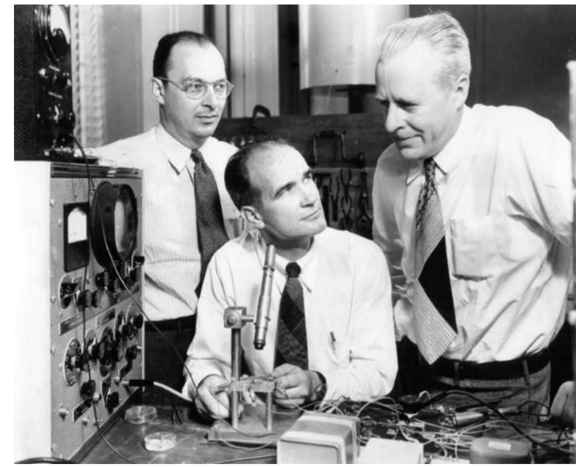
Ch8: Transistors

Bipolar Junction Transistors (BJTs)

Transistors

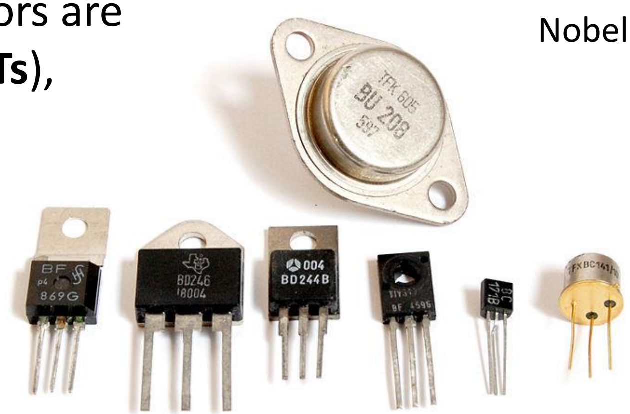
Transistor is one of the greatest inventions of the 20th century (1947) [Transfer + resistor → Transistor].

- Transistors are semiconductor devices that act as either **electrically controlled switches** (digital electronics) or **linear amplifier** (analogue electronics).



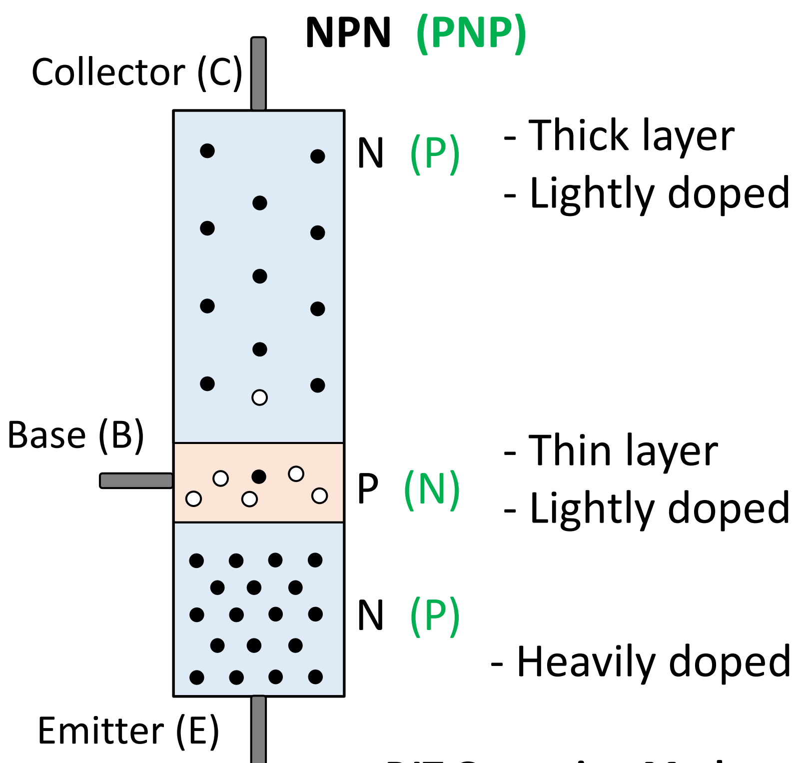
J. Bardeen, W. Shockley, W. Brattain
Invention: 1947
Nobel Prize: 1956

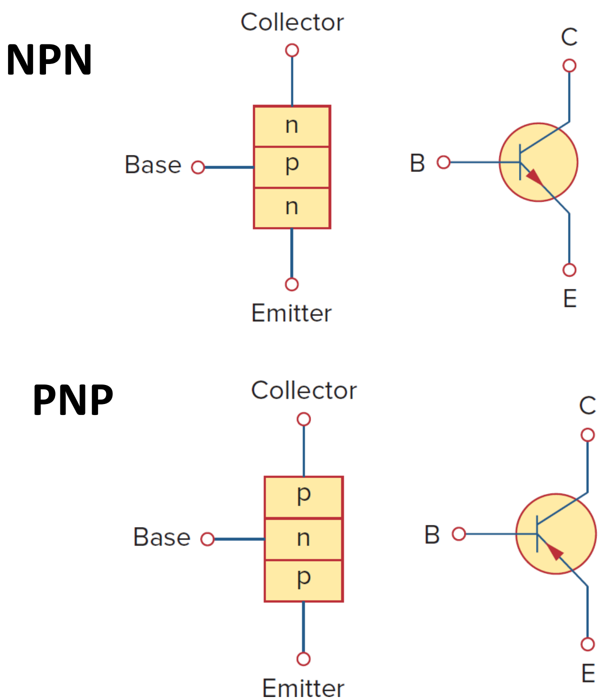
The two major families of transistors are
- **Bipolar Junction Transistors** (**BJTs**),
- **Field-Effect Transistors** (**FETs**).



Bipolar Junction Transistor (BJT)

A **Bipolar Junction Transistor** (**BJT**) consists of three adjacent regions of doped silicon, each of which is connected to an external lead (i.e., **Collector**, **Base**, and **Emitter**). There are two types of BJTs: **npn** and **pnp** transistors (**npn** is the most common type).

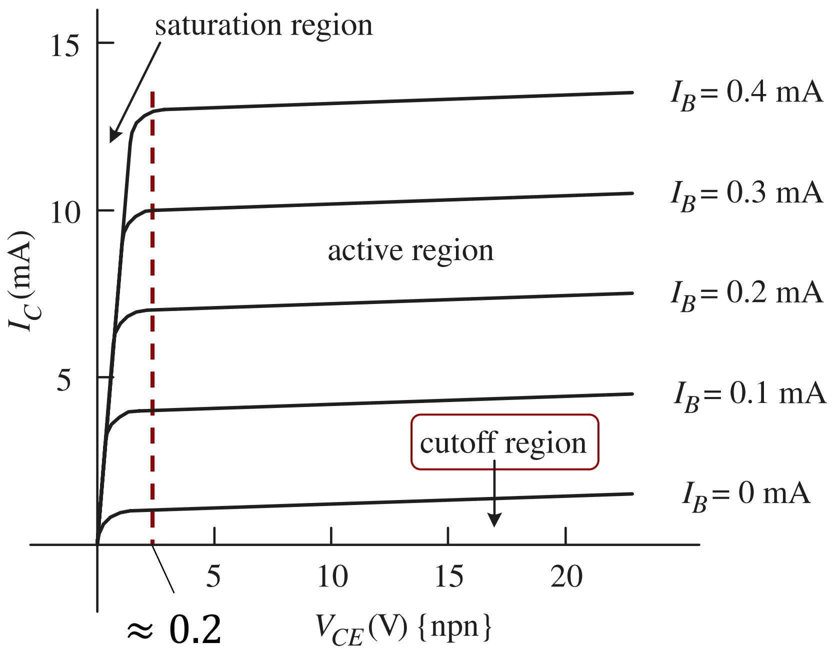


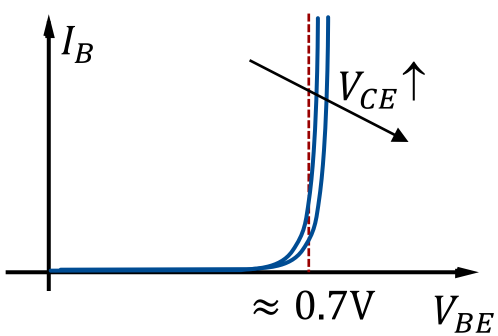


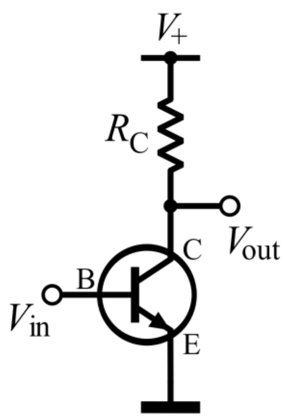
BJT Operation Modes are **Cutoff Mode**, **Saturation Mode**, and **Active Mode**.

BJT Operation Modes: Cutoff Mode

When $V_{BE} < 0.7\mathrm{V}$, and consequently, $I_B = 0$, the transistor acts like an open switch (i.e., transistor is **Fully OFF**) and only a very small **leakage** current (I_C) flows in this mode of operation.

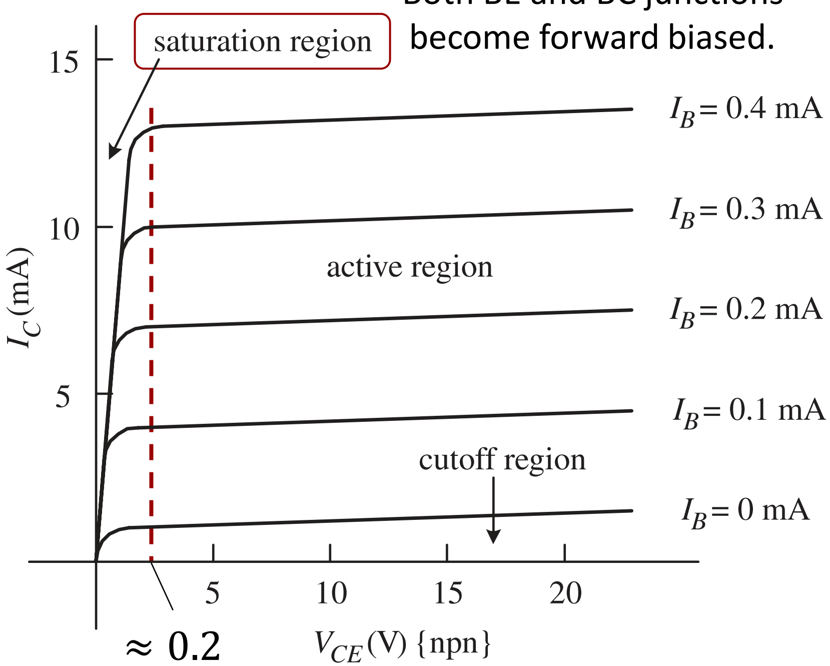






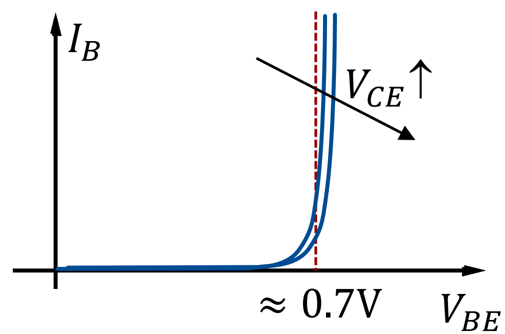
BJT Operation Modes: Saturation Mode

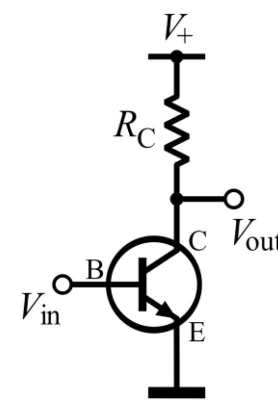
When $V_{BE} \cong 0.7\text{V}$, (and consequently, $I_B > 0$ (sufficiently)) and V_{CE} reaches its minimum ($V_{CE} \leq 0.2$ for a BJT), **maximum** collector current flows to emitter and the transistor acts much like a closed switch (i.e., transistor is **Fully ON**).



$$I_E = I_C + I_B \qquad I_C \gg I_B$$

$$V_{BE} \cong 0.7\text{ V}$$
$$V_{CE} \cong 0.2\text{ V}$$

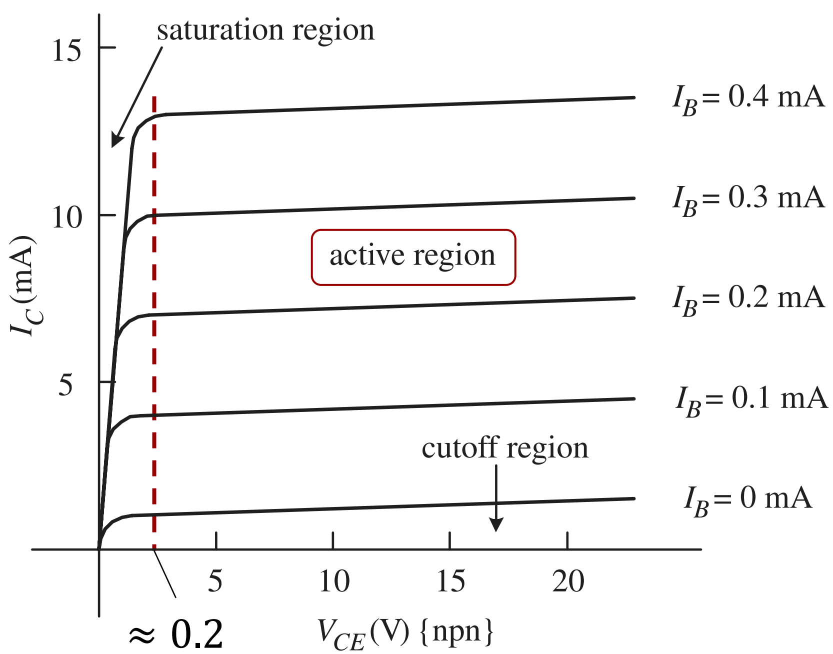




Note: In this mode, I_C is independent of I_B, as long as there is enough I_B to ensure saturation. Thus, $I_C \neq \beta I_B$ and I_C is determined by R_C.

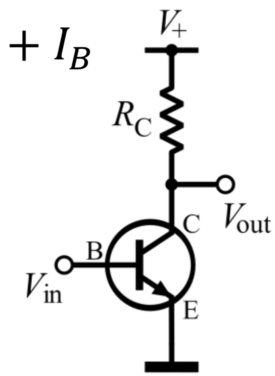
BJT Operation Modes: Active Mode

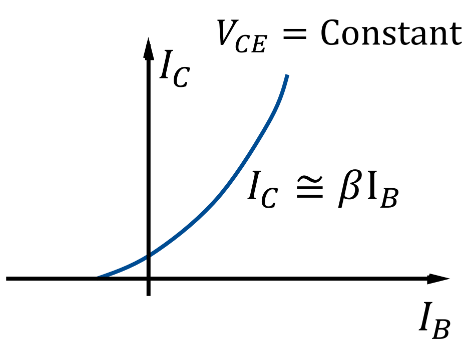
When $V_{BE} \cong 0.7\text{V}$, (and consequently, $I_B > 0$) and $V_{CE} > 0.2$, the transistor acts like an **amplifier** and a nearly-linear relationship exists between terminal currents I_B and I_C.

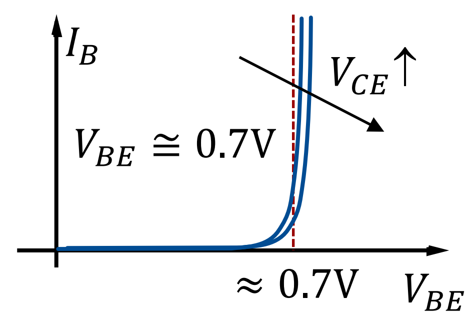


$I_C \cong \beta I_B$ $\qquad I_C \gg I_B$ $\qquad I_E = I_C + I_B$

β is **current gain** which can range from 50-1000.



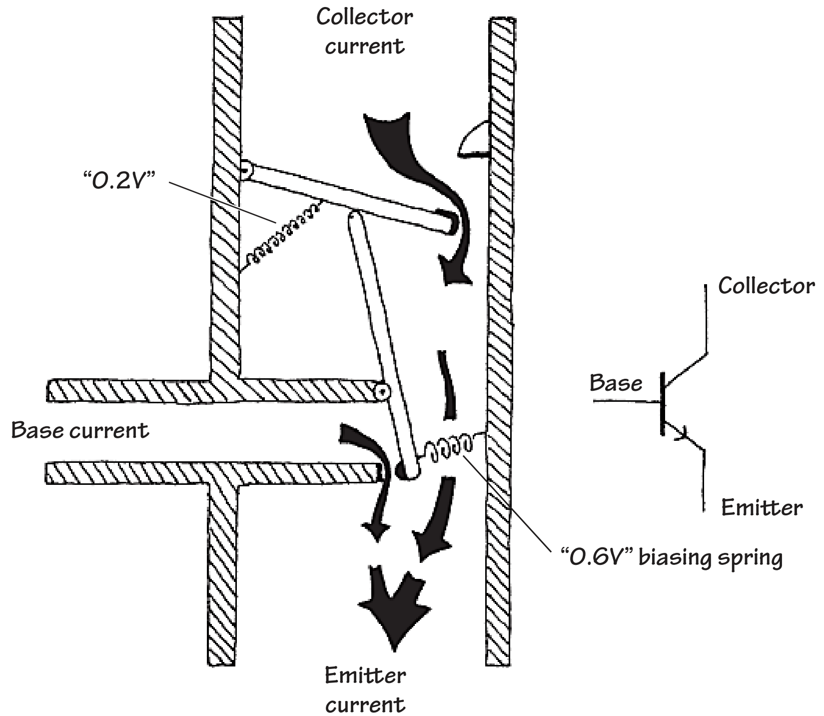


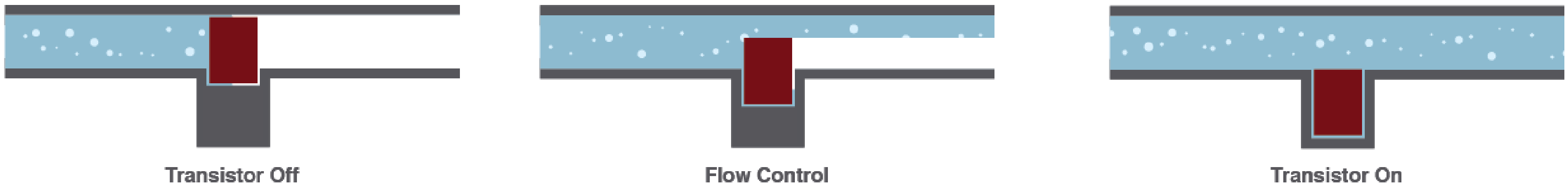


Thus, in **active mode**, small base current I_B flows from the base to the emitter controls a larger current $I_C \gg I_B$ flows from the collector to the emitter.

Fluid Analogy

NPN



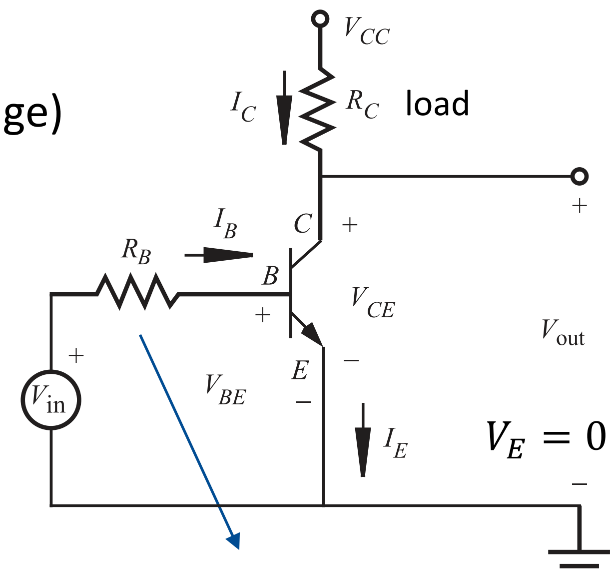


Summary: Voltages & Currents in Cutoff & Saturation Modes (Transistor as a Switch)

The simplest way to switch moderate to high amounts of power using a low-output current device (e.g., ICs) is to use a transistor. When using a transistor as a **switch** it must be either in **Cutoff Mode** (Fully-OFF) or **Saturation Mode** (Fully-ON).

Cutoff or **Fully-OFF Mode:**

$V_{\text{in}} < 0.7\text{V} \Rightarrow V_{BE} < 0.7\text{V} \Rightarrow I_B = 0 \Rightarrow I_C = I_E \cong 0$ (leakage) $\Rightarrow V_{\text{out}} = V_{CC}, V_{BE} = V_{\text{in}} \Rightarrow$ open switch.



For limiting the base current.

$$I_B = \frac{V_{\text{in}} - V_{BE}}{R_B}$$

Saturation or **Fully-ON Mode:**

$V_{\text{in}} > 0.7\text{V}$ (sufficiently) $\Rightarrow V_{BE} \cong 0.7\text{V} \Rightarrow I_B > 0$ (sufficiently) $\Rightarrow V_{CE}$ reaches its minimum ($V_{CE} = V_{\text{out}} \leq 0.2\text{V}$ for a BJT) $\Rightarrow$ maximum I_C flows $\Rightarrow$ closed switch.

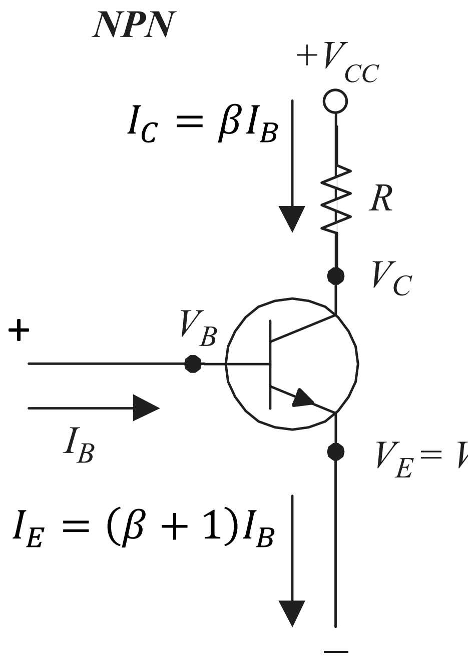
$$V_{CC} - V_C = R_C I_C$$

Summary: Voltages & Currents in Active Mode

Using KCL: $I_E = I_B + I_C$

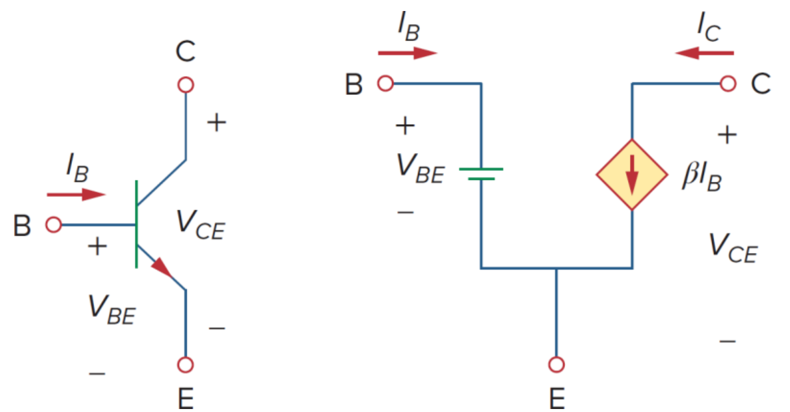
Using KVL: $V_{CE} + V_{EB} + V_{BC} = 0$

In active mode: $V_{BE} \simeq 0.7\text{V}$
$I_C = \beta I_B$



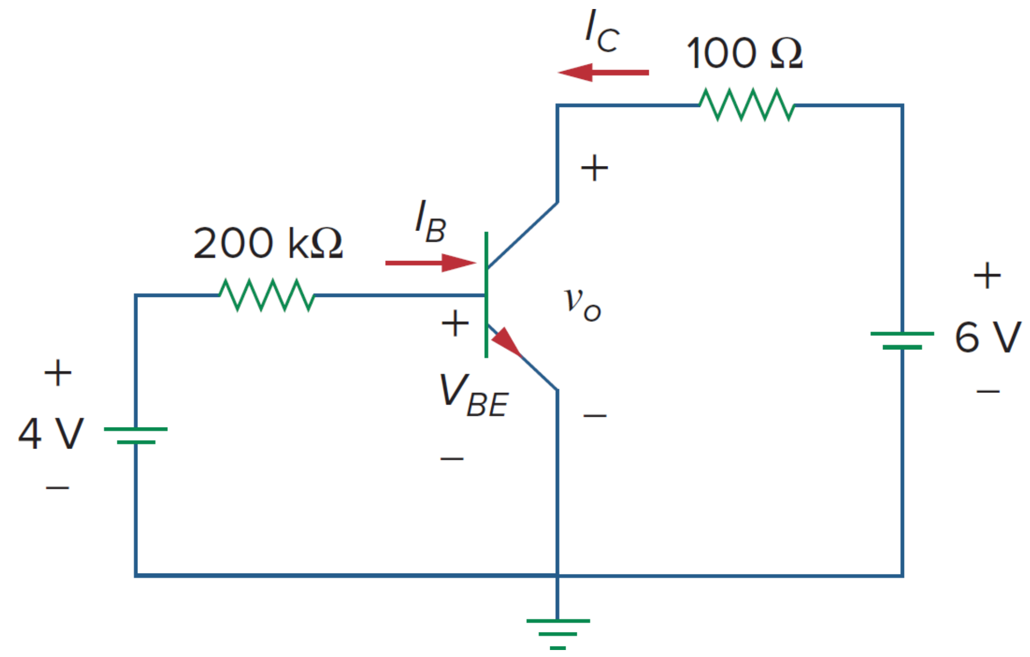
$$V_C = V_{CC} - I_C R$$
$$= V_{CC} - (\beta I_B) R$$

In active mode, the BJT can be modeled as a dependent current-controlled current source.



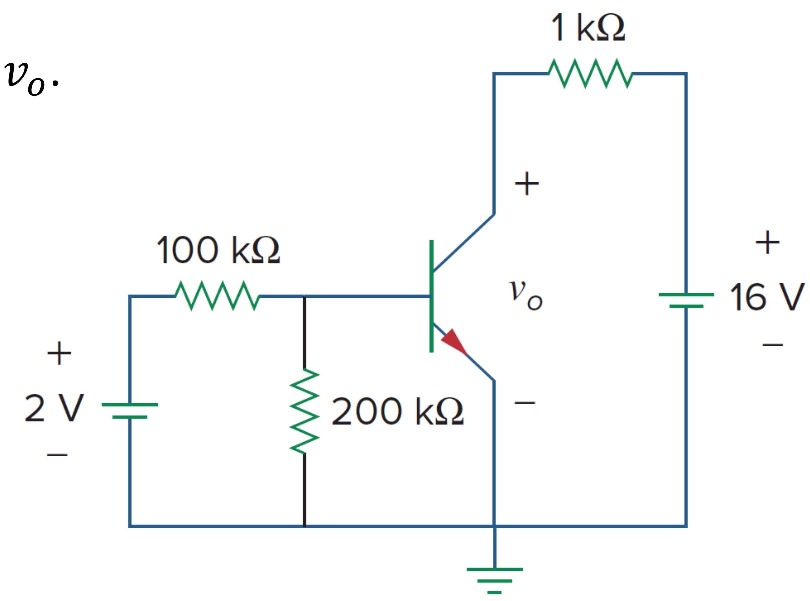
Example

Find I_B, I_C, and v_o in the transistor circuit. Assume that the transistor operates in the active mode, $\beta = 50$, and $V_{BE} = 0.7$ V.



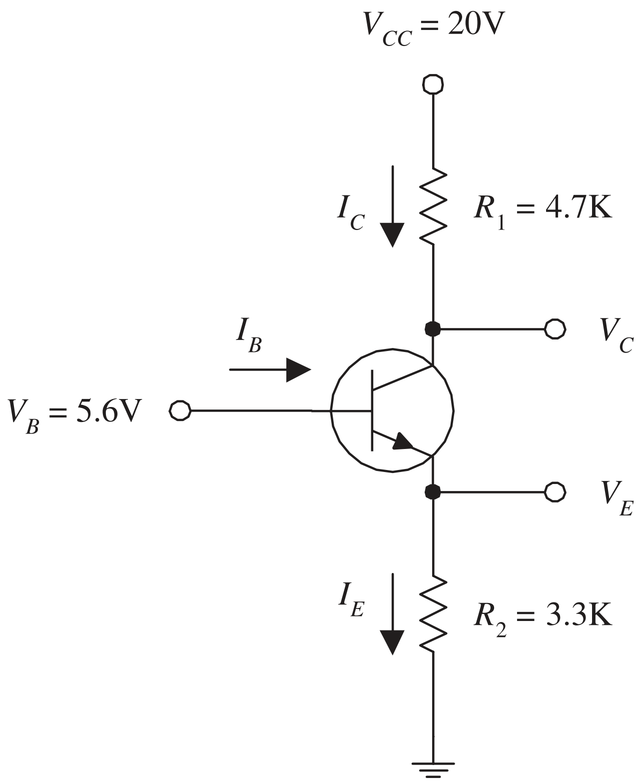
Example

For the BJT circuit, $\beta = 150$ and $V_{BE} = 0.7$ V. Find v_o.



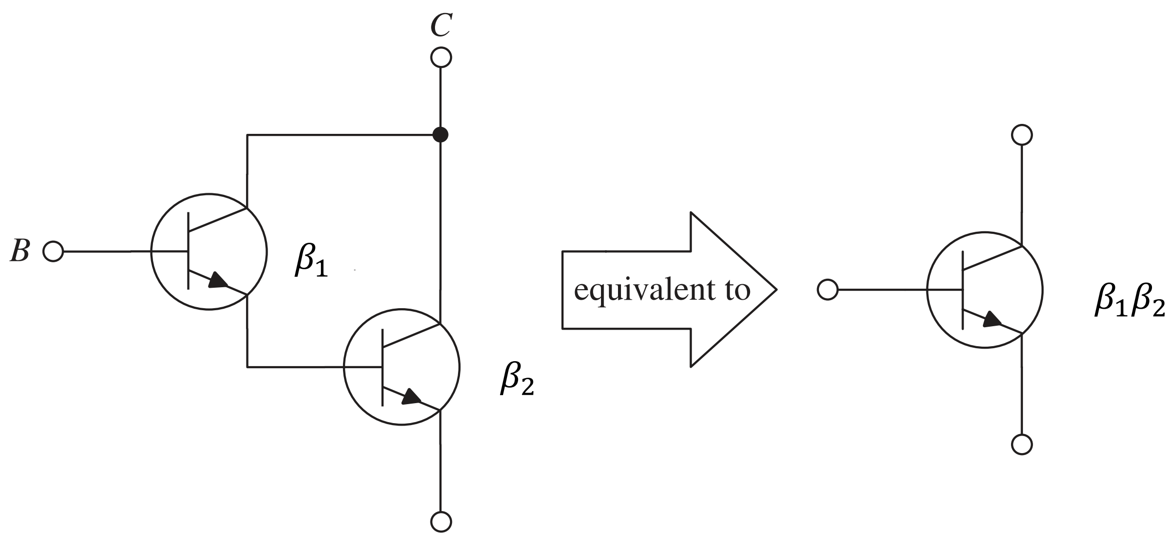
Example

Assume that the transistor is in Active Mode and $\beta = 100$, find V_E , I_E, I_B, I_C, and V_C ($V_{BE} = 0.6$ V).



Darlington Transistor

By attaching two transistors together, a larger β equivalent transistor circuit, which is equal to the product of the individual transistor's β values ($\beta = \beta_1\beta_2$), is formed.

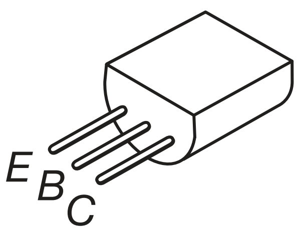


Darlington Pairs usually comes in a single package and they are used for **large current** applications and as input stages for amplifiers, where big input impedances are required. They come in npn (D-npn) and pnp (D-pnp) Darlington packages.

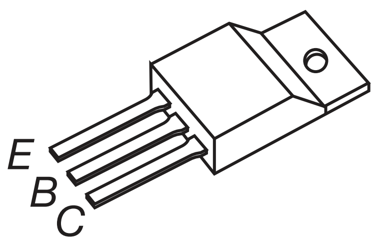
Common BJT Packages

- **TO-92, TO-5, TO-18**: Small-signal transistor package,
- **TO-220**: Power transistor package,
- **TO-3**: High-Power transistor package,
- **SOT-23**: Surface mount transistor package for use on production printed circuit boards (PCBs), but they are less useful for prototyping because of their small size.
- **IC**: A number of transistors combined into a single integrated package.

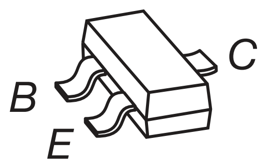
(**TO**: **T**ransistor **O**utline)



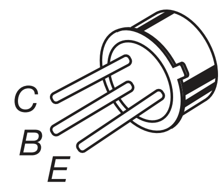
TO-92



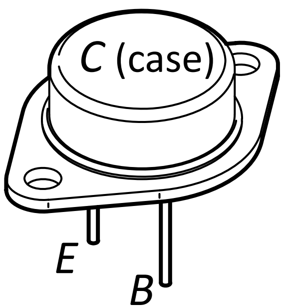
TO-220



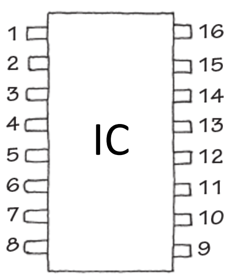
SOT-23
(SOT: Small-Outline Transistor)

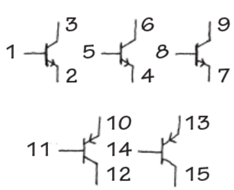


TO-5
TO-18

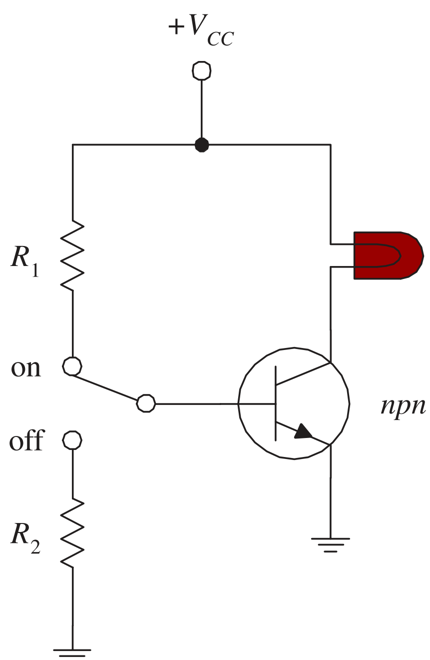


TO-3

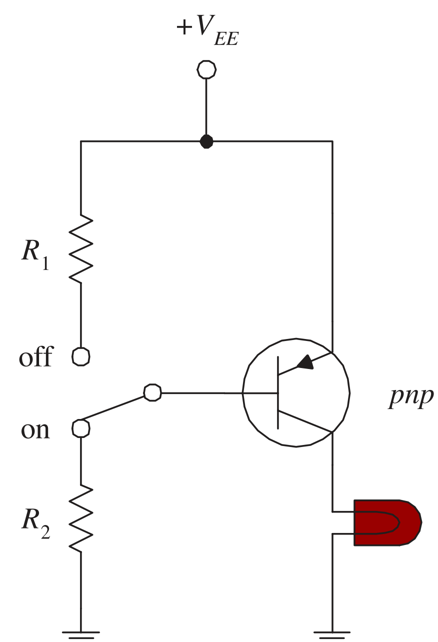




Basic Operation: NPN & PNP Transistors as Switch



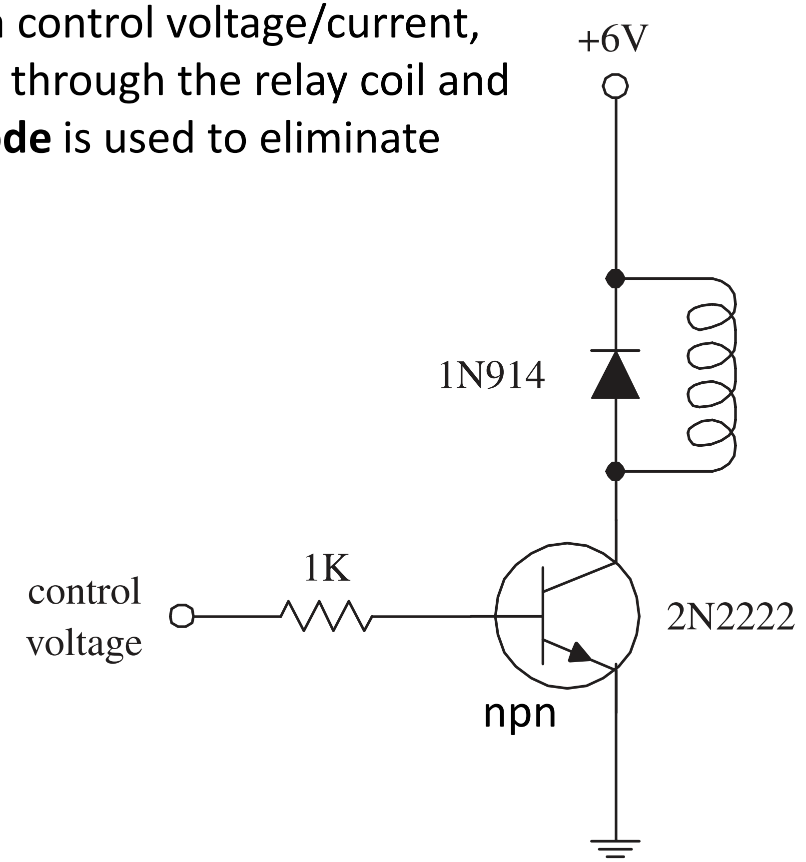
NPN transistor (sinking current)



PNP transistor (sourcing current)

Application: Controlling an Inductive Load

In this circuit, when the transistor's base receives a control voltage/current, the transistor will turn on, allowing current to flow through the relay coil and causing the relay to switch states. The **Fly-Back diode** is used to eliminate voltage spikes created by the relay's coil.

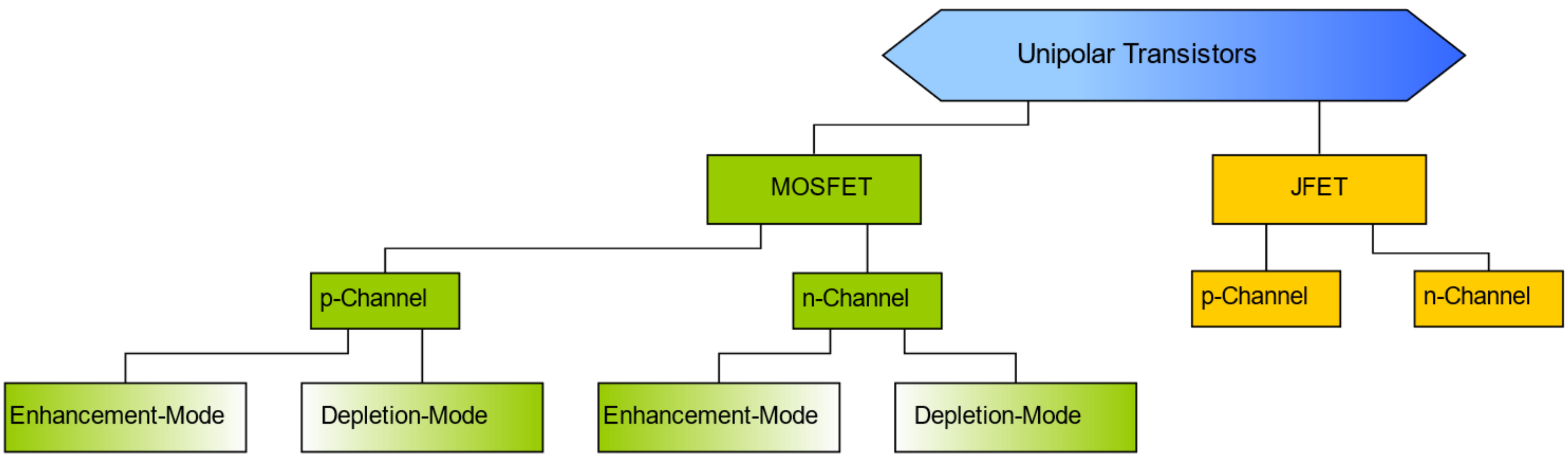


Junction Field-Effect Transistors (JFET)

Field-Effect Transistor (FET)

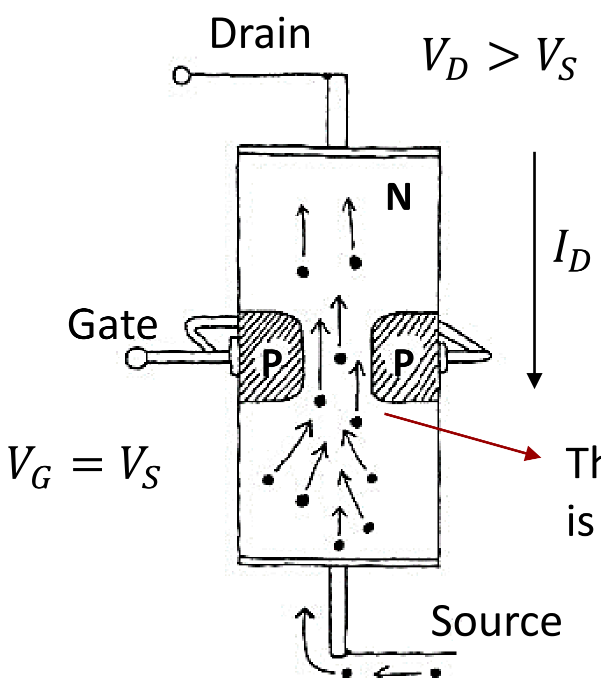
Field-Effect Transistors (**FETs**) or **Unipolar Transistors** operates similar to BJTs but on a **different principle**. A FET is a three terminal (namely **Drain**, **Source**, and **Gate**) semiconductor device in which current conduction is by **only one type** of charge carriers (electrons for n-channel type or holes for p-channel type).

Two main types of FETs:
(1) Junction Field-Effect Transistor (**JFET**),
(2) Metal-Oxide-Semiconductor FET (**MOSFET**).



How an N-Channel JFET Works

Junction Field-Effect Transistors (JFETs) come in either n-channel or p-channel configurations. An n-channel JFET is made with an n-type silicon channel that contains two p-type silicon "bumps" placed on either side. The **gate** lead is connected to the p-type bumps, while the **drain** and **source** leads are connected to either end of the n-type channel.



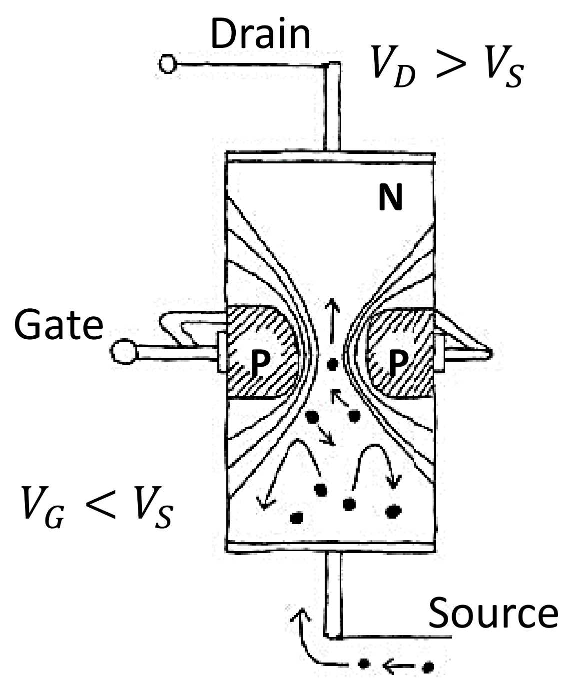
(n-channel JFET)

The narrow region is called **Channel.**

When **no voltage** is applied to the gate (i.e., $V_G = V_S$), current flows freely through the central n-channel (since there are a lot of negative charger carriers already there).

How an N-Channel JFET Works

If the **gate** is set to a **negative voltage** relative to the source (i.e., $V_G < V_S$), an **electric field** is produces and the area in between the p-type semiconductor bumps and the center of the n-channel will form two reverse-biased junctions and a **depletion region** that extends into the channel. The more negative the gate voltage, the larger is the depletion region, and hence the harder it is for electrons to make it through the channel.



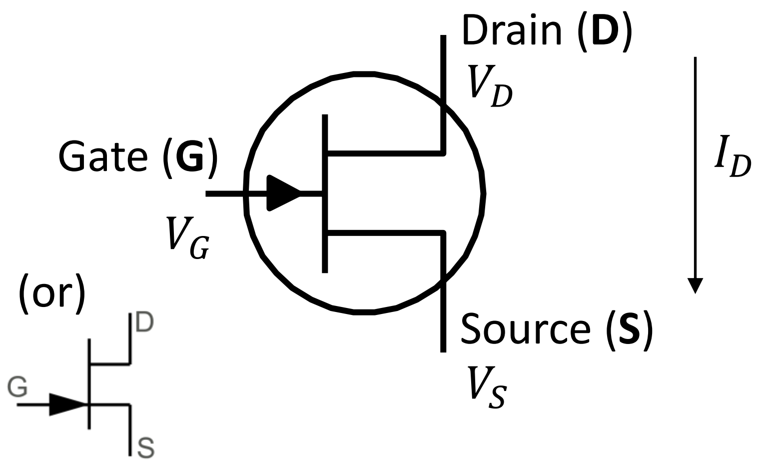
❖ For a p-channel JFET, everything is reversed!

N-Channel JFET

JFETs are **normally on** when there is **no voltage difference** between its gate and source leads and $V_D > V_S$.

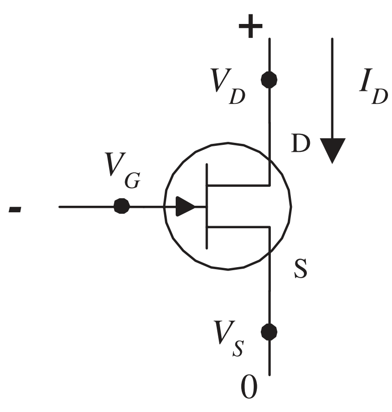
With an **n-channel JFET**, if a **negative** voltage relative to source is applied to gate ($V_{GS} < 0$), the JFET becomes **more resistive to current flow** and reduces current flow from drain to source when $V_D > V_S$.

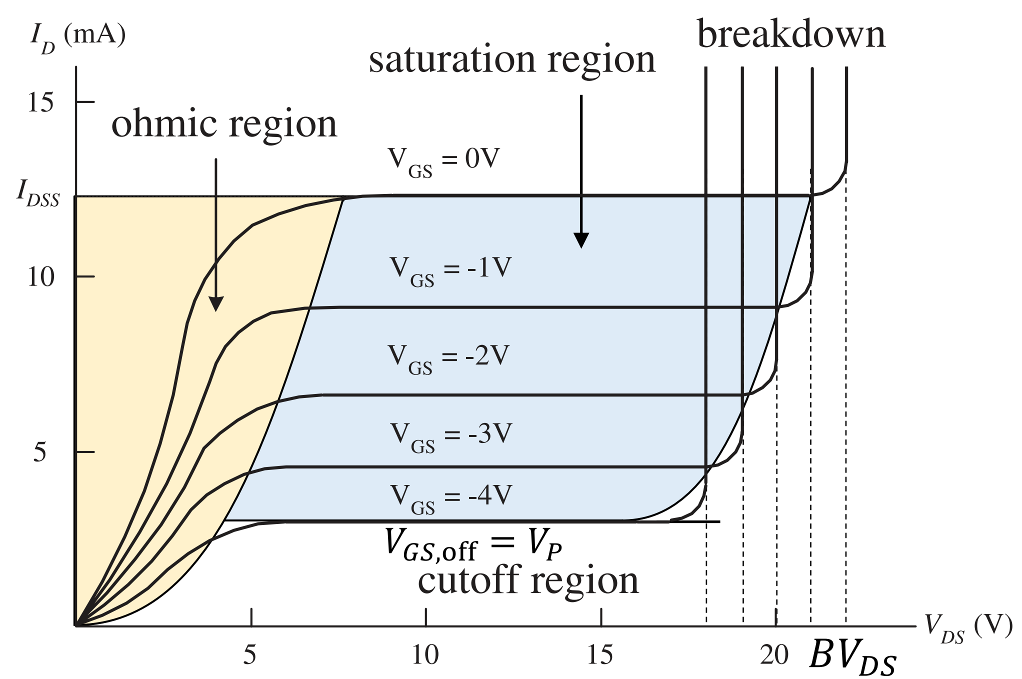
$$V_{GS} = V_G - V_S$$



N-Channel JFET Graph

- When $V_{GS} = V_G - V_S = 0$ V, **maximum current** flows through the JFET. This current is called drain current for zero bias (I_{DSS}) which is **constant** for a JFET.
- When V_{DS} is small, the drain current I_D varies nearly linearly with V_{DS}. This region is called the **ohmic** or **linear region** and the JFET behaves like a **voltage-controlled resistor**.
- The section of the graph where the curves flatten out is called the **active** or **saturation region**, and the drain current I_D is strongly influenced by V_{GS} but hardly at all influenced by $V_{DS} = V_D - V_S$.

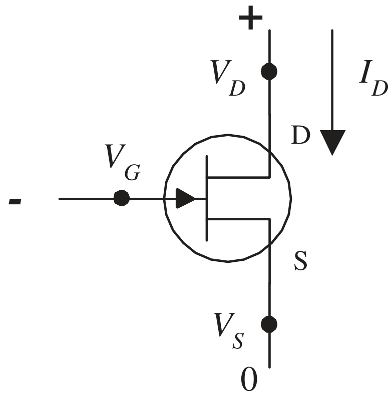


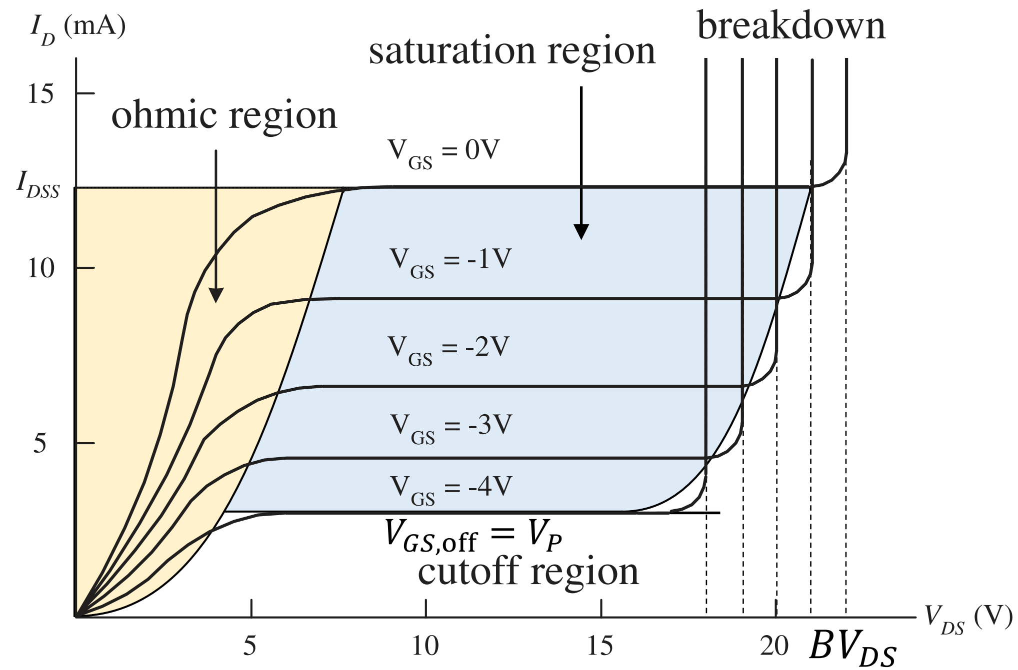


N-Channel JFET Graph

- $V_{GS,\text{off}}$ is the particular V_{GS} voltage that causes the JFET to **turn off** (practically no current flows through device and the JFET behaves like an open circuit) is called the **cutoff voltage**.

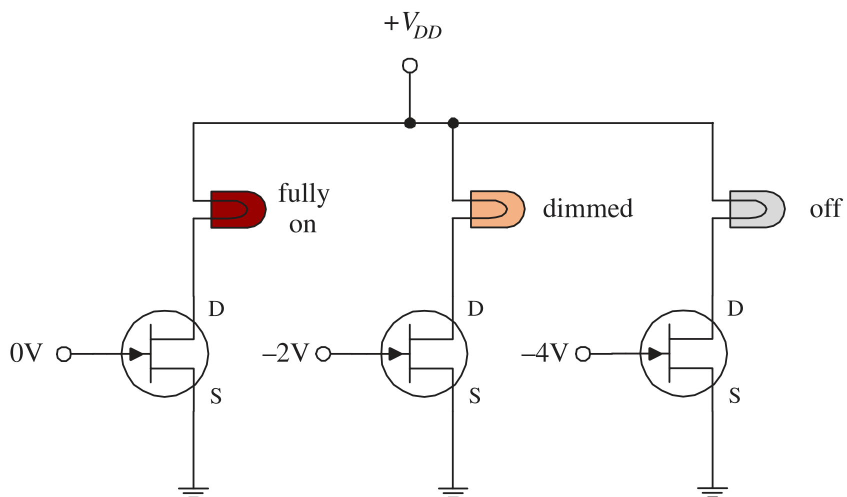
- When V_{DS} increases, I_D increases extremely and the **JFET loses its ability to resist current**. This effect is called **drain-source breakdown**, and its voltage is expressed as BV_{DS}.





Basic Operation: Light Dimmer

n-channel JFET



In the **n-channel** circuit, a more negative gate voltage causes a larger drain-to-source resistance, hence causing the light bulb to receive less current.

Metal-Oxide-Semiconductor FET (MOSFET)

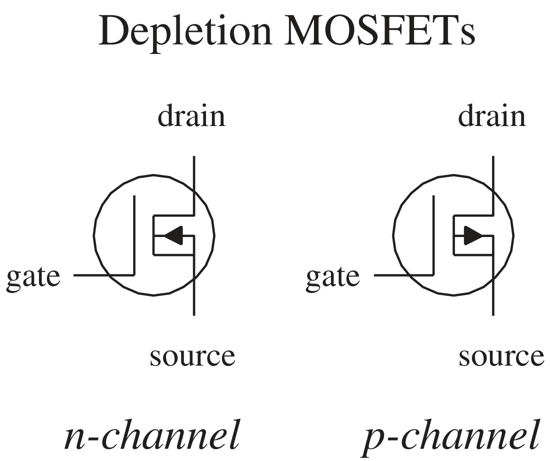
Metal-Oxide-Semiconductor FET (MOSFET)

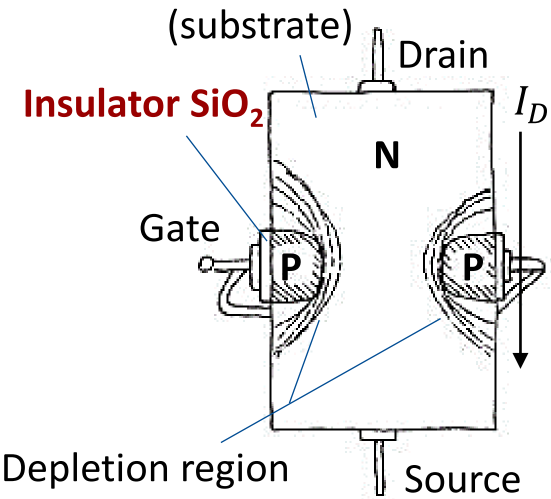
Metal-Oxide-Semiconductor Field-Effect Transistors (**MOSFETs**) are the **most popular** transistors used today that in some ways resemble JFETs. When a small voltage is applied at its gate lead, the current flow through its drain-source channel is altered. However, unlike JFETS, MOSFETs have **larger** gate lead **input impedances** ($\geq 10^{14}$ vs 10^{10} Ω), which means that they draw almost no gate current at all. This is because of **a thin silicon dioxide layer insulating** the gate from the **substrate** (drain-source channel).

The two major kinds of MOSFETs are **depletion-type** MOSFETs and **enhancement-type** MOSFETs. Each type comes in either **n-channel** or **p-channel** forms.

How an N-Channel Depletion-Type MOSFET Works

A **depletion-type** MOSFET is **normally on** or **normally conductive** (maximum current flows from drain to source) when $V_{GS} = 0\ \mathrm{V}$. However, if a voltage is applied to its gate lead ($V_G < V_S$ for n-channel), the drain-source channel becomes **more resistive (similar to a JFET)**.

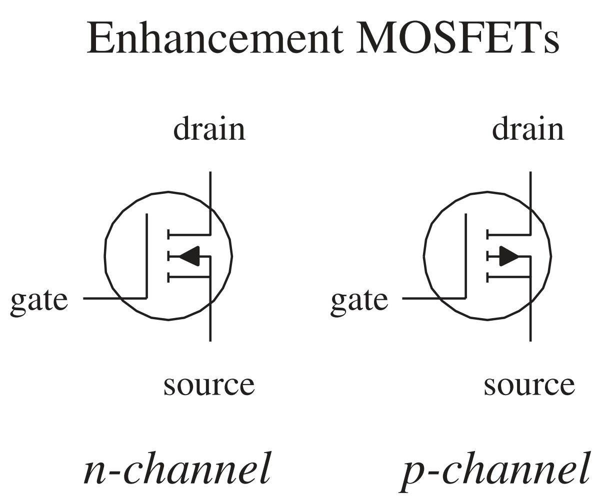


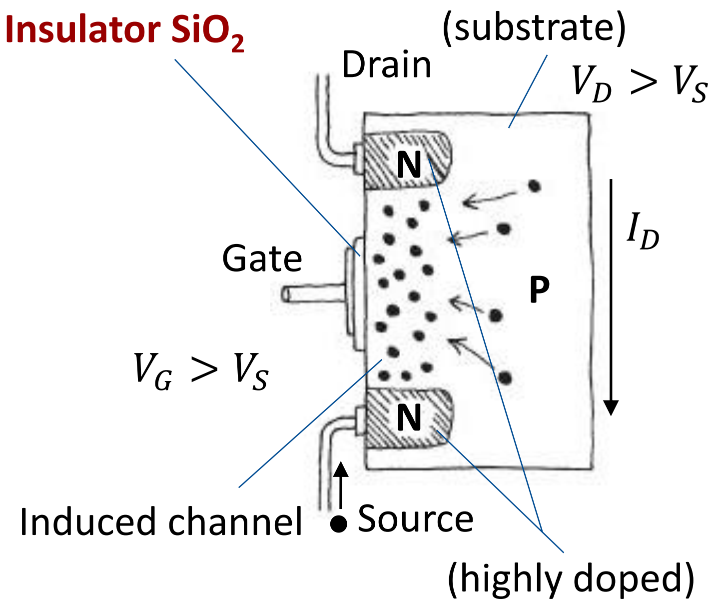


❖ For a p-channel depletion-type MOSFET, everything is reversed!

How an N-Channel Enhancement-Type MOSFET Works

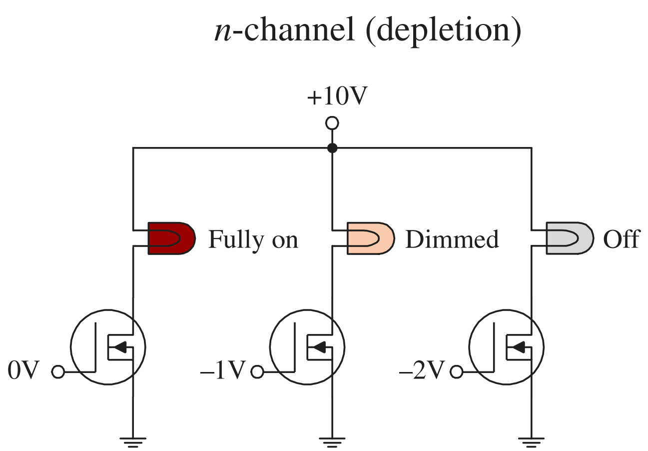
An **enhancement-type** MOSFET is **normally off** or **normally resistive** (minimum current flows from drain to source) when $V_{GS} = 0\ \mathrm{V}$. However, if a voltage is applied to its gate lead ($V_G > V_S$ for n-channel), the drain-source channel becomes **less resistive**.

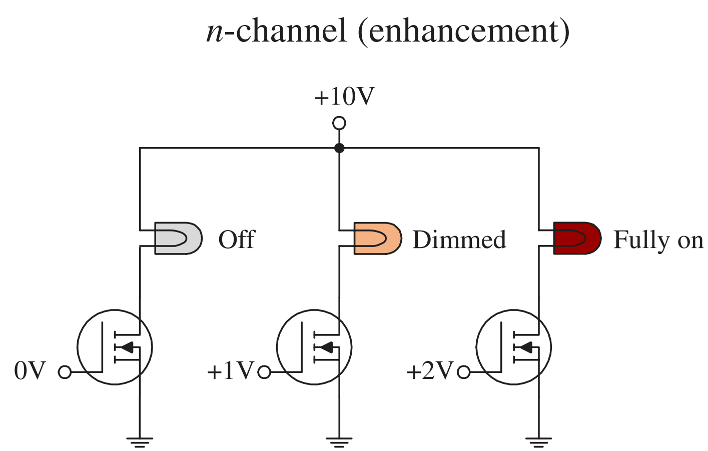




❖ For a p-channel enhancement-type MOSFET, everything is reversed!

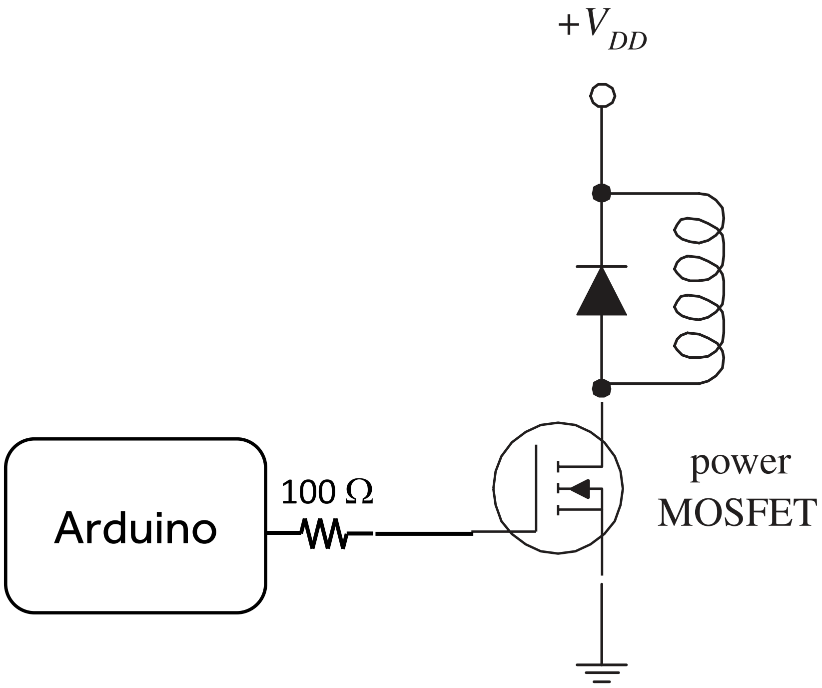
Basic Operation: Light Dimmer





Application: Controlling an Inductive Load

The MOSFET is a good choice to use as a digital-to-analog interface; its extremely high input resistance and low input current make it a good choice for powering high-voltage or high-current analog circuits **without** worrying about **drawing current** from the driving logic like an Arduino Board.



- 100 Ω gives protection to the logic pin.

BJT and FET

Both BJTs and FETs operate by **controlling current between two terminals** using a **voltage** applied to a third terminal. However, BJTs require a biasing input (or output) **current** at their control leads, whereas FETs require **only a voltage** (practically no current) to conduct the charge carriers.

Advantages of FETs:

- Drawing little or **no input (or output) current** at their control leads, which results in high input impedance ($\geq 10^{10}\ \Omega$); i.e., in contrast with BJTs, the FET's control lead will not have much influence on the current dynamics of the control circuit,
- **Easier and cheaper** to manufacture,
- Can be made **extremely small** (FETs are important components in design of digital ICs),
- Generally, much **less noisy** than the BJTs.