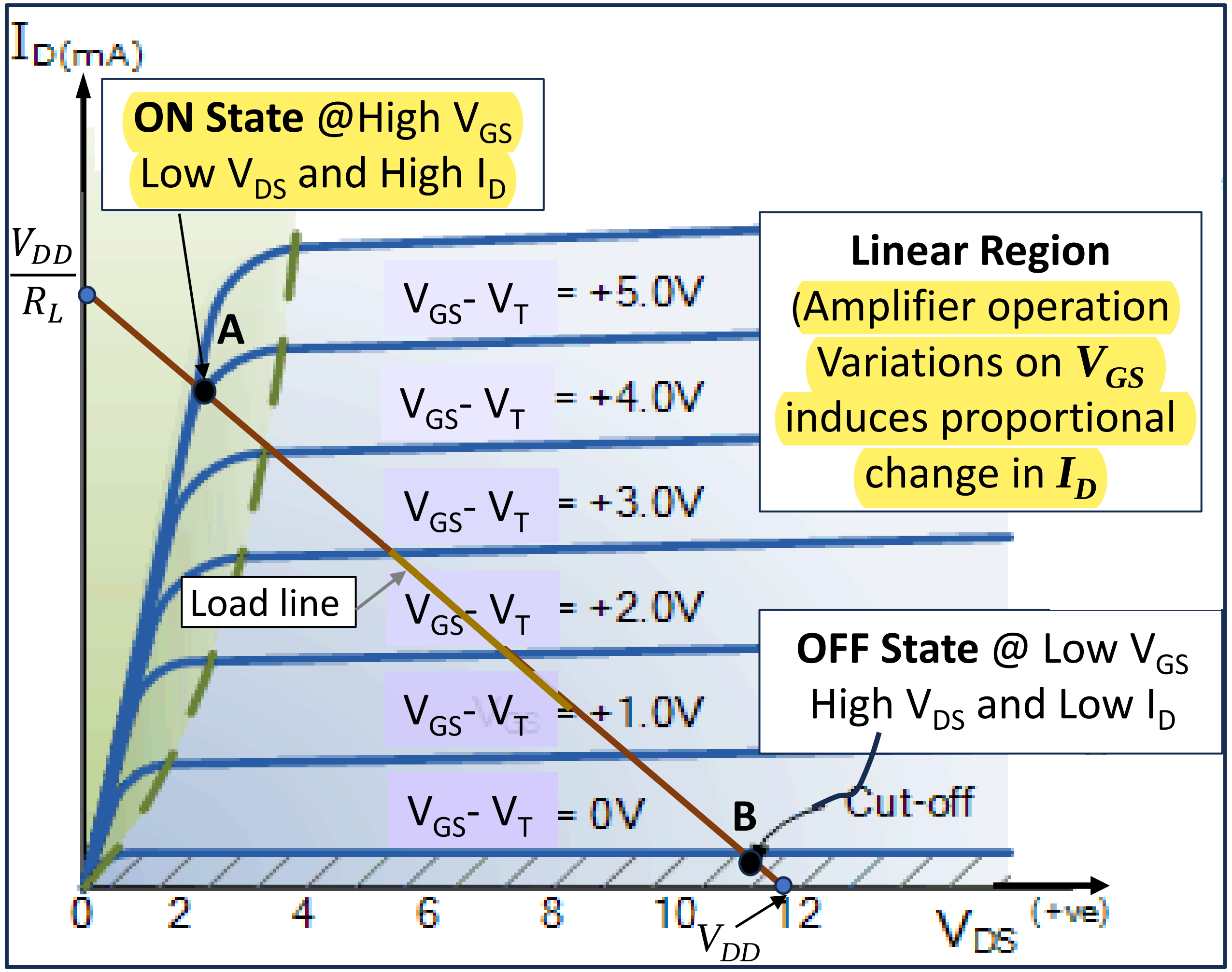
Base currents $I_{B1} < I_{B2} < I_{B3} < I_{B4} < I_{B5} < I_{B6} < I_{B7}$

Typical 'V_{CE} - I_C' characteristics for BJT
A & B are the operating points for the switching action

Switching Characteristics of N-Channel Enhancement mode MOSFET (Presented On V_{DS}-I_D Plane)

In BJT current controls output current
In MOSFET voltage controls output current

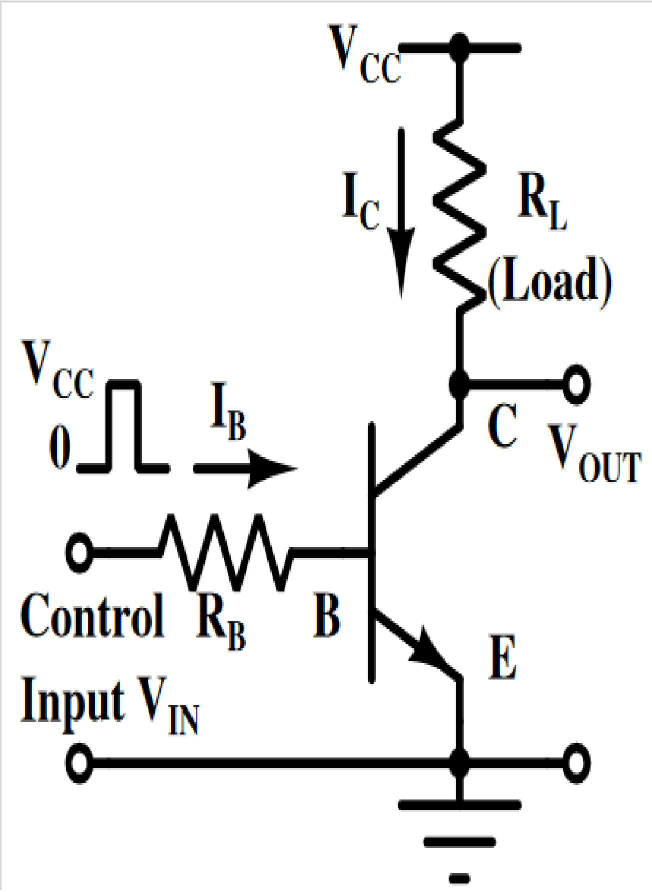




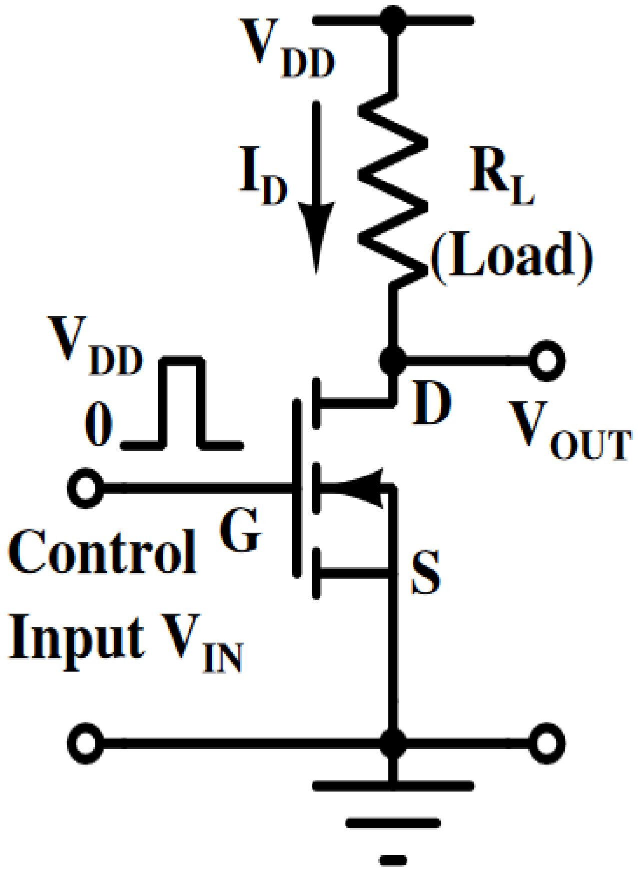
- Enhancement MOSFETs start conducting when the channel between the Drain and Source is formed.
- In N-Channel MOSFETs, N-channel is formed.
- V_T is the minimum value of V_{GS} for the formation of the channel (Hence, $V_{GS} > V_T$ for MOSFET to be ON)
- I_D increases as V_{GS} increases further

Typical 'V_{DS}-I_D' characteristics for N channel Enhancement mode MOSFET
A & B: operating points for switching action
The load line between A and B represents Linear region

Switching Transistors with Vin as Control Input

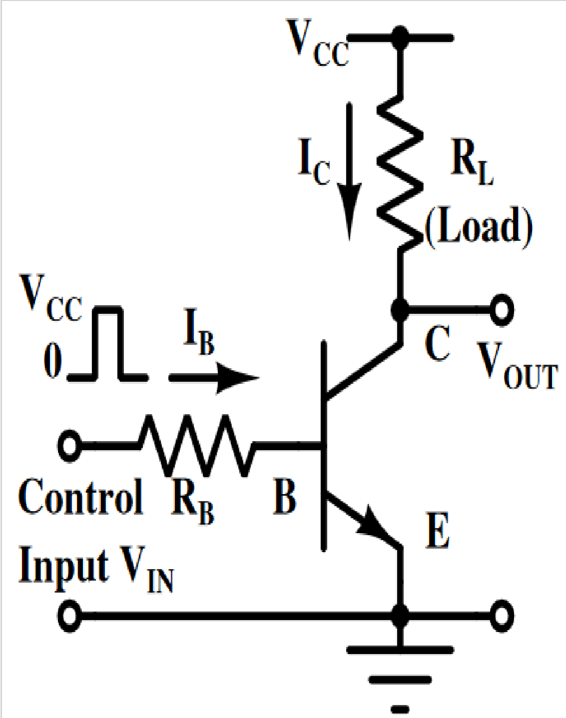


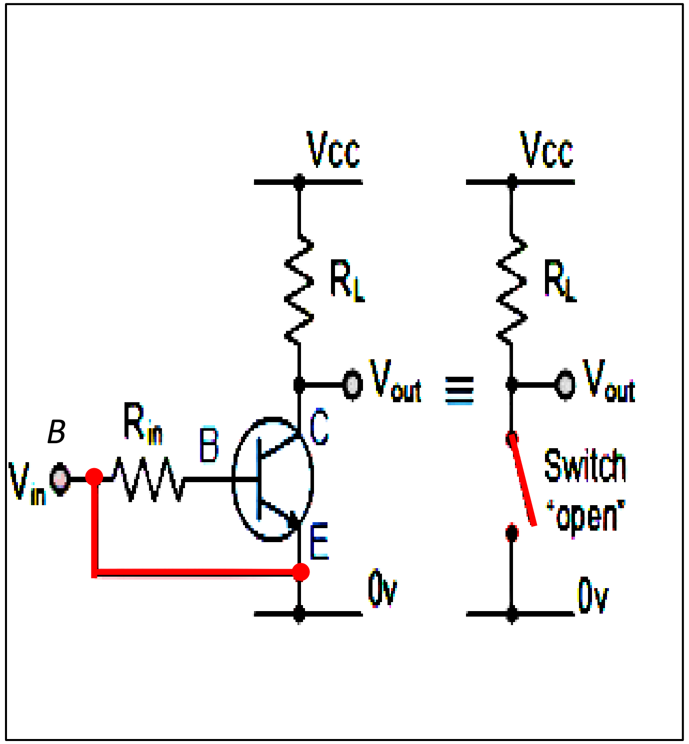
V_{in} to control NPN BJT



V_{in} to control N-Channel enhancement MOSFET

Switching Operation for BJT

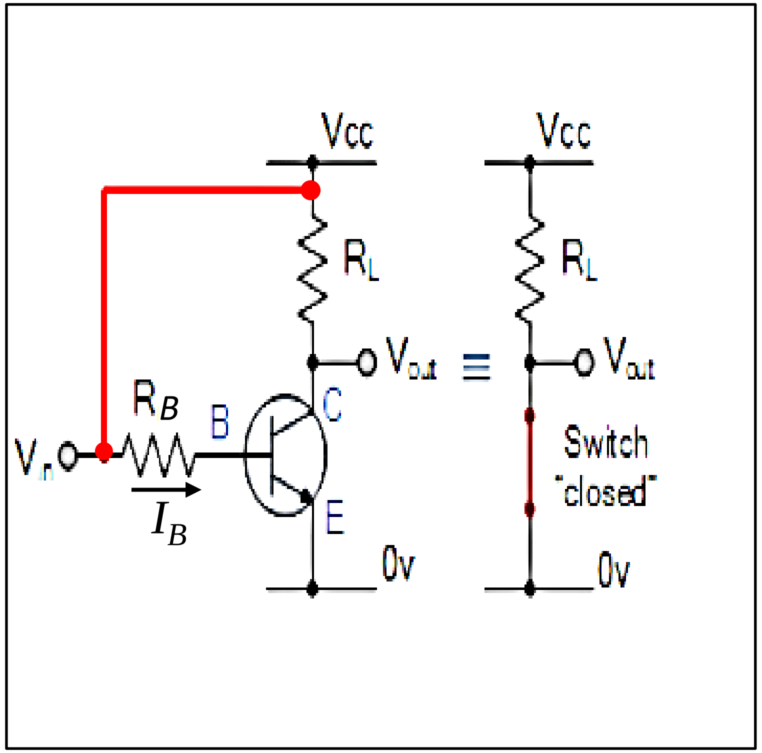




Input Grounded → $\mathbf{I_B \approx 0}$, 0FF state.

$\mathbf{I_C \approx 0} \rightarrow V_{OUT} = V_{CE} \approx V_{CC.}$

Transistor as '**Open Switch**'.



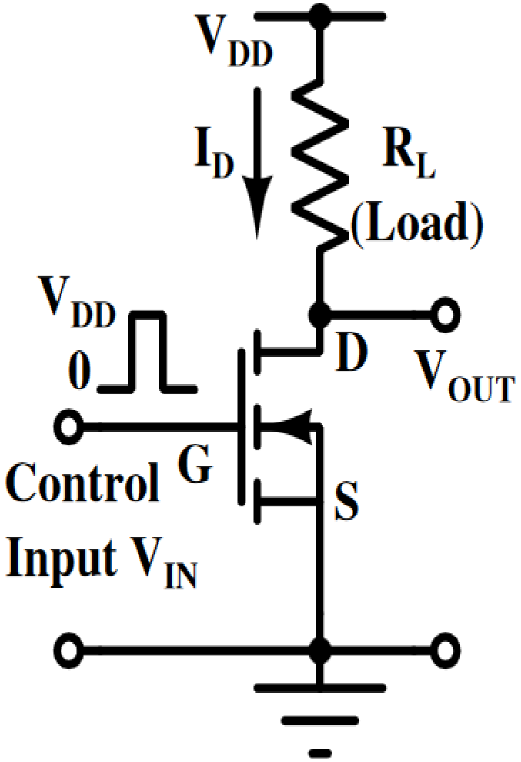
Input connected to $\mathbf{V_{cc}}$→ High value of $\mathbf{I_C}$

$V_{OUT} = V_{CE} \approx 0.2$ V

$I_B = (V_{CC} - V_{BES}) / R_B, V_{BES} \approx 0.8$ V

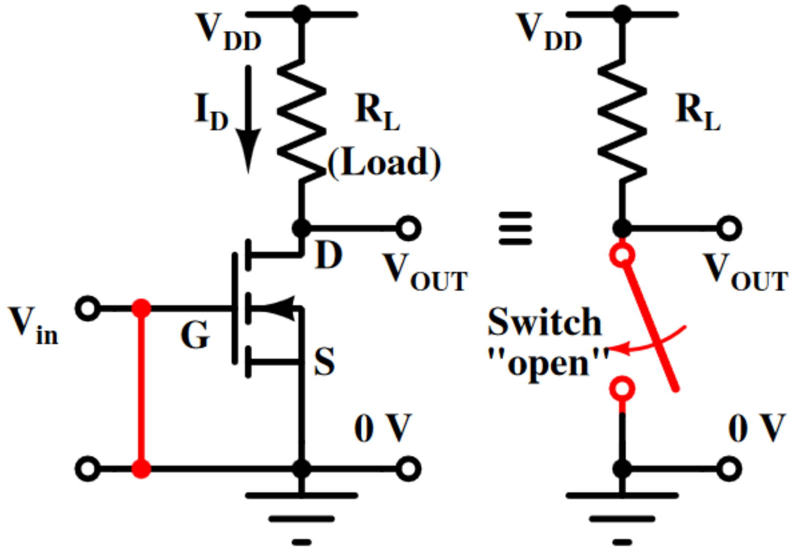
Transistor as '**Closed Switch**'.

Switching Operation for N-Channel Enhancement MOSFET



V_{in} to control
N-Channel MOSFET

Connecting V_{in} to Ground $V_{GS} < V_T$

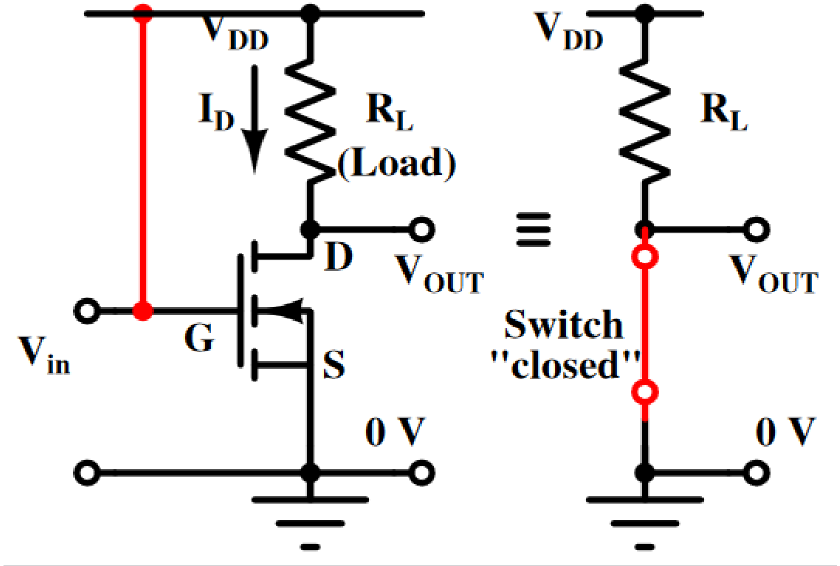


Input Grounded → $\mathbf{V_{GS} = 0}$, OFF state.

$\mathbf{I_D \approx 0} \rightarrow V_{OUT} = V_{DS} \approx V_{DD}$.

Transistor as '**Open Switch**'.

Connecting V_{in} to V_{DD} → $V_{GS} >> V_T$

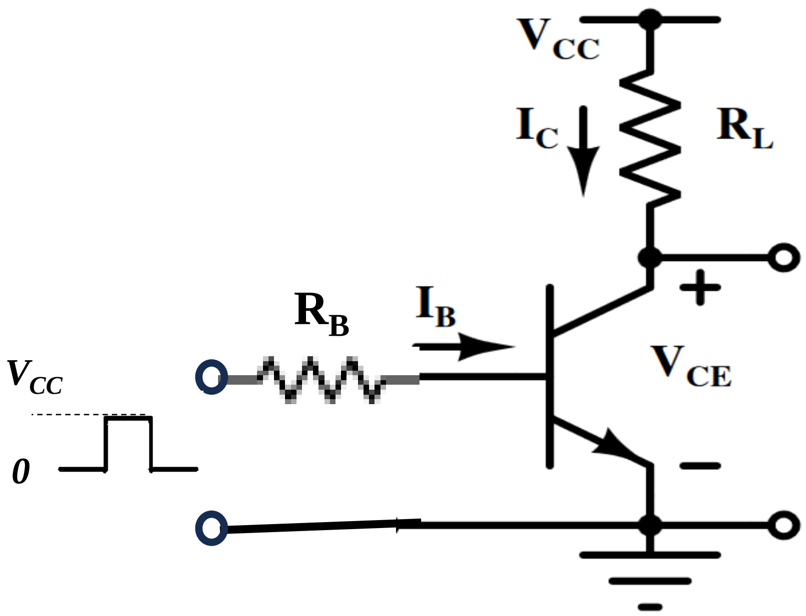


Input connected to $\mathbf{V_{DD}}$ → High $\mathbf{I_D}$, **ON state.**

$V_{OUT} = V_{DS} \approx 0$ V $(= I_D R_{DSON} = 0.1$ to 0.8 V, depending on current & R_{DSON}).

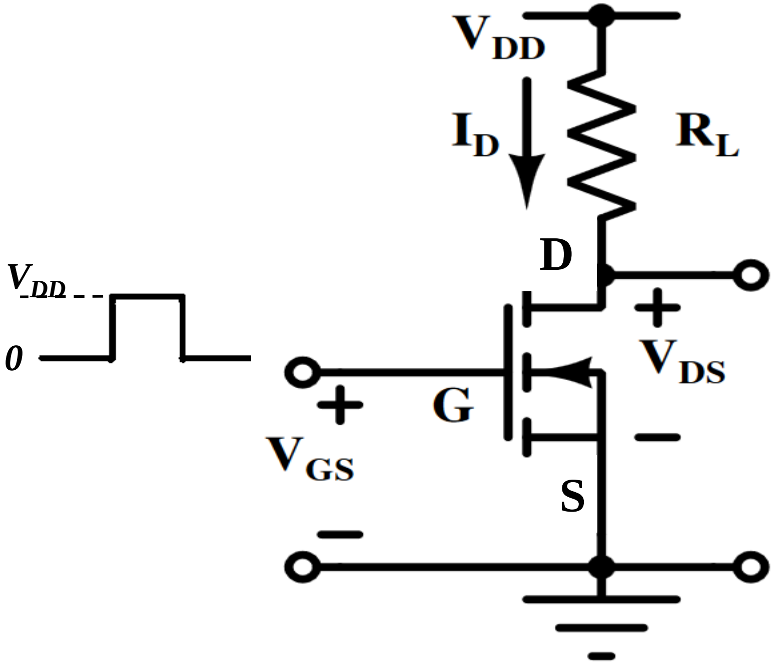
Transistor as '**Closed Switch**'

Switching Loads Connected to Supply



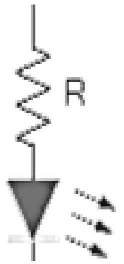
Switching loads using NPN type BJT

1. Load connected to supply is switched using an NPN transistor OR an N-Channel Enhancement MOSFET.
2. The switch is ON when the control voltage goes to the higher value.

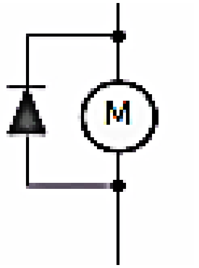


Switching loads using N-Channel MOSFET

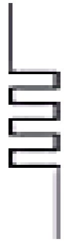
Other loads to be switched can be connected in place of the resistor R_L.



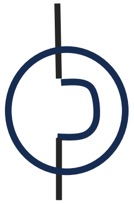
LED Diode Array with Current Limiting Resistor



DC Motors

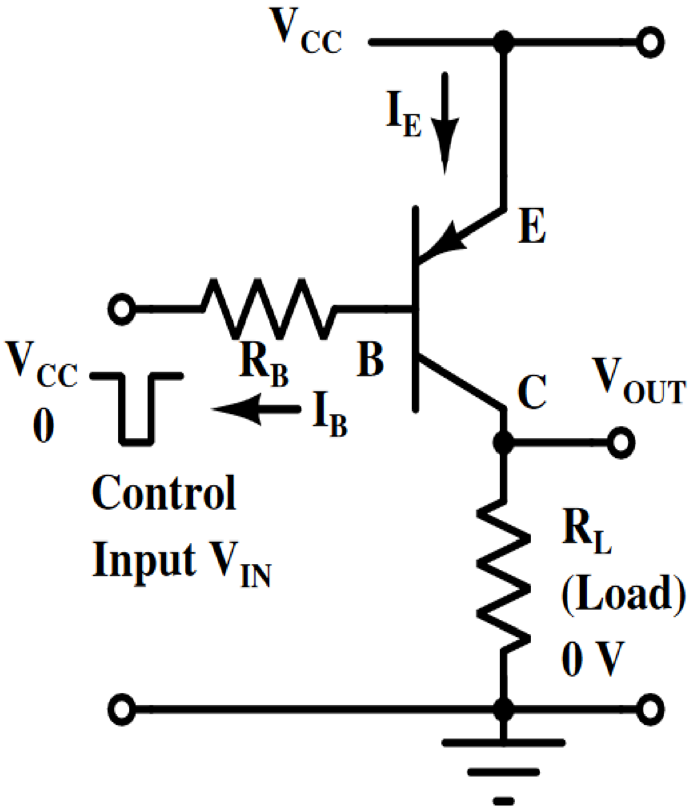


Heating Element



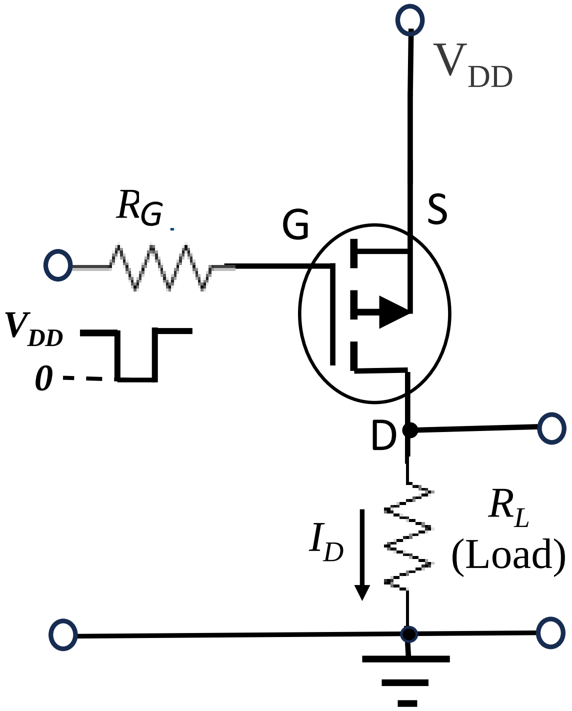
Incandescent Lamp

Switching Loads Connected to Ground



Switching loads using PNP type BJT

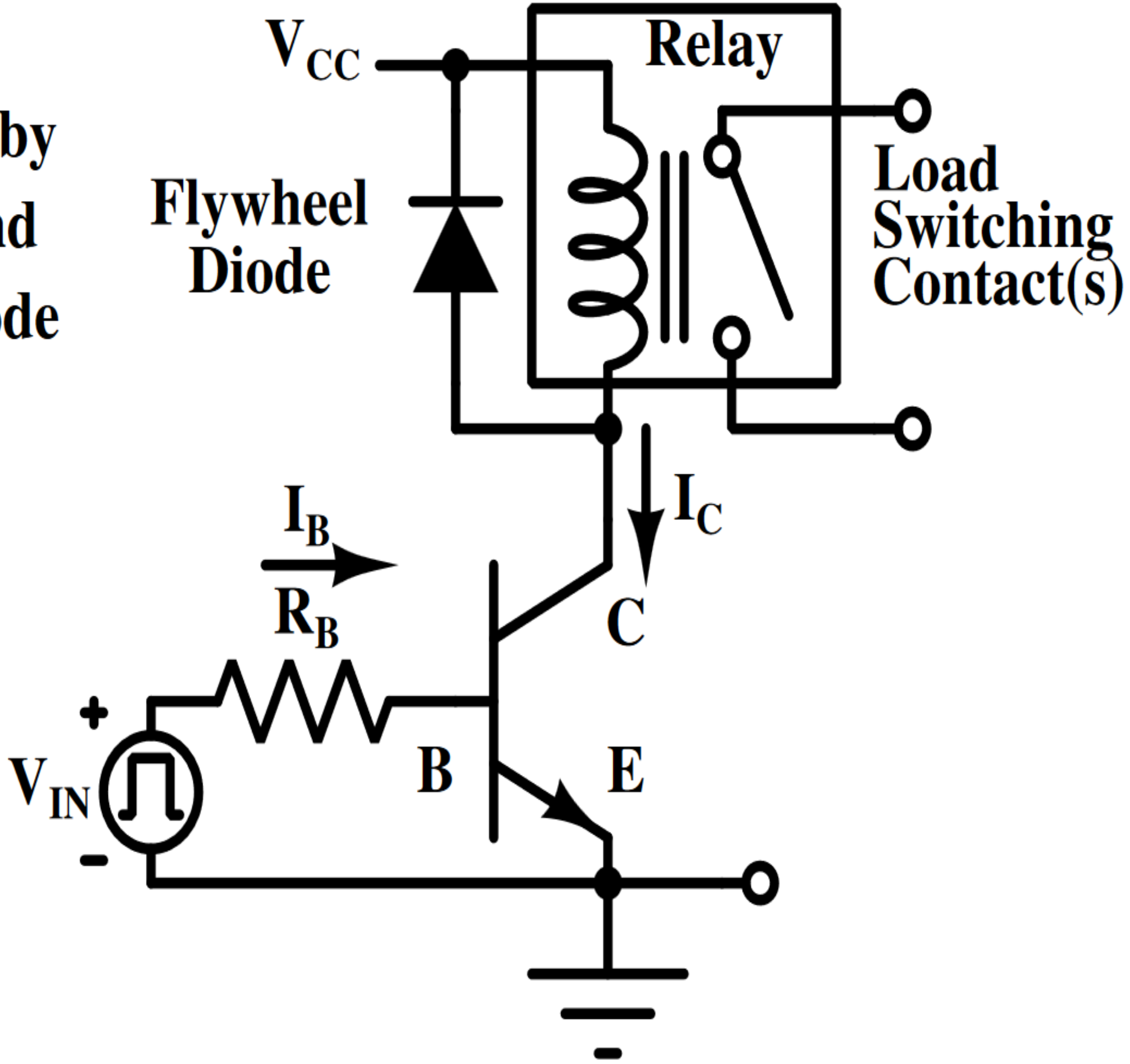
1. Load connected to ground is switched using a PNP transistor OR a P-Channel Enhancement MOSFET.
2. The switch is ON when the control voltage goes to the lower value.

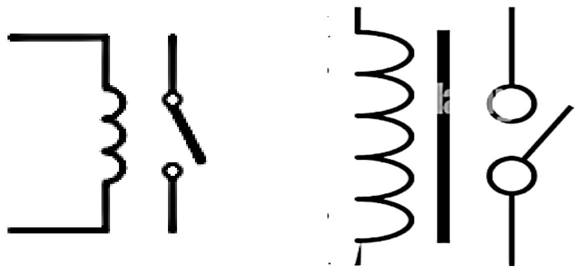


Switching loads using P-Channel Enhancement mode MOSFET

Relay Operation Using a BJT Switch

R_L replaced by Relay coil and Flywheel diode



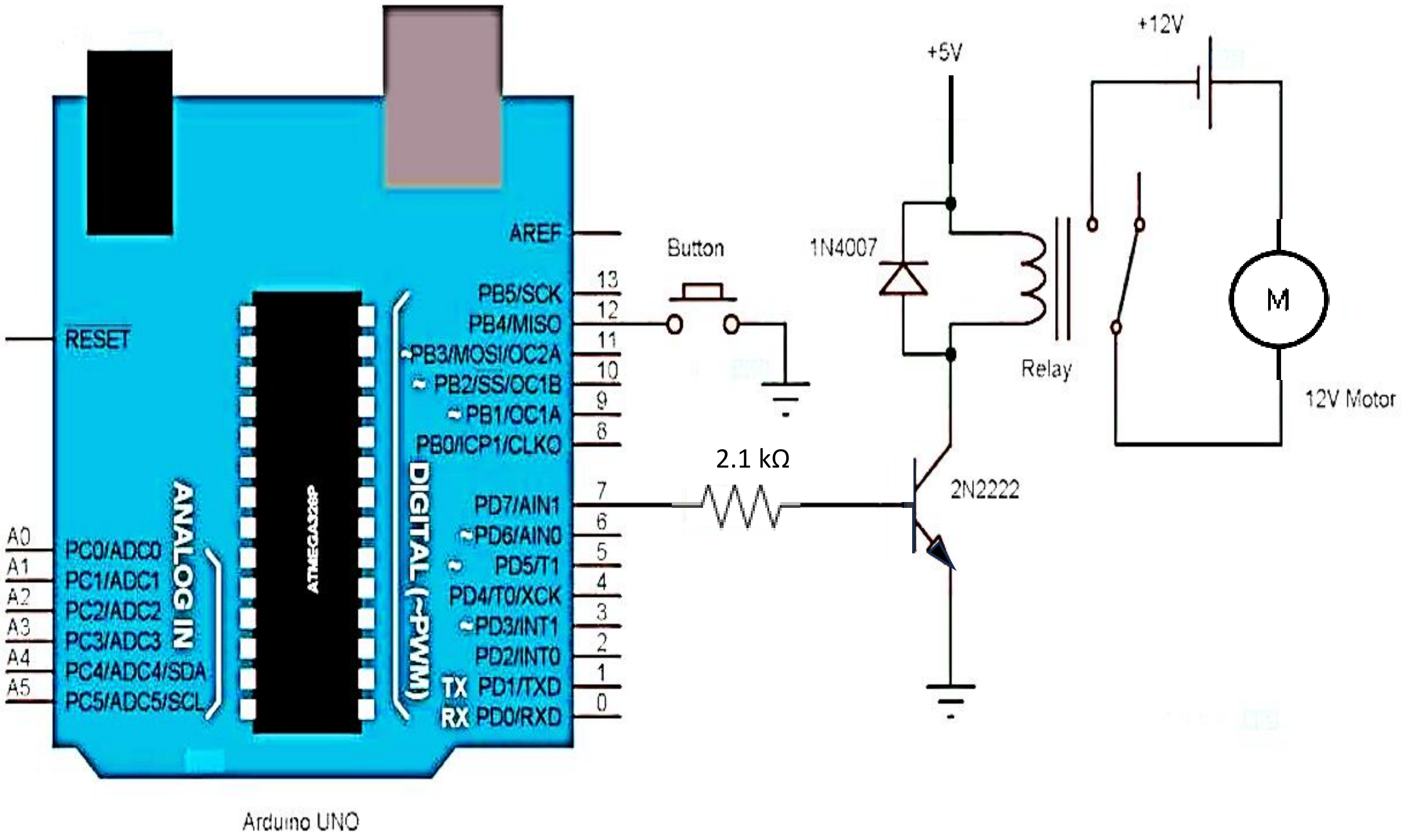


Circuit Symbols for a Relay

By controlling base current (I_B) of BJT, high relay coil current (= I_C) can be switched.

Current Gain: $\beta = I_C / I_B$

Relay Switching Using Micro-Controller (Arduino)



Arduino Relay Control Circuit Diagram

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

This is an example of operating a relay with 'Arduino digital output pin (**PD7**) and NPN transistor.

Relay Coil Current = **60 mA**,

Common emitter current gain in saturation mode, β_{min} = 3**0**.

Action: Set the pin **PD7** to '**Hi**'.

This will put the transistor in saturation mode or **ON** state.

This shall allow the current to flow through the relay coil making the relay **ON**.

Base current ($\mathbf{I_B}$) required to drive the transistor to ON state is 2 mA.

($\mathbf{I_B} = \mathbf{I_c} / \boldsymbol{\beta}_{min} = 60 / 30 = 2$ mA)

Questions and Discussions