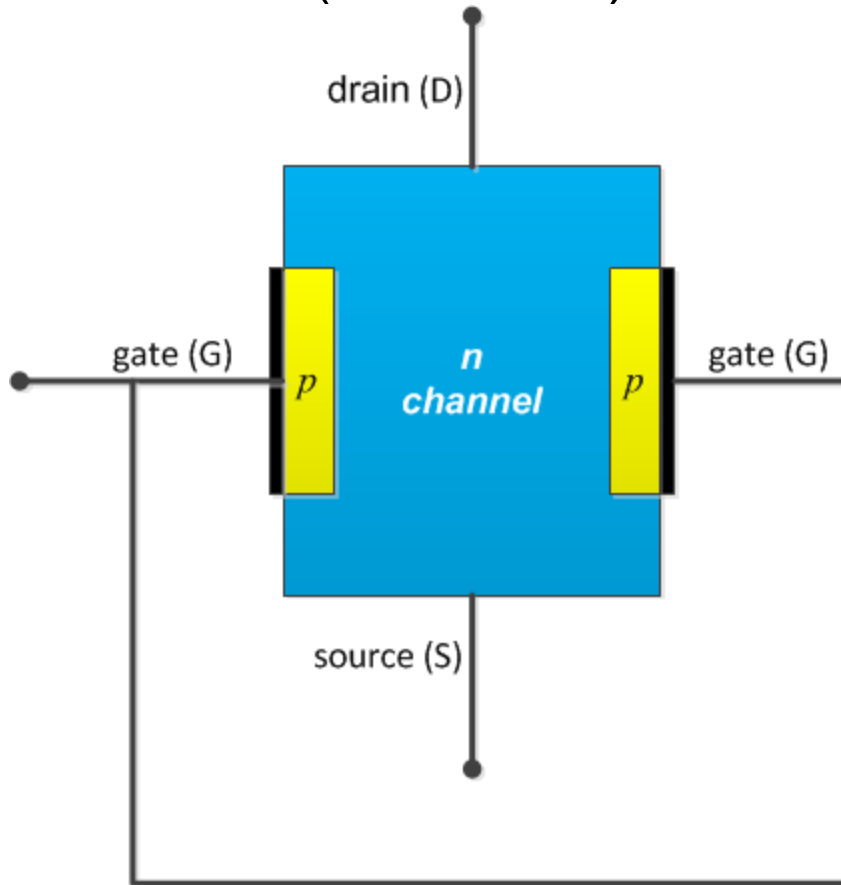# JFET

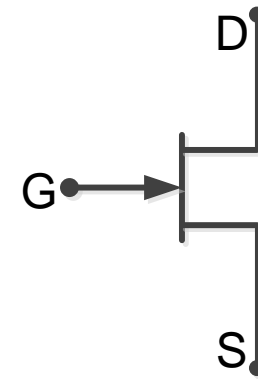## Construction (n channel)

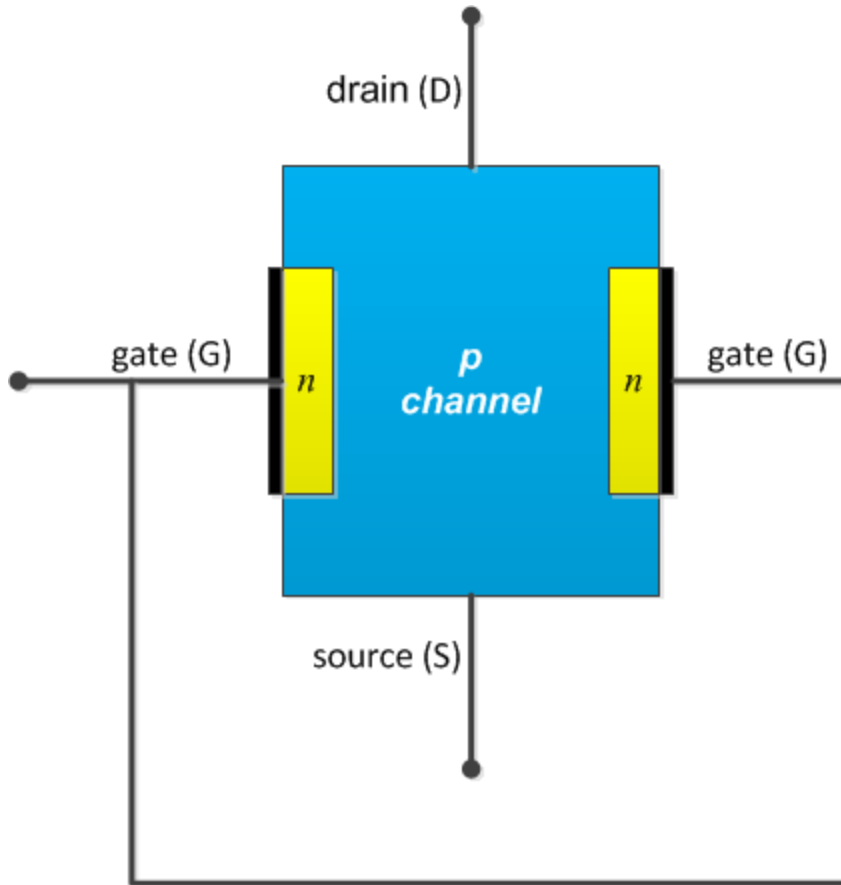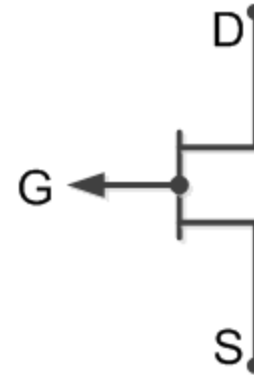## Symbol

JFET

Construction (p channel)

Symbol

JFET

drain (D)

gate (G) p n
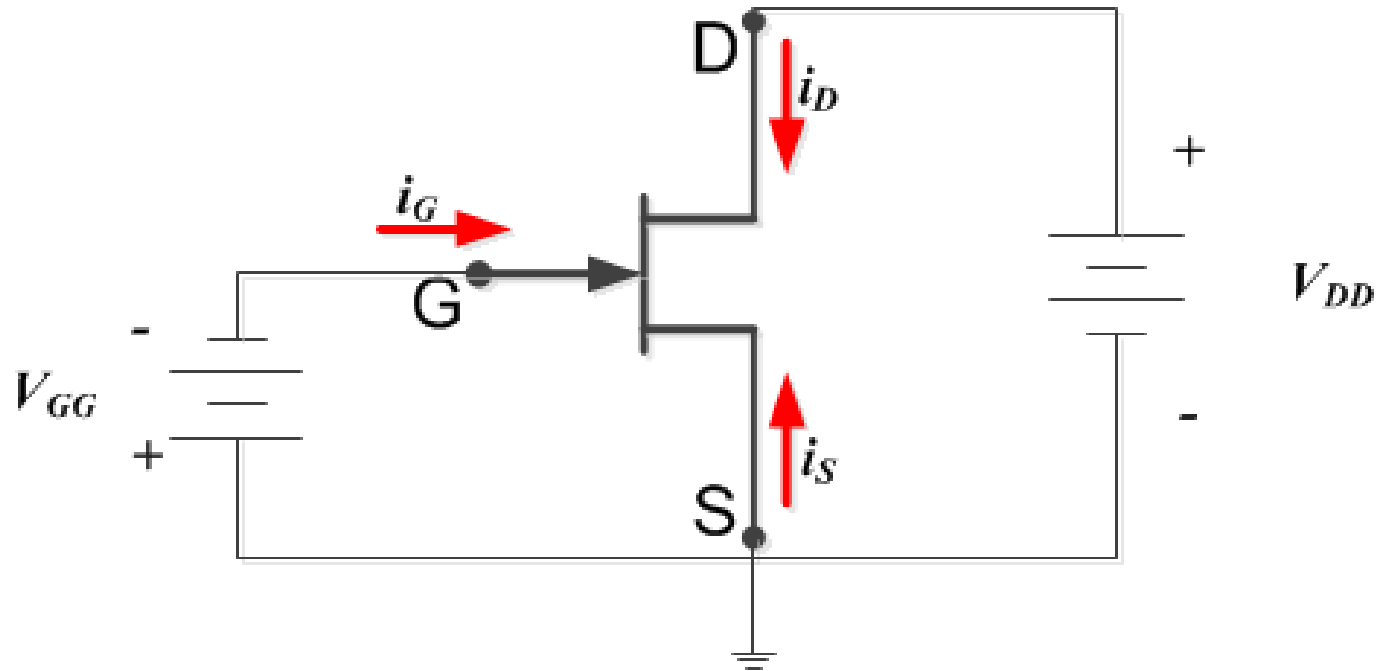   channel p gate (G)   G
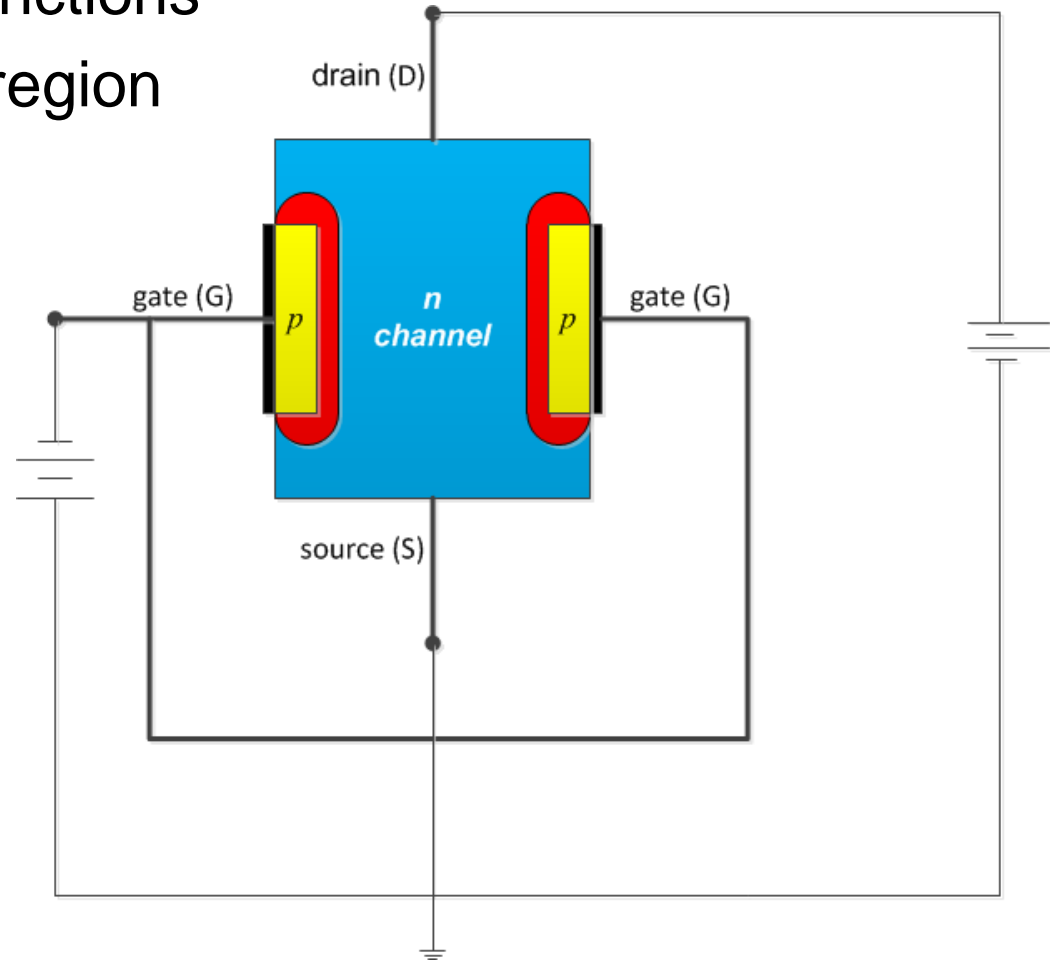
source (S)
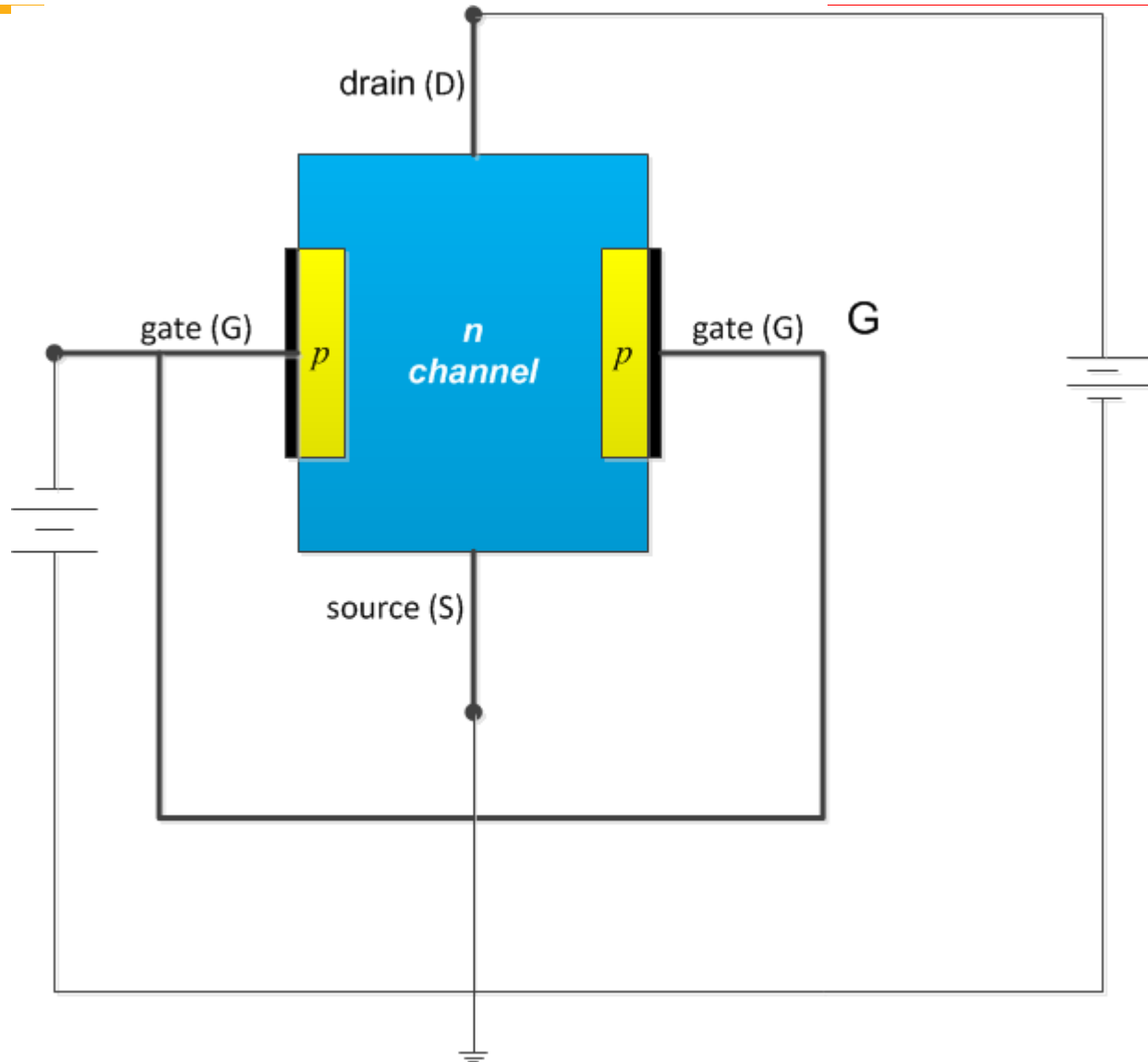
JFET

Circuit analysis

JFET

When $V_{DD} = V_{GG}=0$, two junctions
with associated depletion region
is shown
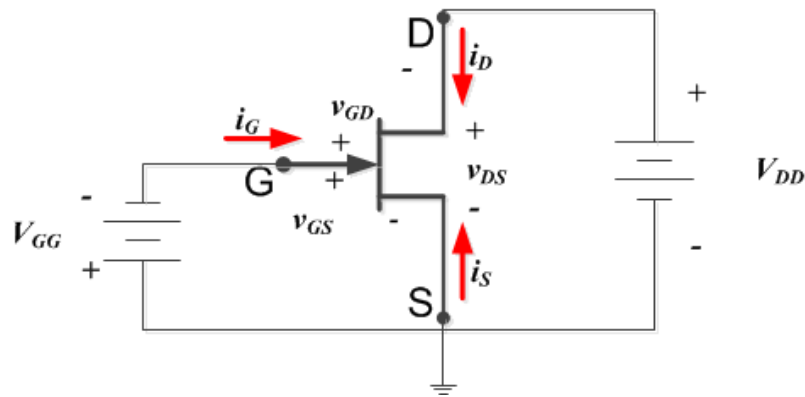
JFET

❑ When the $V_{DD}=v_{DS}$ is small (positive) number, a small positive drain current results. The potential at drain v_D is approximately equal to source voltage v_S $(v_S \approx v_D = 0)$

❑ However if V_{GG} is increased, since $v_{GS}= -V_{GG}$, then pn junction will become more reverse biased and depletion region gets wider.

❑ Because v_S $(v_S \approx v_D = 0)$, the depletion regions are symmetrical.

❑ When the VGG is sufficiently increased , the depletion region will be widened and channel will become narrower.

❑ The value of $v_{GS}= -V_{GG}$, which eliminates the channel is called as pinchoff voltage.

JFET

As long as $V_{DD}= v_{DS}= v_D\text{-}v_S$ remains small , the depletion region will be essentially symmetrical and i_D will be proportional to v_{DS}, i. e channel will behave as a linear resistor.

However, if $V_{DD}=v_{DS}=v_D\text{-}v_S$ gets larger, then i_D gets larger and v_D becomes greater than v_S
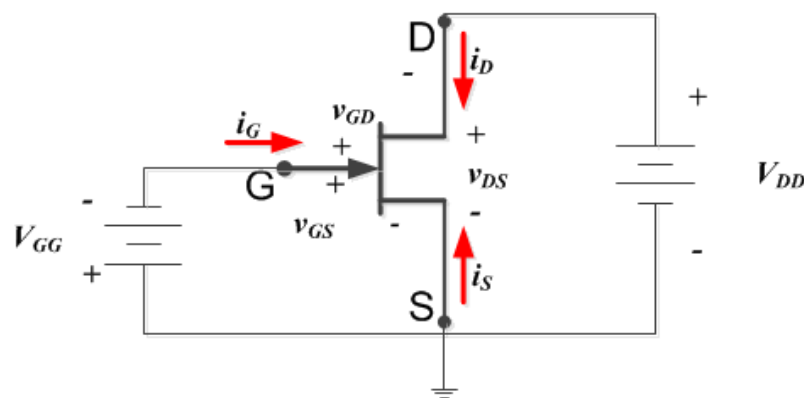
Since $v_{GS}=0$ V

$v_{GD}=v_{GS}\text{-}v_{DS}= 0\text{-}v_{DS}=\text{-}v_{DS}$

JFET

❑ Since gate drain voltage is negative and gate source voltage is zero, portion of the pn junction between the gate and drain is more reverse biased than portion between gate and source.

❑ Due to this channel is narrower at the drain end than source end.
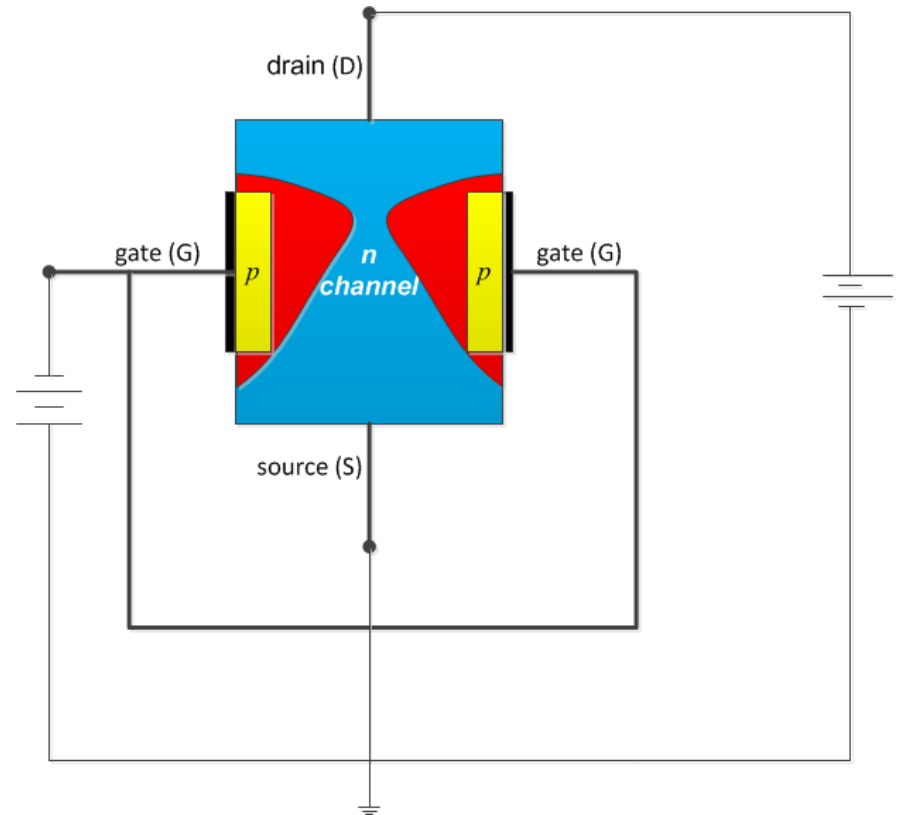
JFET

❑ As v_{DS} increases, i_D also increases , channel gets narrower at the drain end than source end. The channel resistance increases and its nature is non linear.

❑ If v_{DS} is made large enough pinch off is reached as shown

❑ $v_{GD} = v_{GS} - v_{DS} = 0 - v_{DS} = V_p$ or $v_{DS} = -V_p$

drain (D)

gate (G)   p   p   gate (G)

n channel

source (S)
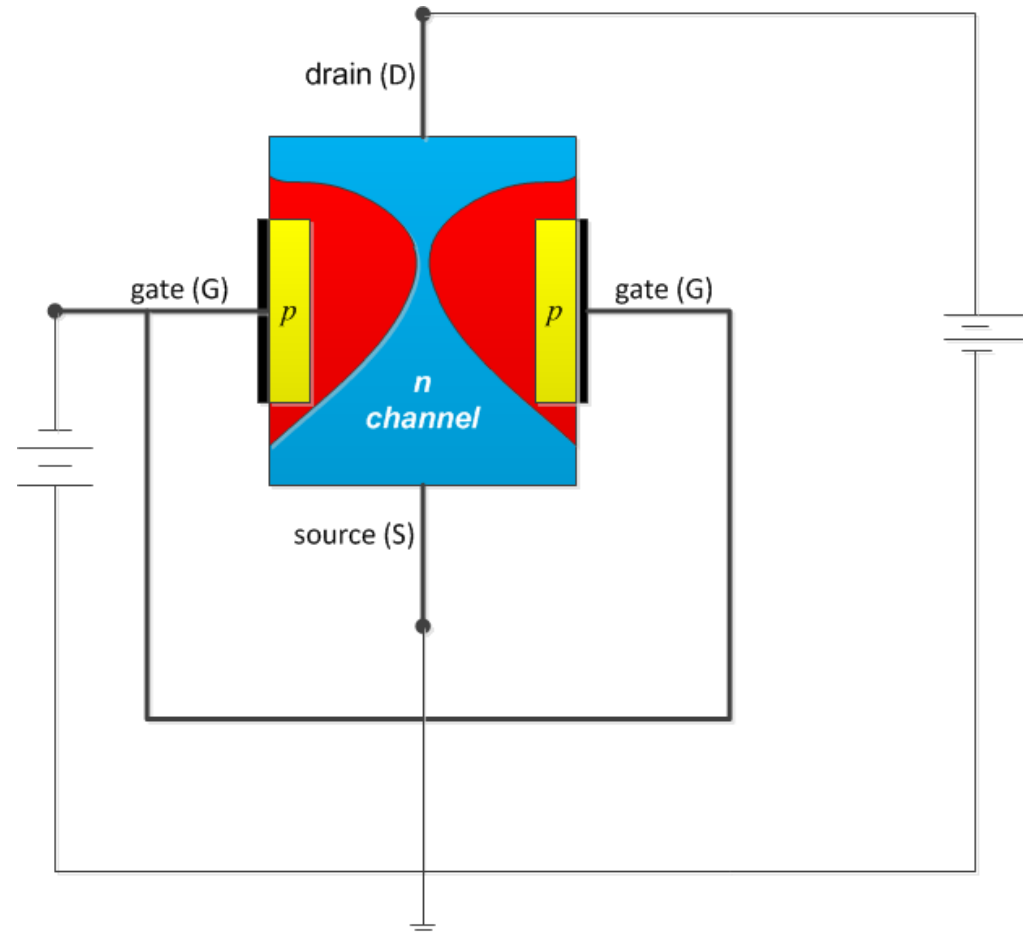
JFET

❑ For $v_{DS} > $ -V$_p$, channel is still pinched off (very narrow), then the drain current will remain constant for $v_{DS} \geq $ -V$_p$, and drain current is said to saturate.

The plot for i_D vss v_{DS} is shown

❑ For v_{GS}=0. The value of constant

saturation current is I_{DSS}, it can

range from tenths of mA to

hundred of mA.

❑ pn junction will breakdown if large

Reverse voltage is applied.

JFET
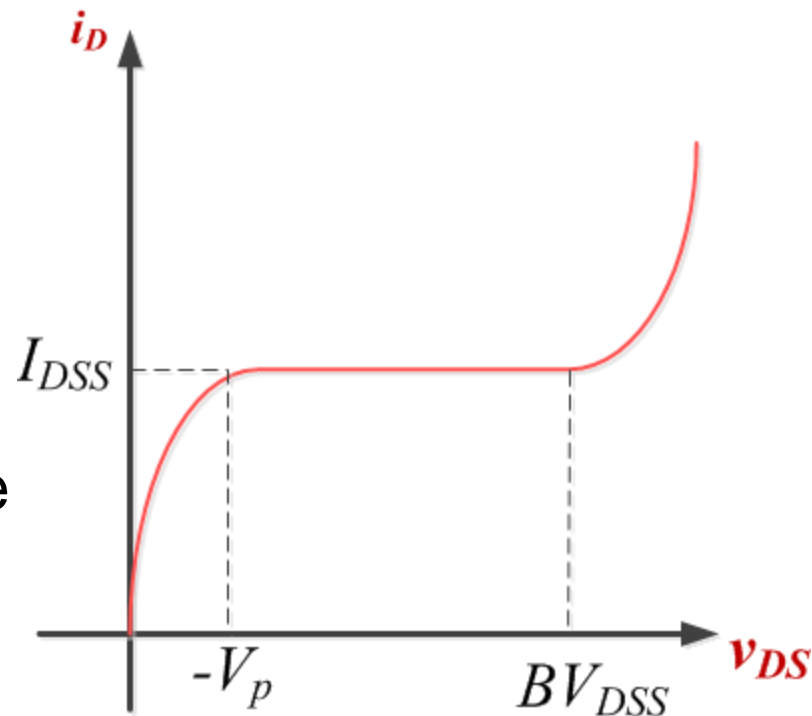
Pinch off can be reached in two ways

1. When $v_{GS} = 0\ V$, the channel is pinched off for $v_{GD} = -v_{DS} = Vp$ or $v_{DS} = -Vp$.

2. When $V_{GG} > 0$ or $v_{GS} < 0$, the channel is pinched off, when $v_{GD} = v_{GS} - v_{DS} = Vp$ or $v_{DS} = v_{GS} - Vp$

❑ Thus by decreasing vGS, the value of vDS required to pinch off the channel decreases.

JFET (Drain characteristics)

I_{DSS}= 12mA and pinch off voltage is $Vp= -3V$.

If $v_{GS}=0$ V, channel pinchoff when $v_{DS=}$-$Vp=3V$

If $v_{GS}=-1V$, channel pinchoff at

$v_{DS} = v_{GS} - Vp = -1+3=2V$
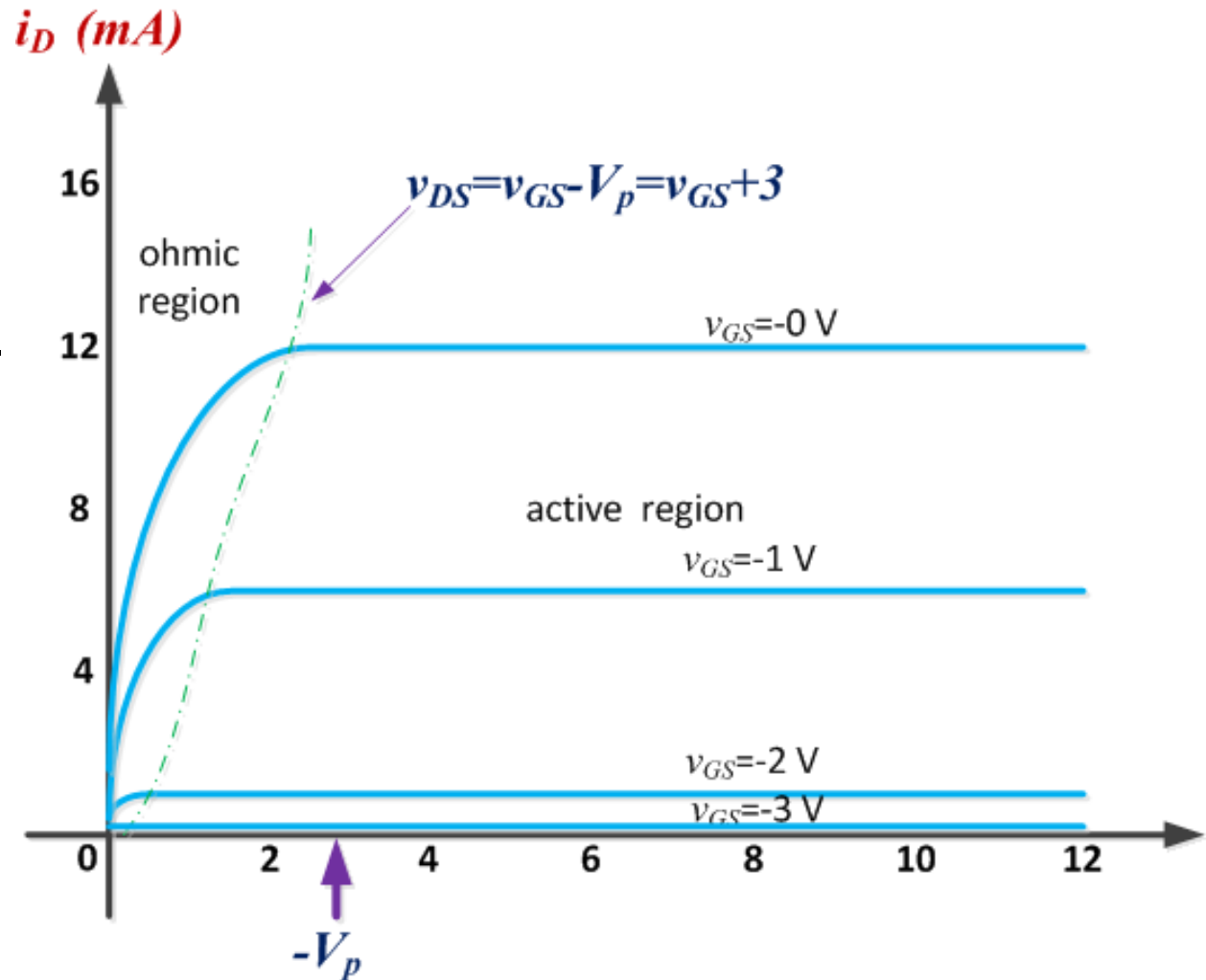
JFET (Drain characteristics)

The dashed curve is corresponding to $v_{DS} = v_{GS} - Vp$

To the right of this curve , ($v_{DS} > v_{GS} - Vp$), The channel is pinched off and this region is called as pinch off region or saturation region. (active region).

To the left of this curve, ($v_{DS} < v_{GS} - Vp$), the *channel is not* pinched off and the region is called as ohmic region.

When the gate is sufficiently reverse biased , channel will be totally eliminated for $v_{GS} < Vp$, under this circumstances increasing v_{DS}, will not be sufficient to produce a drain current. $i_D = 0$ and JFET is said to be in cutoff.

JFET (Equations)

When the JFET is in the ohmic region, drain current iD is given by

$$i_D = I_{DSS}\left[2\left(1-\frac{v_{GS}}{V_p}\right)\frac{v_{DS}}{-V_p}-\left(\frac{v_{DS}}{V_p}\right)^2\right]$$

For a small value of vDS, we have –Vp >> vDS, so $\left(\frac{v_{DS}}{V_p}\right)^2$ is small , thus

$$i_D = I_{DSS}\left[2\left(1-\frac{v_{GS}}{V_p}\right)\frac{v_{DS}}{-V_p}\right] = \frac{2I_{DSS}}{-V_p}\left(1-\frac{v_{GS}}{V_p}\right)v_{DS}$$

JFET (Equations)

From which we can write $\dfrac{i_D}{v_{DS}} \approx \dfrac{2I_{DSS}}{-V_p}\left(1 - \dfrac{v_{GS}}{V_p}\right) = \dfrac{2I_{DSS}(v_{GS} - V_p)}{V_p^2}$

Thus for a small v_{DS}, channel behaves as a linear resistor r_{DS} and is given by

$$r_{DS} = \frac{v_{DS}}{i_D} \approx \frac{V_p^2}{2I_{DSS}(v_{GS} - V_p)}$$

When the JFET is in the active region, drain current is

$$i_D = I_{DSS}\left(1 - \frac{v_{GS}}{V_p}\right)^2$$

MOSFET
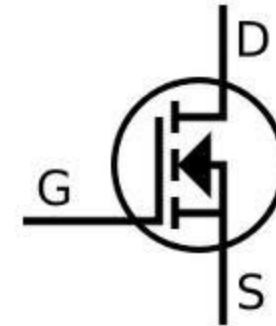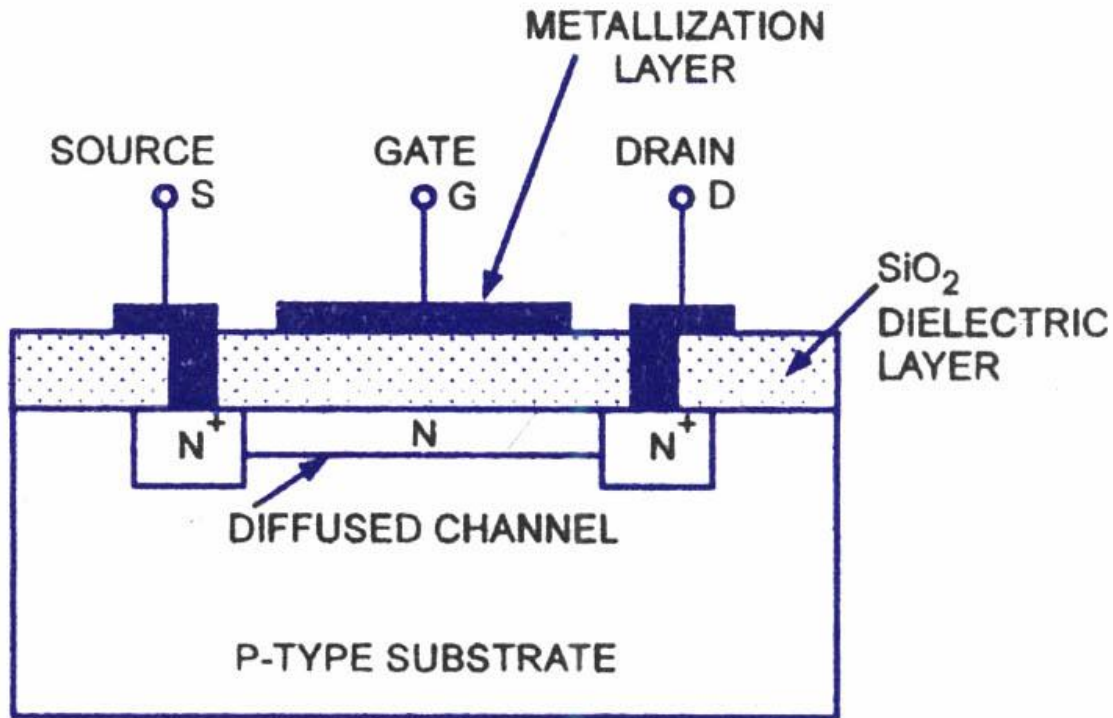
N-Channel DE-MOSFET Structure

MOSFET

- The resistance between reverse biased gate and source is typically in megaohms.

- For MOSFET, because of the insulation between gate and the substrate , the resistance between the gate and source is extremely high (in 10^{10} to 10^{15})

- If v_{GS} is made negative, the positive charges are induced on the n channel, there by effectively narrowing it.

- For varying value of vDS , the behavior of the device is similar to the JFET.

- Since it operates in the depletion mode, it is called as depletion MOSFET.

MOSFET
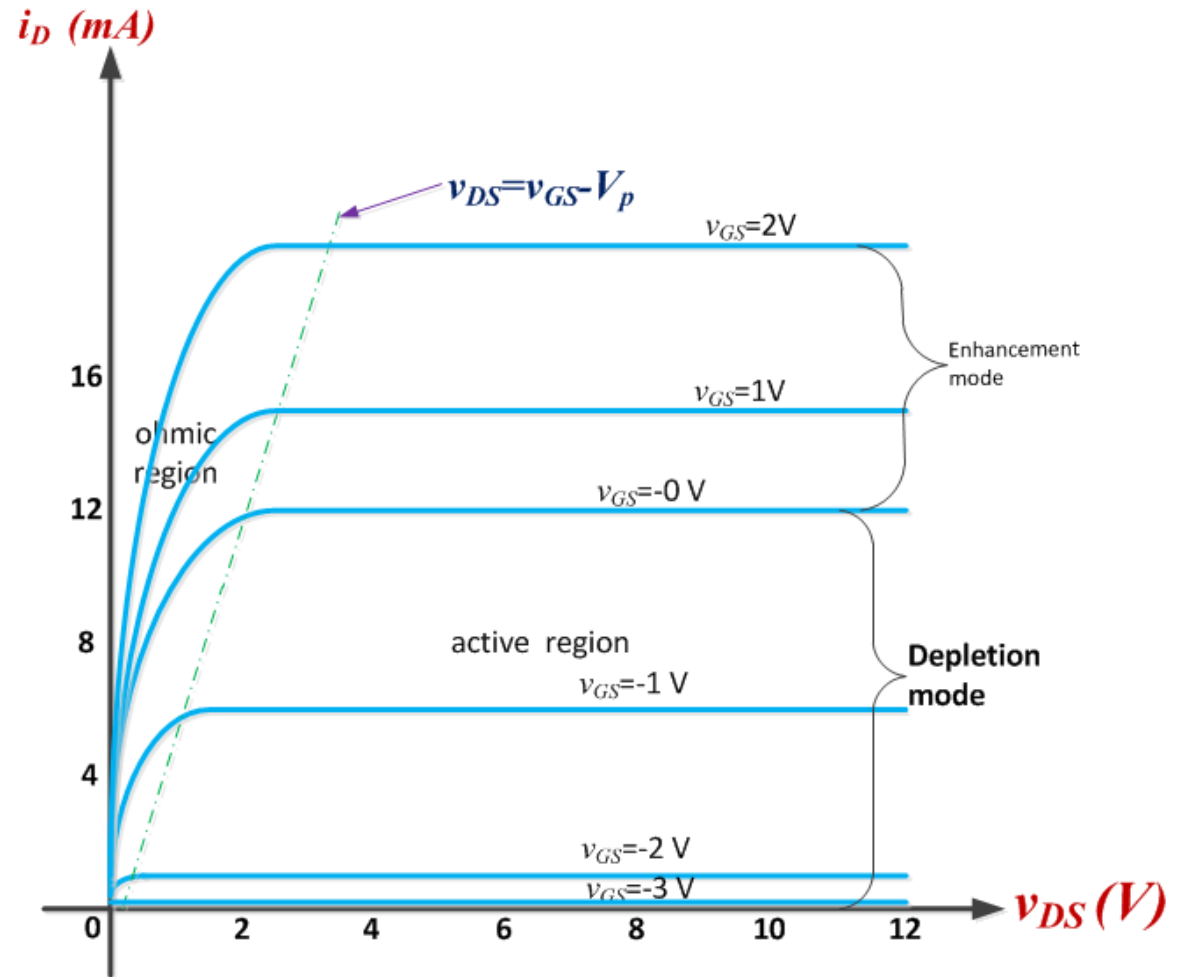
MOSFET

Given that I_{DSS}=8mA and V_p=-2V. Find v_{GS}, i_D, v_{DS}.

By inspecting the circuit , vGS=1V. Assume that MOSFET is in active region, then

$$i_D = I_{DSS}\left(1 - \frac{v_{GS}}{V_P}\right)^2 = 18mA$$

$$v_{DS} = -500\,(18\text{x}10^{-3}) + 16 = 7V$$

Since v_{DS} = 7 > v_{GS}-V_p= 1+2=3V, then the MOSFET is indeed in the active region

+16V

R_D=500Ω

i_D

+ V_{DS} -

+ V_{GS} -

1V
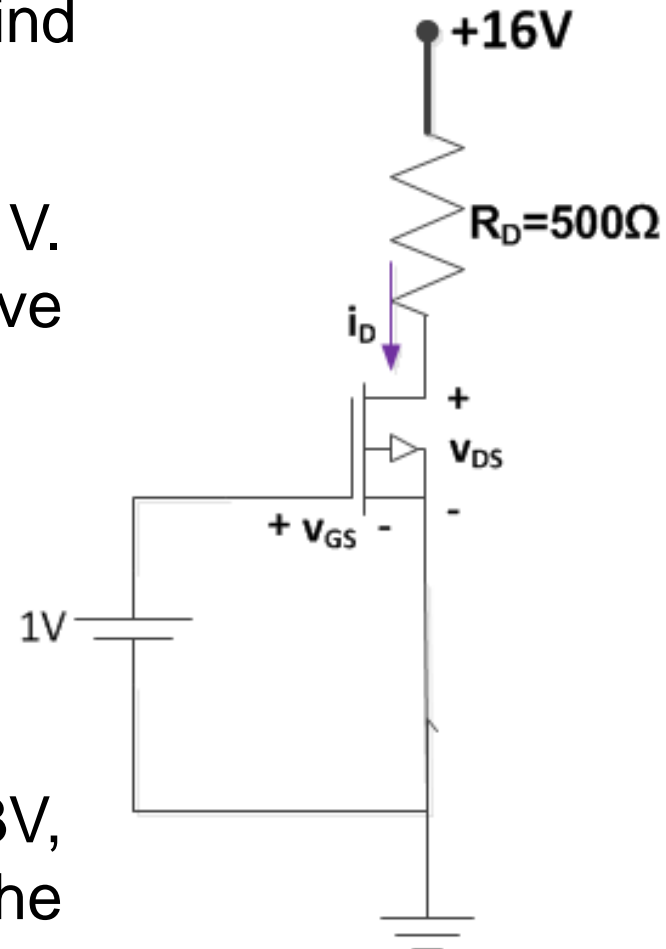
Notes on Operational Amplifiers (Op Amps).

Comments. The name *Op Amp* comes from "*op*erational *amp*lifier."

Op Amp Golden Rules (memorize these rules)

1) The op amp has infinite open-loop gain.
2) The input impedance of the +/− inputs is infinite. (The inputs are ideal voltmeters). The output impedance is zero. (The output is an ideal voltage source.)
3) No current flows into the +/− inputs of the op amp. This is really a restatement of golden rule **2**.
4) In a circuit with negative feedback, the output of the op amp will try to adjust its output so that the voltage difference between the + and − inputs is zero ($V_+ = V_-$).

IDEAL OP AMP BEHAVOIR.

The relationship between the input ant the output of an ideal op amp (assumptions: infinite open loop gain, unlimited voltage).

$$\text{for } V_+ - V_- > 0 : \quad V_{out} \to +\infty$$

$$\text{for } V_+ - V_- < 0 : \quad V_{out} \to -\infty$$

$$\text{for } V_+ - V_- = 0 : \quad V_{out} = 0$$

Op Amp Schematic Symbol (The upper input is usually the inverting input. Occasionally it is drawn with the non-inverting input on top when it makes the schematic easier to read. The position of the inputs may vary within the same schematic, so always look closely at the schematic!)
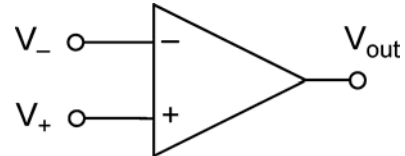
Negative Feedback. Most of the basic op amp building blocks rely on negative feedback. You can easily identify the type of feedback used by the op amp circuit. For negative feedback, the output is connected to the inverting input (− input). For positive feedback, the output is connected to the non-inverting input (+ input).

The Input Impedance of the Circuit is defined as the rate of change of V_{in} with respect to a change of I_{in}. This is simply the derivative $\dfrac{dV_{in}}{dI_{in}}$. The input impedance of the *circuit* is not in general the same as the impedance of the op amps inputs.

The Output Impedance of the Circuit, for the examples shown here, is the output impedance of the op amp. Output impedance is defined as the rate of change of V_{out} with respect to a change of I_{out}. This is simply the derivative $\dfrac{dV_{out}}{dI_{out}}$. For the ideal op amp, the output impedance is zero.

Basic Op Amp Building Blocks

Inverting Amplifier
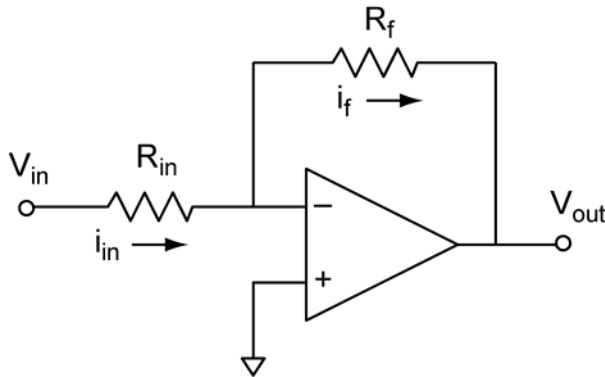
$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

$$A_V = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$$

$$\frac{dV_{in}}{dI_{in}} = R_{in}$$

Analysis of the inverting amplifier starts with our op amp golden rules. From rule #4 we know that $V_- = V_+$ and that $V_- = 0$ because V_+ is connected to ground. From rule #3 we know that $I_{in} = I_f$ because no current flows into the inverting input.

$$V_- = V_+ \qquad V_+ = 0 \qquad I_{in} = I_f = I$$

Then we can find the relationship between V_{in} and V_{out} using Ohm's law (OL) and Kirchhoff's voltage law (KVL).

$$V_{in} - V_- = I_{in} R_{in} \qquad V_{in} - 0 = IR_{in} \qquad V_{in} = IR_{in} \qquad I = \frac{V_{in}}{R_{in}}$$

$$V_- - V_{out} = I_f R_f \qquad 0 - V_{out} = IR_f \qquad V_{out} = -IR_f$$

$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

The voltage gain A_V is the derivative of V_{out} with respect to V_{in}. When the amplifier has only one input and $V_{out} = 0$ when $V_{in} = 0$, we will make the assumption that $A_V = V_{out}/V_{in}$.

$$A_v = \frac{V_{out}}{V_{in}} = \frac{-IR_f}{IR_{in}} = -\frac{R_f}{R_{in}}$$

Alternatively we could have started our analysis from the voltage divider formed by R_f and R_{in}. The voltage divider will relate the voltage at V_- with V_{out} and V_{in}. In this case The total voltage across the divider is $V_{out} - V_{in}$. Because the bottom end of the divider is not connected to ground, we must add the extra V_{in} term to offset V_-. We arrive at the same result.
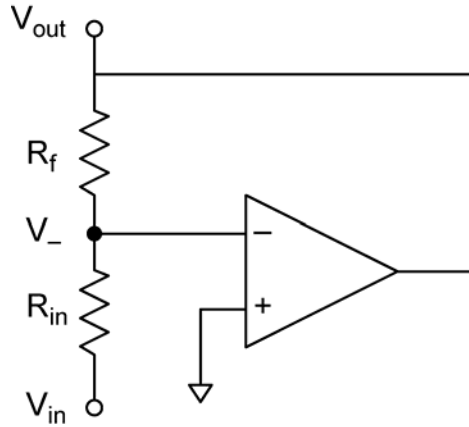
$$V_- = \left(V_{out} - V_{in}\right)\left(\frac{R_{in}}{R_{in} + R_f}\right) + V_{in} = 0$$

$$V_{out}\left(\frac{R_{in}}{R_{in} + R_f}\right) = V_{in}\left(\frac{R_{in}}{R_{in} + R_f}\right) - V_{in}$$

$$V_{out}\left(\frac{R_{in}}{R_{in} + R_f}\right)\left(\frac{R_{in} + R_f}{R_{in}}\right) = V_{in}\left(\frac{R_{in}}{R_{in} + R_f}\right)\left(\frac{R_{in} + R_f}{R_{in}}\right) - V_{in}\left(\frac{R_{in} + R_f}{R_{in}}\right)$$

$$V_{out} = V_{in} - V_{in}\left(\frac{R_{in} + R_f}{R_{in}}\right) = V_{in}\left(1 - \frac{R_{in} + R_f}{R_{in}}\right) = -\frac{R_f}{R_{in}}V_{in}$$

$$V_{out} = -\frac{R_f}{R_{in}}V_{in}$$

The input impedance of the inverting amplifier is determined by R_{in}. Note that V_- is held at the same voltage as V_+ by the op amp feedback. Because V_+ is connected to ground, the input impedance is just R_{in}.

Non-inverting Amplifier
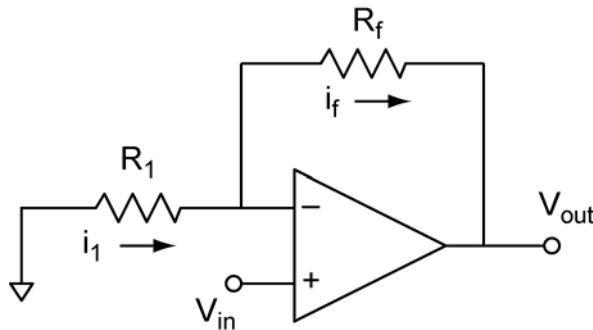
$$V_{out} = \left(1 + \frac{R_f}{R_{in}}\right)V_{in}$$

$$A_V = \frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_{in}}$$

$$\frac{dV_{in}}{dI_{in}} \to \infty$$

Analysis of the non-inverting amplifier starts with our op amp golden rules. From rule #4 we know that $V_- = V_+$ and that $V_- = V_{in}$ because V_+ is connected to V_{in}. From rule #3 we know that $I_{in} = I_f$ because no current flows into the inverting input.

$$V_- = V_+ \qquad V_+ = V_{in} \qquad I_{in} = I_f = I$$

Then we can find the relationship between V_{in} and V_{out} using Ohm's law (OL) and Kirchhoff's voltage law (KVL).

$$-V_- = I_1 R_1 \qquad\qquad -V_{in} = I R_1 \qquad\qquad I = -\frac{V_{in}}{R_1}$$

$$V_- - V_{out} = I_f R_f \qquad V_{in} - V_{out} = I R_f \qquad V_{out} = V_{in} - I R_f$$

$$V_{out} = V_{in} - \left(-\frac{V_{in}}{R_1} \right) R_f = V_{in}\left(1 + \frac{R_f}{R_{in}} \right)$$

The voltage gain A_V is the derivative of V_{out} with respect to V_{in}. When the amplifier has only one input and $V_{out} = 0$ when $V_{in} = 0$, we will make the assumption that $A_V = V_{out}/V_{in}$.

$$A_v = \frac{V_{out}}{V_{in}} = \left(1 + \frac{R_f}{R_{in}} \right)$$

Alternatively we could have started out analysis from the voltage divider formed by R_f and R_{in}. The voltage divider will relate the voltage at V_- with V_{out} and V_{in}. In this case The total voltage across the divider is V_{out} and the we know that $V_- = V_{in}$. We arrive at the same result.
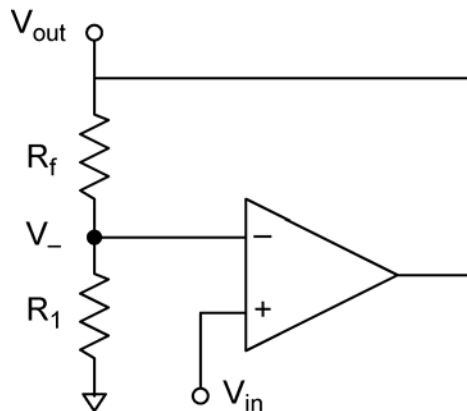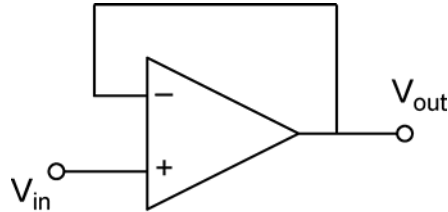

$$V_- = V_{out}\left(\frac{R_1}{R_1 + R_f} \right) = V_{in}$$

$$V_{out}\left(\frac{R_1}{R_1 + R_f} \right)\left(\frac{R_1 + R_f}{R_1} \right) = V_{in}\left(\frac{R_1 + R_f}{R_1} \right) = V_{in}\left(1 + \frac{R_f}{R_1} \right)$$

$$V_{out} = V_{in}\left(1 + \frac{R_f}{R_1} \right)$$

The input impedance of the follower is the input impedance of the op amps input. For an ideal op amp the input impedance is infinite.

Voltage Follower

$$V_{out} = V_{in}$$

$$A_V = \frac{V_{out}}{V_{in}} = 1$$

$$\frac{dV_{in}}{dI_{in}} \to \infty$$

This is a special case of the non-inverting amplifier with $R_{in} \to \infty$ and $R_f = 0$. The follower has a very high input impedance. Voltage follower has application when the source voltage can not supply very much current, a pH meter for example.

Current-to-Voltage Converter (AKA, I-V Converter, Transimpedance Amplifier).
This circuit takes an input current and converts it to an output voltage. The input impedance of the ideal current to voltage converter is zero (the ideal current meter).
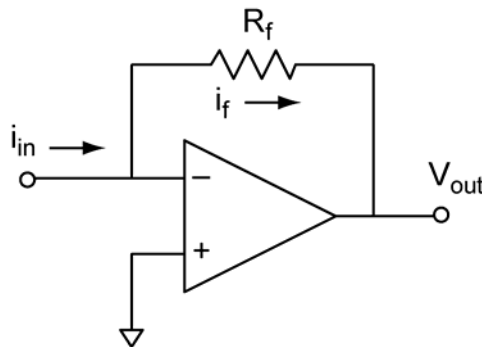
$$V_{out} = -R_f I_{in}$$

$$A_Z = \frac{V_{out}}{I_{in}} = -R_f$$

$$\frac{dV_{in}}{dI_{in}} = 0$$

Analysis of the current-to-voltage converter starts with our op amp golden rules. From rule #4 we know that $V_- = V_+$ and that $V_- = 0$ because V_+ is connected to ground. From rule #3 we know that $I_{in} = I_f$ because no current flows into the inverting input.

$$V_- = V_+ \qquad V_+ = 0 \qquad I_{in} = I_f = I$$

Then we can find the relationship between V_{in} and V_{out} using Ohm's law (OL) and Kirchhoff's voltage law (KVL).

$$I_{in} = I_f$$

$$V_- - V_{out} = I_f R_f \qquad 0 - V_{out} = I_f R_f \qquad V_{out} = -I_f R_f$$

$$V_{out} = -I_f R_f = -I_{in} R_f$$

The current-to-voltage converter has transimpedance gain. Transimpedance gain is not unitless, it has units of impedance (Ohms). The transimpedance gain A_Z is the derivative

of V_{out} with respect to I_{in}. When the amplifier has only one input and $V_{out} = 0$ when $I_{in} = 0$, we will make the assumption that $A_V = V_{out}/I_{in}$.

$$A_Z = \frac{V_{out}}{I_{in}} = \frac{-I_{in}R_f}{I_{in}} = -R_f$$

Summing Amplifier. This circuit will add (and subtract) the input voltages. Subtraction is accomplished by inverting the voltages before adding them. Note that summing can only occur for inputs to the inverting side of the op amp. This is because of the V_- node is a current summing junction where the input currents sum to the feedback current.
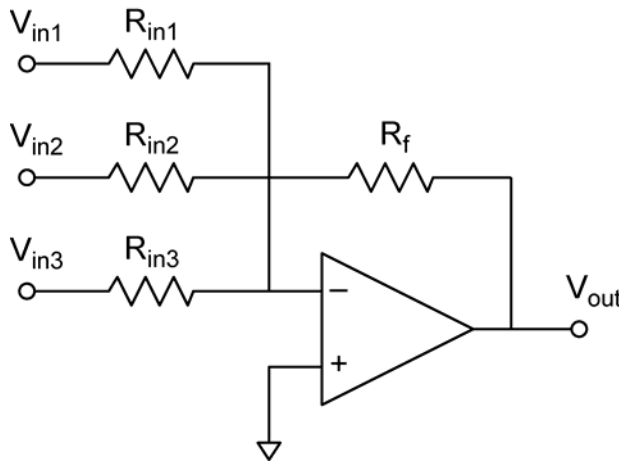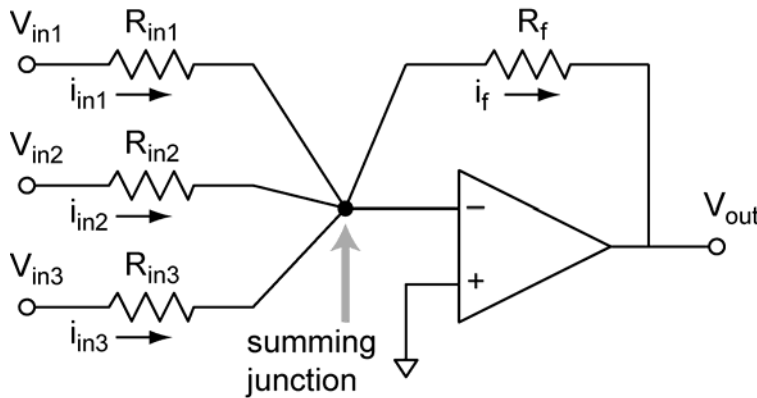

$$V_{out} = A_{V1}V_{in1} + A_{V2}V_{in2} + A_{V3}V_{in3} + \cdots$$

$$\text{the gain of the } n\text{th input}: \ A_{Vn} = \frac{dV_{out}}{dV_{inn}} = -\frac{R_f}{R_{inn}}$$

$$\text{the impedance of the } n\text{th input}: \ Z_{inn} = \frac{dV_{inn}}{dI_{inn}} = R_{inn}$$

This is another look at the summing amplifier that emphases the summing junction.

Analysis of the summing amplifier starts with our op amp golden rules. From rule #4 we know that $V_- = V_+$ and that $V_- = 0$ because V_+ is connected to ground. From rule #3 we know that $\sum I_{inn} = I_f$ because no current flows into the inverting input. (I_{inn} is the current of the nth input.)

$$V_- = V_+ \qquad V_+ = 0 \qquad \sum I_{inn} = I_{in1} + I_{in2} + I_{in3} = I_f$$

Then we can find the relationship between V_{in} and V_{out} using Ohm's law (OL) and Kirchhoff's voltage law (KVL).

$$V_{inn} - V_- = I_{inn} R_{inn} \qquad V_{inn} - 0 = I R_{inn} \qquad V_{inn} = I_{inn} R_{inn} \qquad I_{inn} = \frac{V_{inn}}{R_{inn}}$$

$$V_- - V_{out} = I_f R_f \qquad 0 - V_{out} = I R_f \qquad V_{out} = -I_f R_f$$

$$V_{out} = -I_f R_f = -R_f \left(I_{in1} + I_{in2} + I_{in3} \right) = -R_f \left(\frac{V_{in1}}{R_{in1}} + \frac{V_{in2}}{R_{in2}} + \frac{V_{in3}}{R_{in3}} \right) = -\frac{R_f}{R_{in1}} V_{in1} - \frac{R_f}{R_{in2}} V_{in2} - \frac{R_f}{R_{in3}} V_{in3}$$

$$V_{out} = -\frac{R_f}{R_{in1}} V_{in1} - \frac{R_f}{R_{in2}} V_{in2} - \frac{R_f}{R_{in3}} V_{in3}$$

The voltage gain A_V is the derivative of V_{out} with respect to V_{in}.

$$V_{out} = A_{V1} V_{in1} + A_{V2} V_{in2} + A_{V3} V_{in3} + \cdots$$

$$\text{the gain of the } n\text{th input}: \ A_{Vn} = \frac{d V_{out}}{d V_{inn}} = -\frac{R_f}{R_{inn}}$$

Differential Amplifier. The term *differential* is used in the sense of *difference*. Do not confuse the differential amplifier with the differentiator. One important application of the differential amplifier over comes the problem of grounding that you encountered in lab when using the oscilloscope to make measurements. The typical oscilloscope always performs voltage measurements with respect to is own ground. A differential amplifier used before the scope input could measure the V_{+in} with respect to V_{-in}. The ground of the differential amplifier would be connected to the ground of the scope for this application, so the V_{out} will be measured correctly.
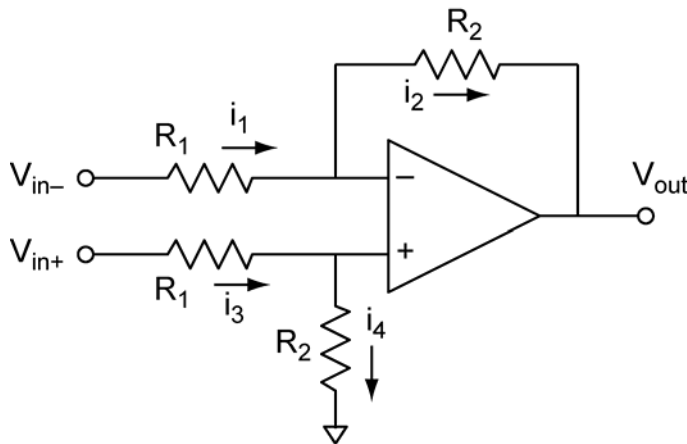
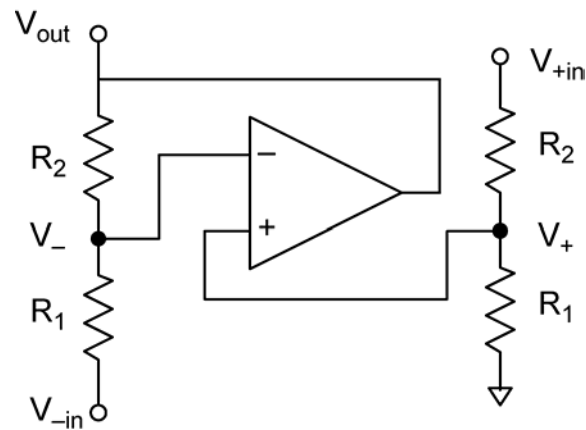$$V_{out} = \frac{R_2}{R_1} \left(V_{+in} - V_{-in} \right)$$

$$\text{the gain for } V_{+in}: \ A_{V+in} = \frac{d V_{out}}{d V_{+in}} = +\frac{R_2}{R_1}$$

$$\text{the gain for } V_{-in}: \ A_{V-in} = \frac{d V_{out}}{d V_{-in}} = -\frac{R_2}{R_1}$$

Analysis of the differential amplifier starts with our op amp golden rules. From rule #4 we know that $V_- = V_+$. From rule #3 we know that $I_1 = I_2$ and that $I_3 = I_4$ because no current flows into the inputs.

$$V_- = V_+ \qquad I_1 = I_2 \qquad I_3 = I_4$$

Then we can find the relationship between V_{+in}, V_{-in}, and V_{out} using the voltage divider equations. We recognize that $V_- = V_+$ and that V_+ will be the output of the voltage divider formed by the two resistors connected to the non-inverting input. The voltage at V_- is the output of the voltage divider formed by the two resistors connected to the inverting input.

$$V_- = \left(V_{out} - V_{-in}\right)\left(\frac{R_1}{R_1 + R_2}\right) + V_{-in} \qquad\qquad V_+ = V_{+in}\left(\frac{R_2}{R_1 + R_2}\right)$$

$$V_- = V_+$$

$$\left(V_{out} - V_{-in}\right)\left(\frac{R_1}{R_1 + R_2}\right) + V_{-in} = V_{+in}\left(\frac{R_2}{R_1 + R_2}\right)$$

$$V_{out}\left(\frac{R_1}{R_1 + R_2}\right) - V_{-in}\left(\frac{R_1}{R_1 + R_2}\right) + V_{-in} = V_{+in}\left(\frac{R_2}{R_1 + R_2}\right)$$

$$V_{out}\left(\frac{R_1}{R_1 + R_2}\right) = V_{+in}\left(\frac{R_2}{R_1 + R_2}\right) + V_{-in}\left(\frac{R_1}{R_1 + R_2}\right) - V_{-in}$$

$$V_{out}\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_1 + R_2}{R_1}\right) = V_{+in}\left(\frac{R_2}{R_1 + R_2}\right)\left(\frac{R_1 + R_2}{R_1}\right) + V_{-in}\left(\frac{R_1}{R_1 + R_2}\right)\left(\frac{R_1 + R_2}{R_1}\right) - V_{-in}\left(\frac{R_1 + R_2}{R_1}\right)$$

$$V_{out} = \left(\frac{R_2}{R_1}\right)V_{+in} - \left(\frac{R_2}{R_1}\right)V_{-in}$$

$$V_{out} = \frac{R_f}{R_{in}}\left(V_{+in} - V_{-in}\right)$$

The voltage gain A_V is the derivative of V_{out} with respect to each input V_{in}.

$$\text{the gain for } V_{+in} : \quad A_{V+in} = \frac{dV_{out}}{dV_{+in}} = +\frac{R_2}{R_1}$$

$$\text{the gain for } V_{-in} : \quad A_{V-in} = \frac{dV_{out}}{dV_{-in}} = -\frac{R_2}{R_1}$$

The inverting amplifier with generalized impedances. The results derived above can be extended to general impedances. Note that Z_f and Z_{in} can be the impedance of any network. The following are examples of the inverting amplifier, but ANY of the previous examples can be generalized in this way.
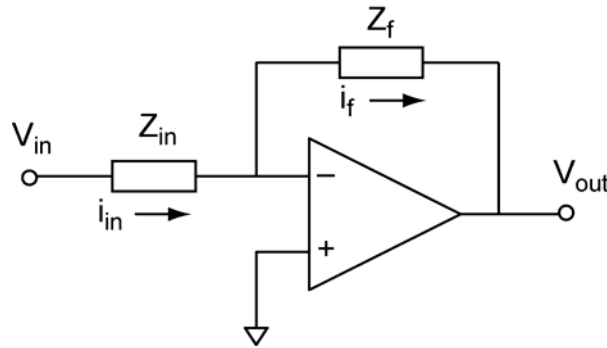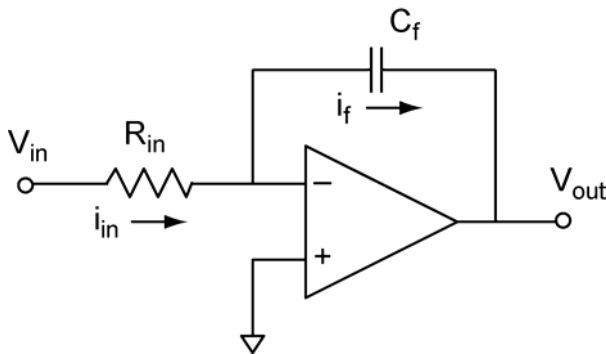

$$V_{out} = -\frac{Z_f}{Z_{in}} V_{in}$$

$$A_V = \frac{V_{out}}{V_{in}} = -\frac{Z_f}{Z_{in}}$$

$$\frac{dV_{in}}{dI_{in}} = Z_{in}$$

Integrator. A capacitor as the feedback impedance.

$$V_{out}(\omega) = \frac{j}{\omega R_{in} C_f} V_{in}(\omega)$$

$$\left| V_{out}(\omega) \right| = \frac{1}{\omega R_{in} C_f} V_{in}(\omega)$$

$$V_{out}(t) = -\frac{1}{R_{in} C_f} \int V_{in}(t)\, dt$$

$$A_V(\omega) = \frac{V_{out}}{V_{in}} = \frac{j}{\omega R_{in} C_f}$$

$$\left| A_V(\omega) \right| = \left| \frac{V_{out}}{V_{in}} \right| = \frac{1}{\omega R_{in} C_f}$$

$$\frac{dV_{in}}{dI_{in}} = R_{in}$$

Analysis of the integrator in the frequency domain is a simple extension of our generalized result for the inverting amplifier.

$$Z_{in} = R_{in} \qquad Z_f = \frac{1}{j\omega C_f} \qquad V_{out} = -\frac{Z_f}{Z_{in}}$$

$$V_{out} = -\frac{Z_f}{Z_{in}}V_{in} = -\frac{\frac{1}{j\omega C_f}}{R_{in}}V_{in} = -\frac{1}{j\omega R_{in}C_f}V_{in} = \frac{j}{\omega R_{in}C_f}V_{in}$$

$$A_V = \frac{V_{out}}{V_{in}} = \frac{j}{\omega R_{in}C_f}$$

$$|A_V| = \left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{\omega R_{in}C_f}$$

Time Domain Analysis of the Integrator starts with our op amp golden rules. From rule #4 we know that $V_- = V_+$ and that $V_- = 0$ because V_+ is connected to ground. From rule #3 we know that $I_{in} = I_f$ because no current flows into the inverting input.

$$V_- = V_+ \qquad V_+ = 0 \qquad I_{in} = I_f = I$$

Then we can find the relationship between V_{in} and V_{out} using Ohm's law (OL) and Kirchhoff's voltage law (KVL).
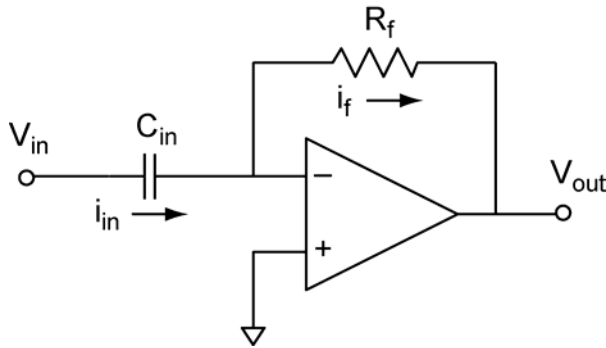
$$V_{in} - V_- = I_{in}R_{in} \qquad V_{in} - 0 = IR_{in} \qquad V_{in} = IR_{in} \qquad I = \frac{V_{in}}{R_{in}}$$

$$\frac{d}{dt}(V_- - V_{out}) = \frac{I_f}{C_f} \qquad \frac{d}{dt}(0 - V_{out}) = \frac{I}{C_f} \qquad \frac{d}{dt}V_{out} = -\frac{I}{C_f} \qquad V_{out} = -\frac{1}{C_f}\int I\,dt$$

$$V_{out} = -\frac{1}{C_f}\int I\,dt = -\frac{1}{C_f}\int \frac{V_{in}}{R_{in}}\,dt = -\frac{1}{R_{in}C_f}\int V_{in}\,dt$$

$$V_{out} = -\frac{1}{R_{in}C_f}\int V_{in}\,dt$$

Differentiator. A capacitor as the input impedance.

$$V_{out}(\omega) = -j\omega R_f C_{in} V_{in}(\omega)$$

$$\left|V_{out}(\omega)\right| = -\omega R_f C_{in} V_{in}(\omega)$$

$$V_{out}(t) = -R_f C_{in} \frac{dV_{in}(t)}{dt}$$

$$A_V(\omega) = \frac{V_{out}}{V_{in}} = -j\omega R_f C_{in}$$

$$\left|A_V(\omega)\right| = \left|\frac{V_{out}}{V_{in}}\right| = -\omega R_f C_{in}$$

Analysis of the differentiator in the frequency domain is a simple extension of our generalized result for the inverting amplifier.

$$\frac{dV_{in}}{dI_{in}} = \frac{1}{j\omega C_{in}}$$

$$Z_{in} = \frac{1}{j\omega C_{in}} \qquad Z_f = R_f \qquad V_{out} = -\frac{Z_f}{Z_{in}}$$

$$V_{out} = -\frac{Z_f}{Z_{in}}V_{in} = -\frac{R_f}{\dfrac{1}{j\omega C_{in}}}V_{in} = -j\omega R_f C_{in} V_{in}$$

$$\left|V_{out}\right| = \omega R_f C_{in} V_{in}$$

$$A_V = \frac{V_{out}}{V_{in}} = -j\omega R_f C_{in}$$

$$\left|A_V\right| = \left|\frac{V_{out}}{V_{in}}\right| = \omega R_f C_{in}$$

Time Domain Analysis of the Differentiator starts with our op amp golden rules. From rule #4 we know that $V_- = V_+$ and that $V_- = 0$ because V_+ is connected to ground. From rule #3 we know that $I_{in} = I_f$ because no current flows into the inverting input.

$$V_- = V_+ \qquad V_+ = 0 \qquad I_{in} = I_f = I$$

Then we can find the relationship between V_{in} and V_{out} using Ohm's law (OL) and Kirchhoff's voltage law (KVL).

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(V_{in} - V_{-}\right) = \frac{I_{in}}{C_{in}} \qquad \frac{\mathrm{d}}{\mathrm{d}t}V_{in} = \frac{I}{C_{in}} \qquad C_{in}\frac{\mathrm{d}}{\mathrm{d}t}V_{in} = I$$

$$V_{-} - V_{out} = I_f R_f \qquad 0 - V_{out} = IR_f \qquad V_{out} = -IR_f$$

$$V_{out} = -\left(C_{in}\frac{\mathrm{d}}{\mathrm{d}t}V_{out}\right)R_f = -R_f C_{in}\frac{\mathrm{d}}{\mathrm{d}t}V_{in}$$

$$V_{out} = -R_f C_{in}\frac{\mathrm{d}}{\mathrm{d}t}V_{in}$$

Bipolar Junction Transistor (BJT)

➢ Beside diodes, the most popular semiconductor devices is transistors. Eg: Bipolar Junction Transistor (BJT)

➢ Few most important applications of transistor are: as an amplifier as an oscillator and as a switch

➢ Amplification can make weak signal strong in general, provide function called *Gain*

➢ BJT is bipolar because both holes (+) and electrons (-) will take part in the current flow through the device
  – N-type regions contains free electrons (negative carriers)
  – P-type regions contains free holes (positive carriers)

Bipolar Junction Transistor (BJT)

npnTransistor
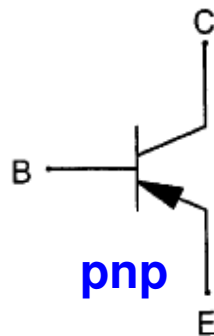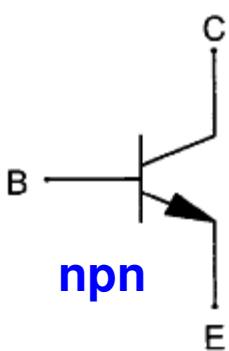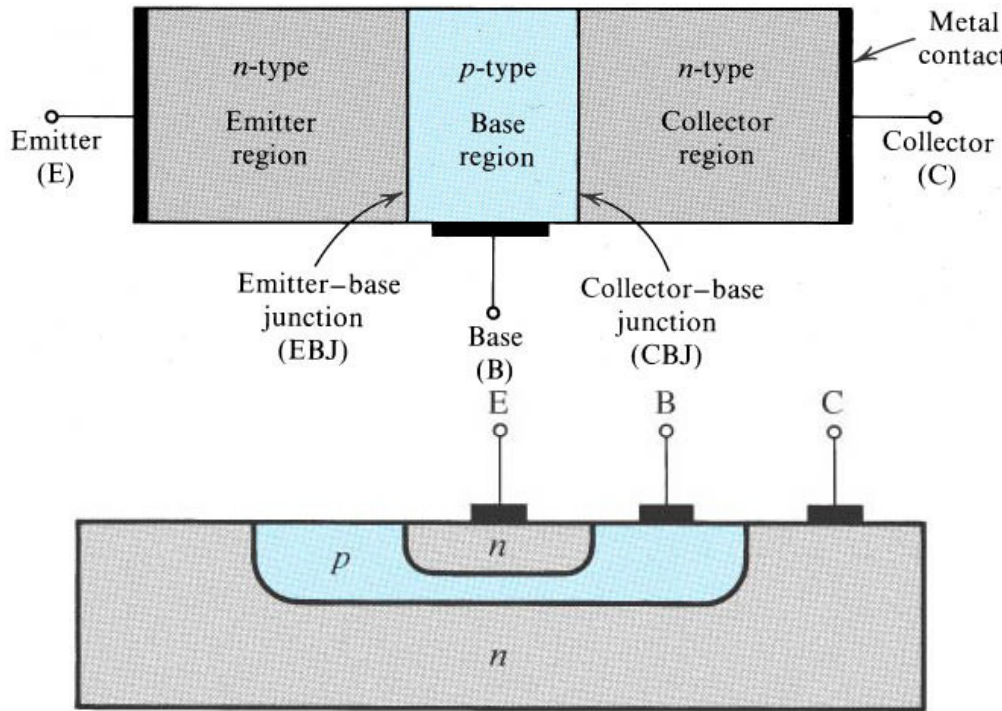
pnpTransistor
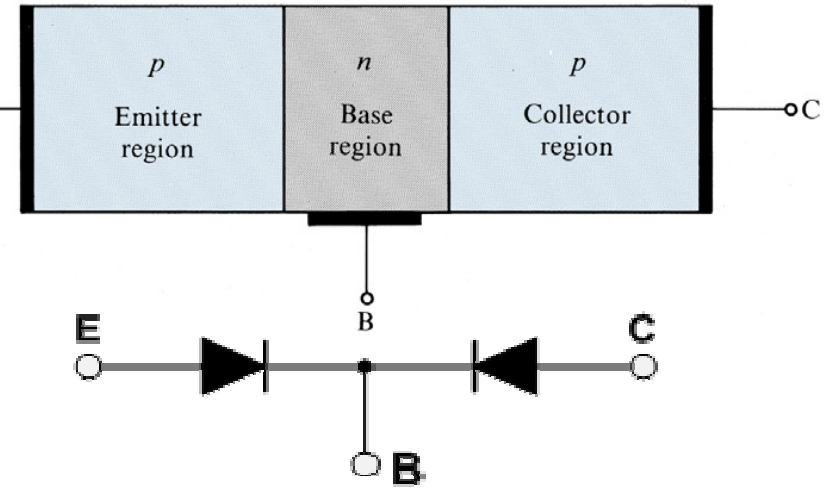
- ➢ BJT is a 3 terminal device. namely- emitter, base and collector

- ➢npn transistor: emitter & collector are n-doped and base is p-doped.

- ➢ Emitter is heavily doped, collector is moderately doped and base is lightly doped and base is very thin. i.e. $N_{DE} \gg N_{DC} \gg N_{AB}$
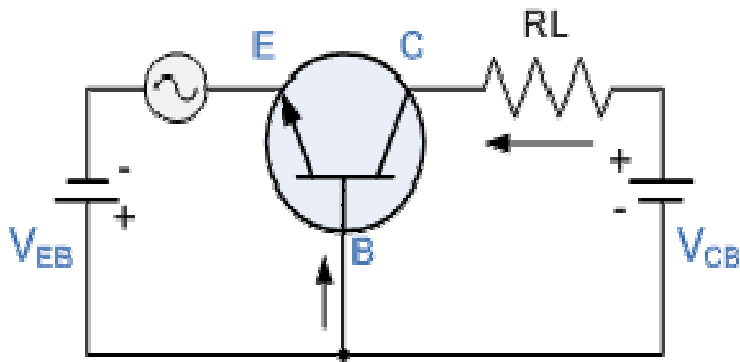
3

Mode of operation for BJT

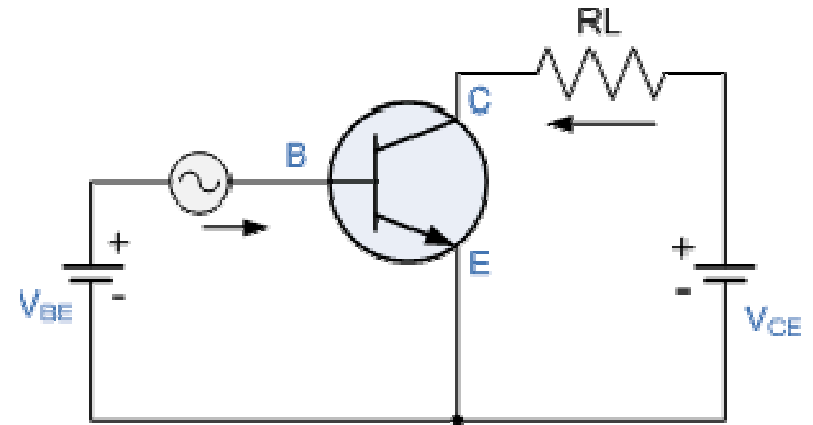| Mode	V_{BE}	V_{BC}
Forward active	Forward bias	Reverse Bias
Reverse active	Reverse Bias	Forward Bias
Saturation	Forward bias	Forward bias
Cut off	Reverse Bias	Reverse Bias

➢ Forward active region is widely used and Reverse active region is rarely used.

Different configuration of BJT
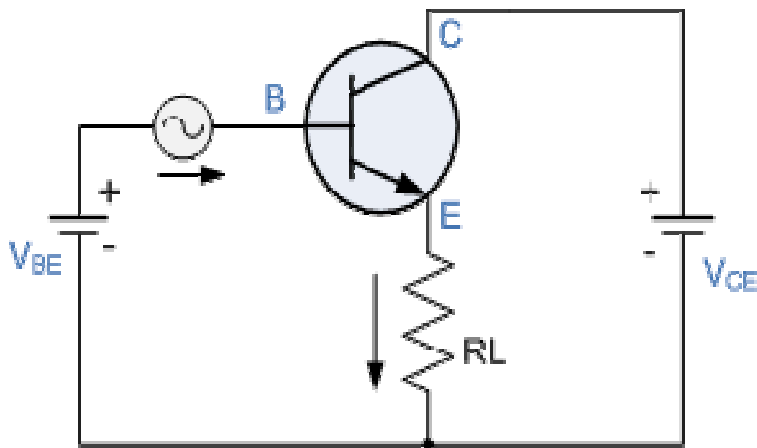
Common base configuration

Non-inverting voltage amplifier circuit

Common emitter configuration

Common collector configuration

This type of configuration is commonly known as a **Voltage Follower** or **Emitter Follower** circuit.

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Summary of BJT characteristics for different configuration

Characteristic	Common Base	Common Emitter	Common Collector
Input impedance	Low	Medium	High
Output impedance	Very High	High	Low
Phase Angle	0°	180°	0°
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

➤The CB mode is generally only used in single stage amplifier circuits such as microphone pre-amplifier or RF radio amplifiers due to its very good high frequency response.

➤ The Emitter follower configuration is very useful for impedance matching applications because of the very high input impedance, in the region of hundreds of thousands of Ohms, and it has relatively low output impedance.
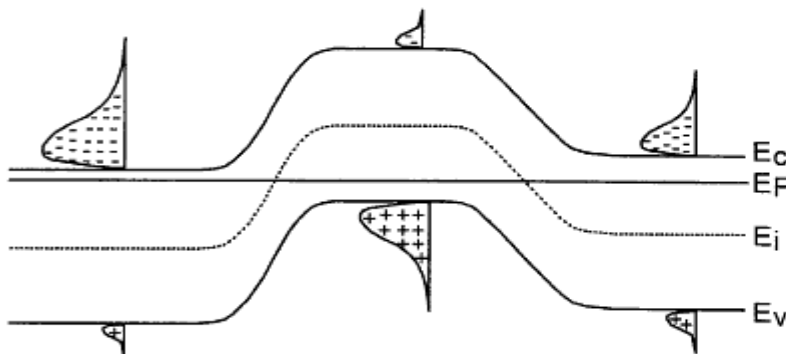
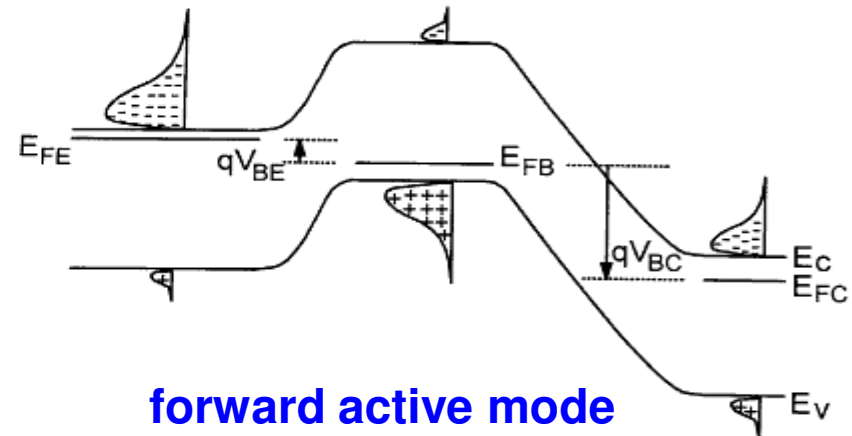# DC operation of npn BJT under forward active mode
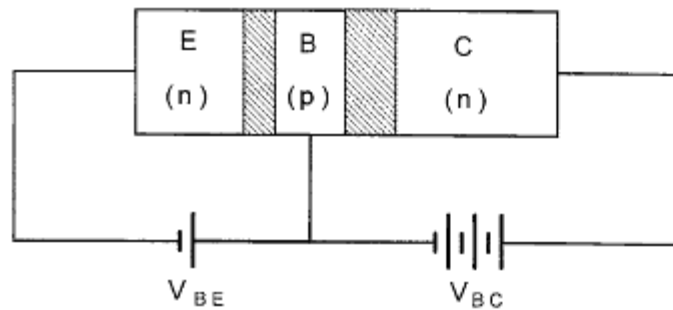
- For npn BJT in forward active mode:

$$V_{BE} > 0 \text{ and } V_{BC} < 0$$
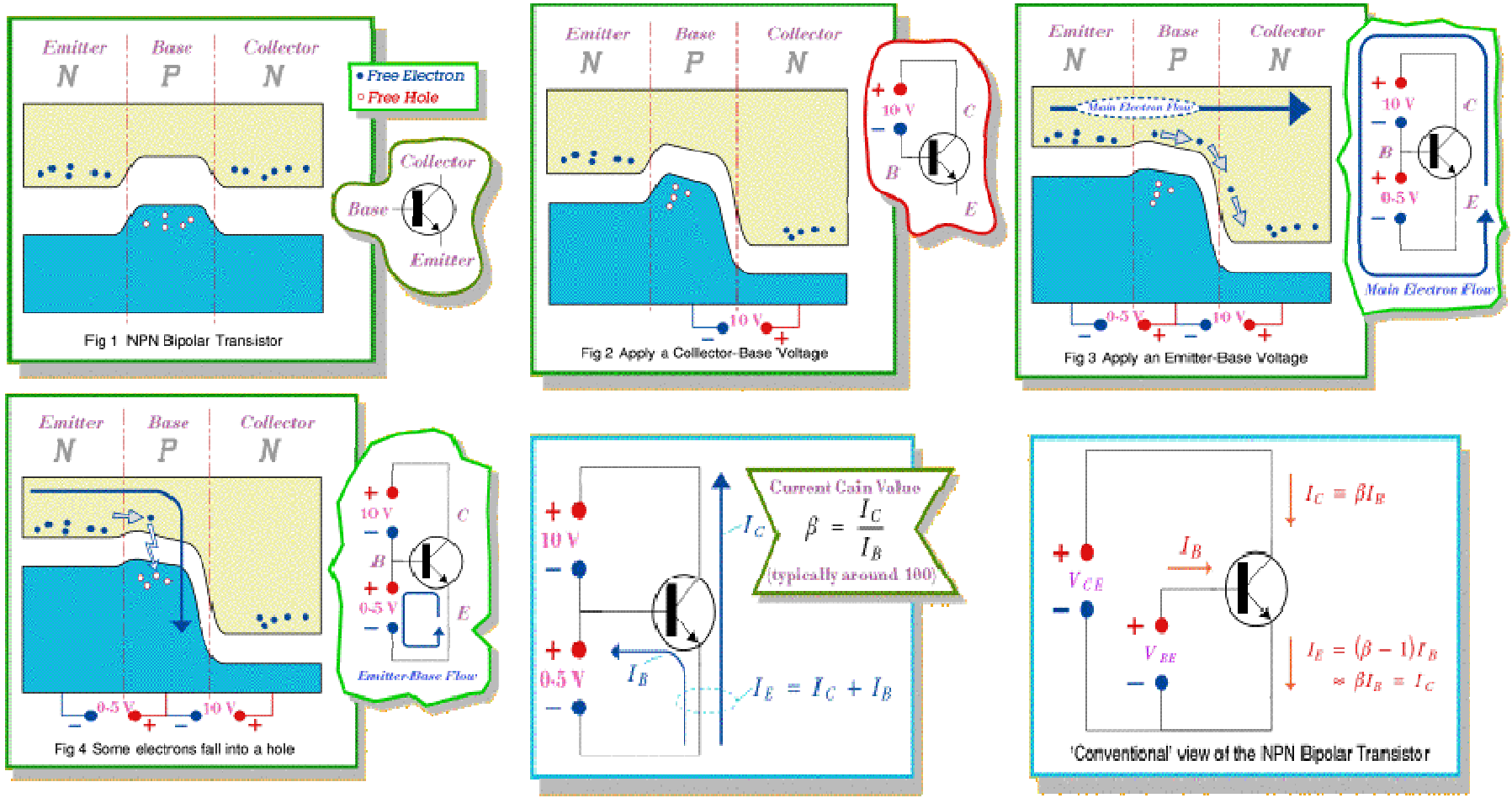
Energy band diagram for npn BJT

At equilibrium, $V_{BE} = V_{BC} = 0$

forward active mode

DC operation of npn BJT under forward active mode

Fig 1 NPN Bipolar Transistor

Fig 2 Apply a Collector-Base Voltage

Fig 3 Apply an Emitter-Base Voltage

Fig 4 Some electrons fall into a hole

$$\beta = \frac{I_C}{I_B}$$

(typically around 100)

$$I_E = I_C + I_B$$

$$I_C = \beta I_B$$

$$I_E = (\beta - 1) I_B$$
$$\approx \beta I_B = I_C$$

'Conventional' view of the NPN Bipolar Transistor

Reference: From L.C.G. Lesurf's (University of St. Andrews) The Scot's Guide to Electronics

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DC operation of npn BJT under forward active mode
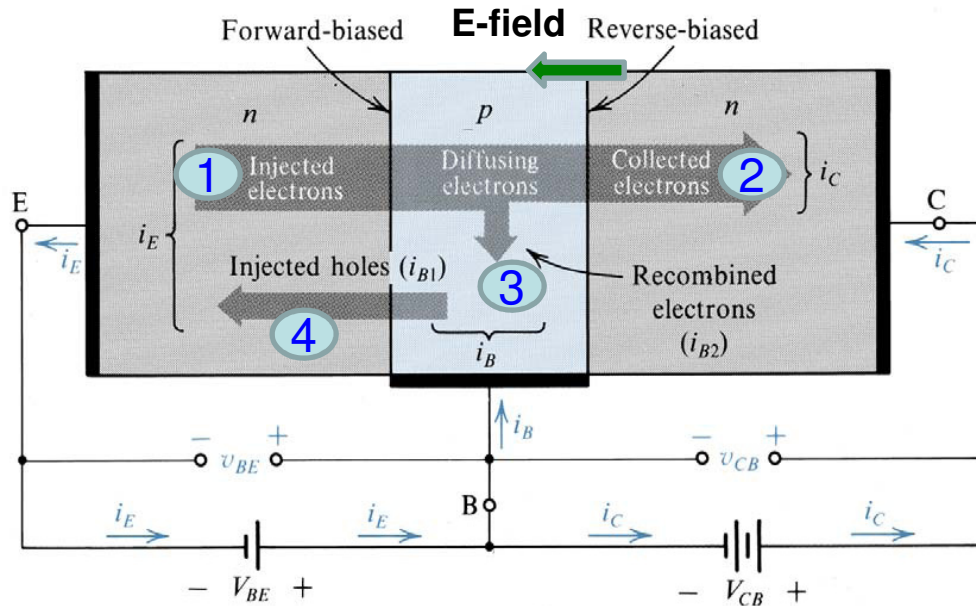
➢ 1 . Forward bias of EBJ causes electrons to diffuse from emitter into base.
➢ 2. As base region is very thin, the majority of these electrons diffuse to the edge of the depletion region of CBJ, and then are swept to the collector by the electric field of the reverse-biased CBJ.
➢ 3. A small fraction of these electrons recombine with the holes in base region.
➢ 4. Holes are injected from base to emitter region. (4) << (1).

➢ The two-carrier flow from [(1) and (4)] forms the emitter current (I_E).

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DC operation of npn BJT under forward active mode

Collector current

Collector-base diode is reverse biased therefore $V_{CB} > 0$

$$I_C = I_s \left[e^{\left(\frac{eV_{BE}}{kT} - 1 \right)} \right] \quad \text{where} \quad I_s = \frac{qA_e D_n n_{po}}{W} = \frac{qA_e D_n n_i^2}{N_A W}$$

A_e Area of base-emitter junction
W   Width of base region
N_A Doping concentration in base
D_n Electron diffusion constant
n_i Intrinsic carrier concentration = f(T)

I_C is independent of collector voltage

Base current

➤ Base current consists of two components: i_{B1} and i_{B2}:
❖ i_{B1}, due to forward bias of EBJ, is an exponential function of V_{BE}.
❖ i_{B2}, due to recombination, is directly proportional to the numbers of electrons injected from the emitter, which in turn is an exponential function of V_{BE}.

Forward Active Mode common base current gain (α)

In common base configuration, the **current transfer mode ratio (α) of a bipolar transistor in the forward active mode is defined as the ratio of the collector current** (I_C) to the emitter current (I_E):

$$\alpha = \frac{I_C}{I_E} \qquad I_E = I_C + I_B$$

Forward Active Mode common emitter current gain (β)

The **current gain (β) of a bipolar transistor under common emitter forward active mode is defined as the ratio of the collector current** (I_C) to the base current (I_B):
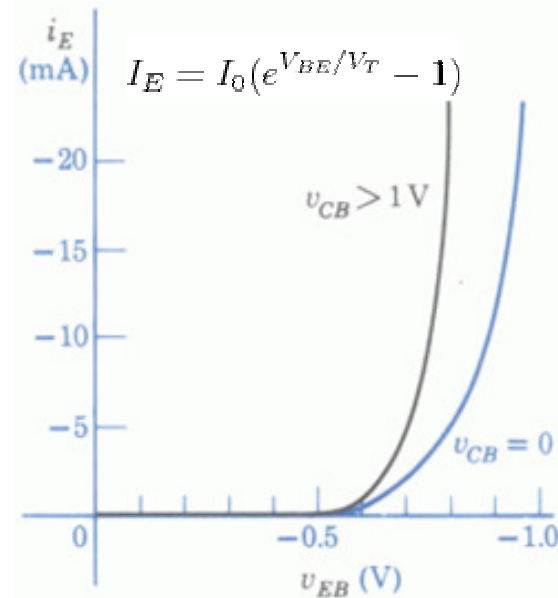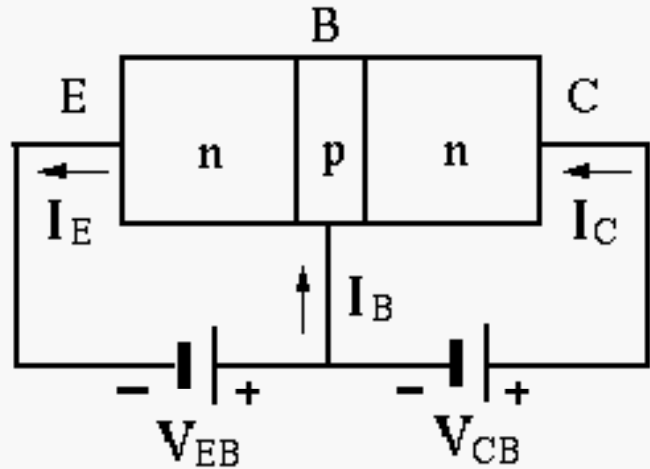
$$\beta = \frac{I_C}{I_B}$$

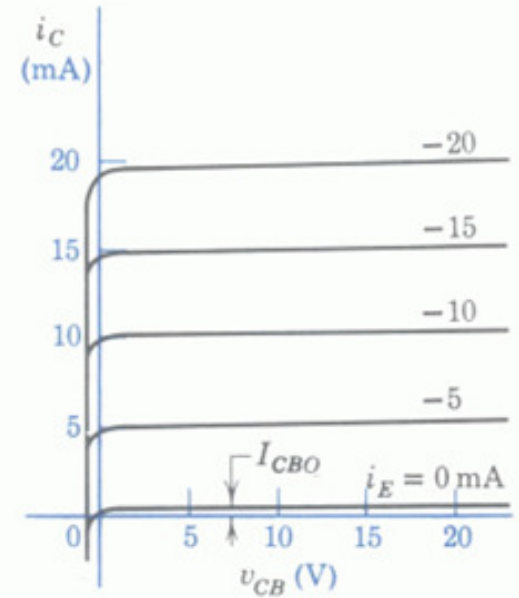$$\frac{I_E}{I_C} = 1 + \frac{I_B}{I_C} \qquad \frac{1}{\alpha} = 1 + \frac{1}{\beta} \qquad \beta = \frac{\alpha}{1-\alpha}$$

I-V Characteristics of npn BJT under forward active mode

Common Base configuration

$$I_E = I_0(e^{V_{BE}/V_T} - 1)$$

Input characteristics   **Output characteristics**

➢ Input characteristics are like a normal forward biased diode. As V_{CB} increased I_E also increased due to Early Effect (increased reverse biased at CB junction causes reduction in effective base width) .

➢As the CB junction is reverse biased, the current I_C depends totally on I_E. When $I_E=0$, $I_C=I_{CB0}$ is the current caused by the minority carriers crossing the pn-junction. I_{cB0} is leakage current called as collector base current with emitter open. When I_E is increased, I_C is increased correspondingly. $I_C = \alpha I_E + I_{CB0}$

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