EE 434
Lecture 21

MOS Amplifiers

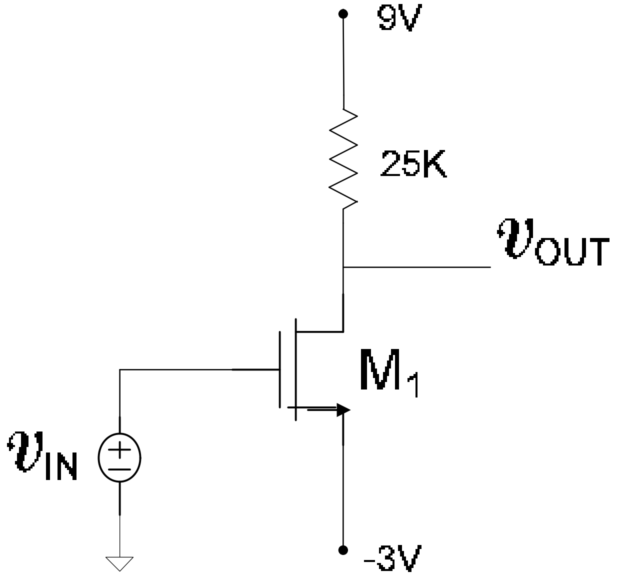
Bipolar Devices

Quiz 13

The quiescent voltage across the 25K resistor in the circuit shown was measured to be 3V.

1) Determine the quiescent output voltage
2) Determine the small signal voltage gain

Assume M_1 is manufactured in a process with μC_{OX}=100uA/V^2 and V_T=1V.



And the number is ….

1 8 7 5 3

6 9 4 2

And the number is ….

1 8 7 5 3

6 9 4 2

1

Quiz 13

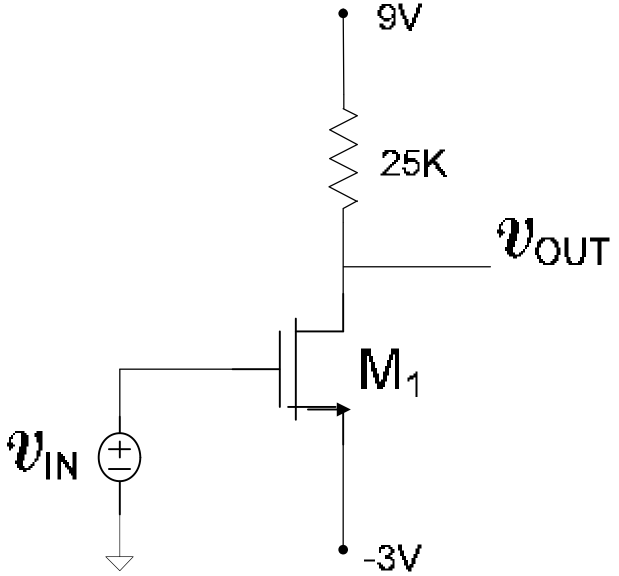
The quiescent voltage across the 25K resistor in the circuit shown was measured to be 3V.

1) Determine the quiescent output voltage
2) Determine the small signal voltage gain

Assume M_1 is manufactured in a process with μC_{OX}=100uA/V^2 and V_T=1V.

Solution:

$$\mathbf{V_{OQ} = V_{DD} - I_{DQ}R_D = 9V - 3V = 6V}$$



Quiz 13

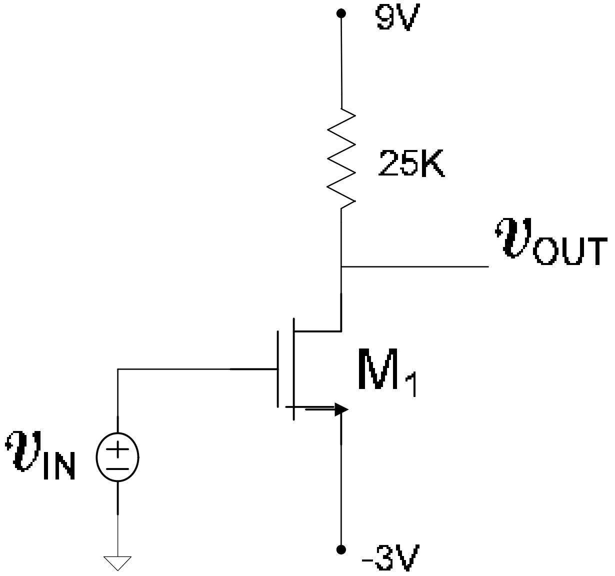
The quiescent voltage across the 25K resistor in the circuit shown was measured to be 3V.

1) Determine the quiescent output voltage
2) Determine the small signal voltage gain

Assume M_1 is manufactured in a process with $\mu C_{OX}=100\text{uA/V}^2$ and $V_T=1\text{V}$.

Solution:

$$A_V = g_M R_D = -\frac{2\boxed{I_{DQ}}}{V_{EB}}\boxed{R_L}$$



Quiz 13

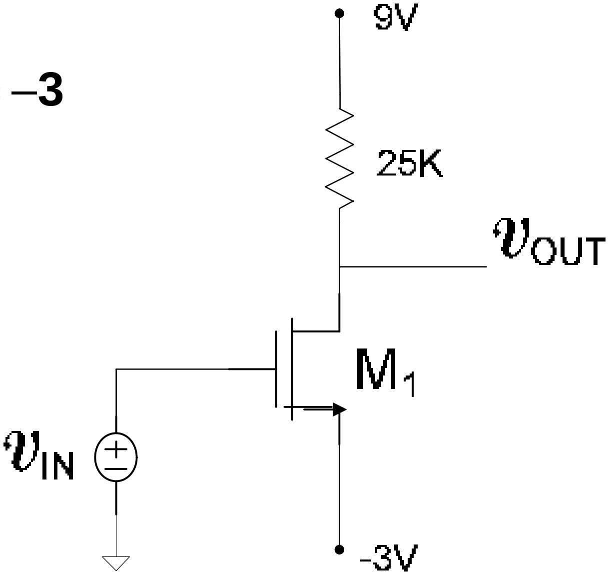
The quiescent voltage across the 25K resistor in the circuit shown was measured to be 3V.

1) Determine the quiescent output voltage
2) Determine the small signal voltage gain

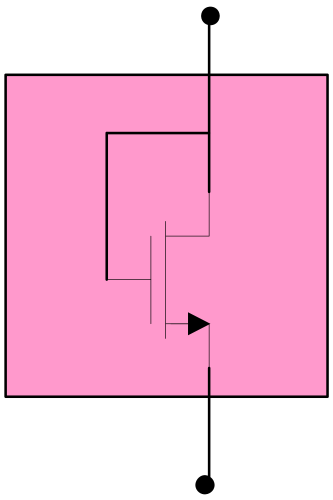
Assume M_1 is manufactured in a process with $\mu C_{OX}=100uA/V^2$ and $V_T=1V$.

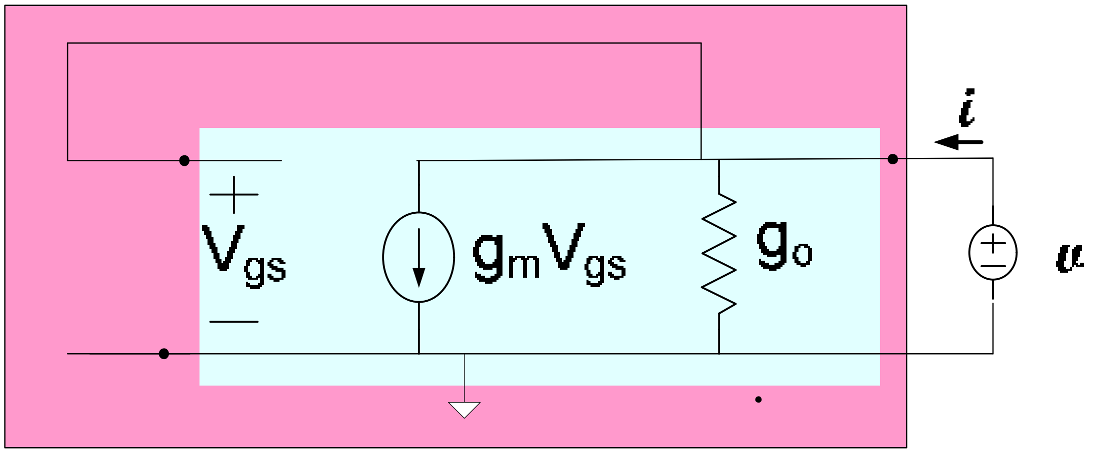
Solution:

$$A_V = g_M R_D = -\frac{2\, I_{DQ}}{V_{EB}} R_L = -\frac{2 \bullet 3V}{3V-1V} = -3$$



Example: Determine the small signal equivalent for the following device. Assume M_1 operating in the saturation region



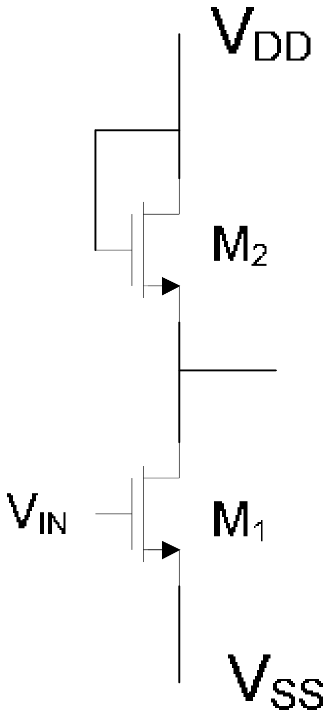


$$i = g_0 V + g_m V$$

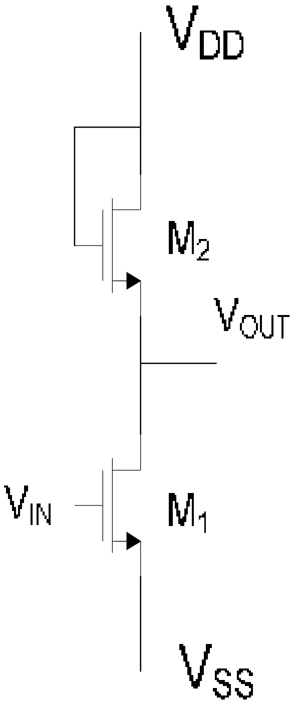
$$G_{EQ} = \frac{i}{V} = g_0 + g_m \cong g_m$$

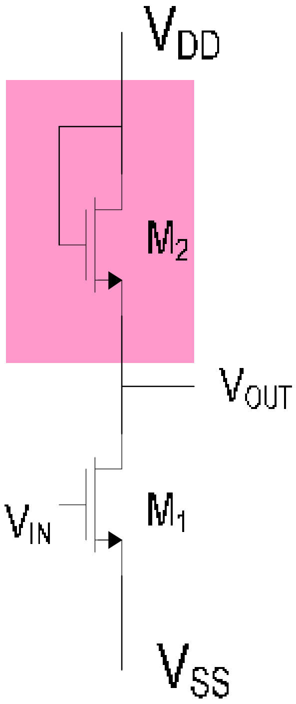
MOS Amplifier

Determine the small signal voltage gain for the following circuit. Assume M_1 and M_2 operating in the saturation region

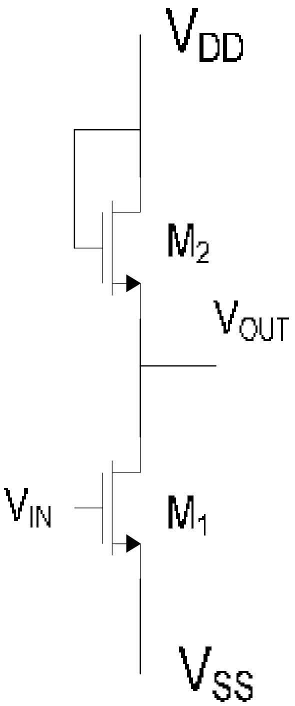


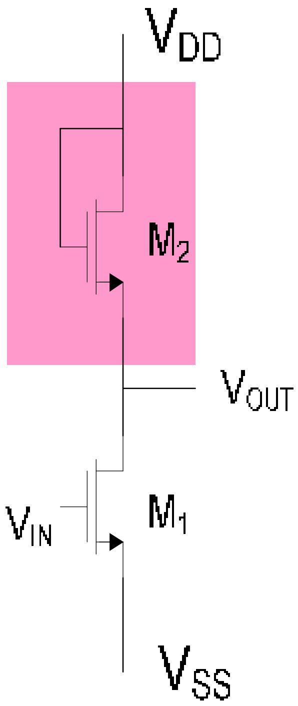
MOS Amplifier Determine the small signal voltage gain for the following circuit. Assume M_1 and M_2 operating in the saturation region

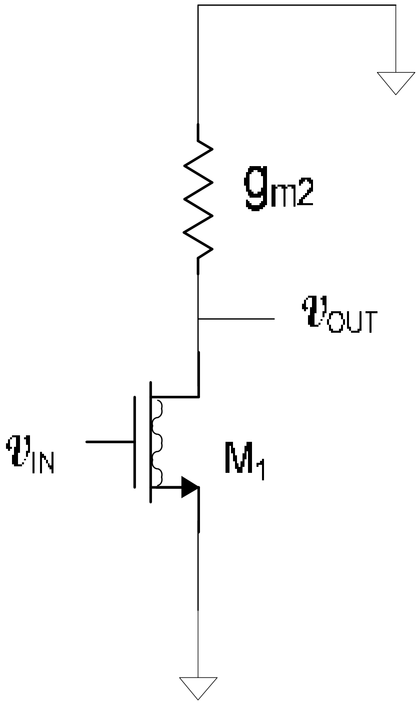




MOS Amplifier Determine the small signal voltage gain for the following circuit. Assume M_1 and M_2 operating in the saturation region

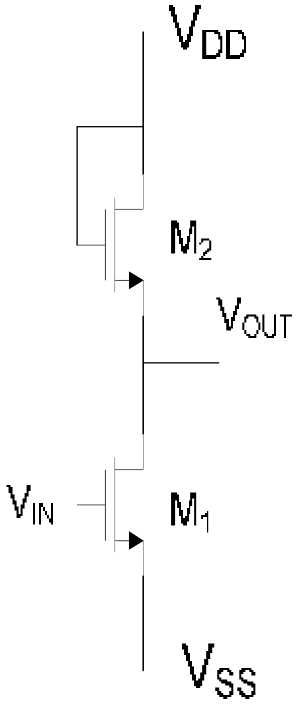






$$A_V = -\frac{g_{m1}}{g_{m2}}$$

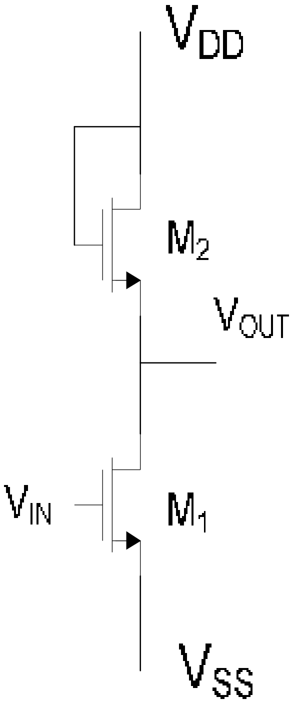
MOS Amplifier Determine the small signal voltage gain for the following circuit. Assume M_1 and M_2 operating in the saturation region



$$A_V = -\frac{g_{m1}}{g_{m2}}$$

$$A_V = -\frac{\sqrt{2 m_1 C_{OX1} \frac{W_1}{L_1} I_{DQ1}}}{\sqrt{2 m_2 C_{OX2} \frac{W_2}{L_2} I_{DQ2}}}$$

MOS Amplifier Determine the small signal voltage gain for the following circuit. Assume M_1 and M_2 operating in the saturation region

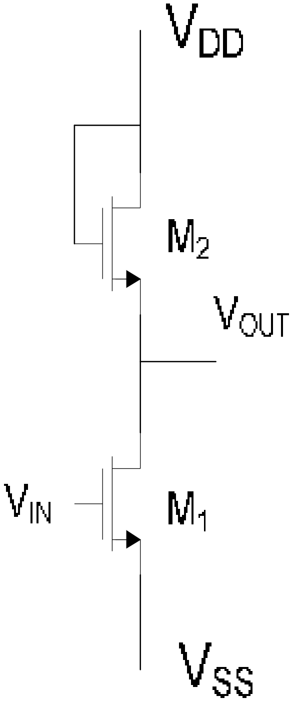


$$A_V = -\frac{g_{m1}}{g_{m2}}$$

$$A_V = -\frac{\sqrt{\cancel{2}\cancel{m_1}\cancel{C}_{OX1}\frac{W_1}{L_1}\cancel{I}_{DQ1}}}{\sqrt{\cancel{2}\cancel{m_2}\cancel{C}_{OX2}\frac{W_2}{L_2}\cancel{I}_{DQ2}}}$$

$$\mathbf{A_V} = \sqrt{\frac{\mathbf{W_1}}{\mathbf{W_2}}\frac{\mathbf{L_2}}{\mathbf{L_1}}}$$

MOS Amplifier Determine the small signal voltage gain for the following circuit. Assume M_1 and M_2 operating in the saturation region



$$A_V = -\frac{g_{m1}}{g_{m2}}$$

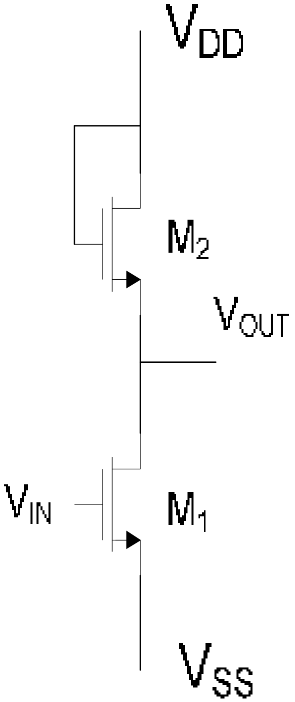
$$A_V = -\frac{\sqrt{\cancel{2}\cancel{\mu_1}\cancel{C}_{OX1}\frac{W_1}{L_1}\cancel{I}_{DQ1}}}{\sqrt{\cancel{2}\cancel{\mu_2}\cancel{C}_{OX2}\frac{W_2}{L_2}\cancel{I}_{DQ2}}}$$

$$\mathbf{A_V} = \sqrt{\frac{\mathbf{W_1}}{\mathbf{W_2}}\frac{\mathbf{L_2}}{\mathbf{L_1}}}$$

Accurate gain control
Nearly independent of process parameters
Can also show (but not from ss analysis) that this is quite very linear !

MOS Amplifier Determine the small signal voltage gain for the following circuit. Assume M_1 and M_2 operating in the saturation region

Linearity of this common-source amplifier



$$I_{D1} \cong \mu_1 C_{OX1} \frac{W_1}{2L_1} \left(V_{IN} - V_{T1}\right)^2$$

$$I_{D2} \cong \mu_2 C_{OX2} \frac{W_2}{2L_2} \left(V_{DD} \text{ - } V_{OUT} \text{ - } V_{T2}\right)^2$$

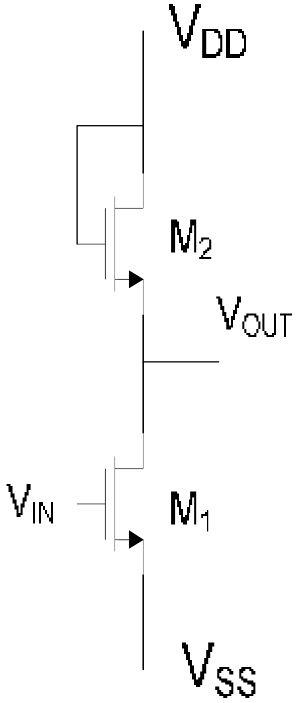
$$I_{D1} = I_{D2} \;\; \Rightarrow \;\; \mu_1 C_{OX1} \frac{W_1}{2L_1} \left(V_{IN} - V_{T1}\right)^2 \cong \mu_2 C_{OX2} \frac{W_2}{2L_2} \left(V_{DDD} - V_{OUT} - V_{T2}\right)^2$$

Taking the square root of both sides of this eqn, obtain

$$V_{OUT} = -\sqrt{\frac{W_1}{W_2}\frac{L_2}{L_1}} V_{IN} + V_{DD} + \sqrt{\frac{W_1}{W_2}\frac{L_2}{L_1}} V_{T1} - V_{T2}$$

MOS Amplifier Determine the small signal voltage gain for the following circuit. Assume M_1 and M_2 operating in the saturation region

Linearity of this common-source amplifier



$$\mathbf{V_{OUT}} = -\sqrt{\frac{\mathbf{W_1}}{\mathbf{W_2}}\frac{\mathbf{L_2}}{\mathbf{L_1}}}\mathbf{V_{IN}} + \mathbf{V_{DD}} + \sqrt{\frac{\mathbf{W_1}}{\mathbf{W_2}}\frac{\mathbf{L_2}}{\mathbf{L_1}}}\mathbf{V_{T1}} - \mathbf{V_{T2}}$$

Appears to be perfectly linear

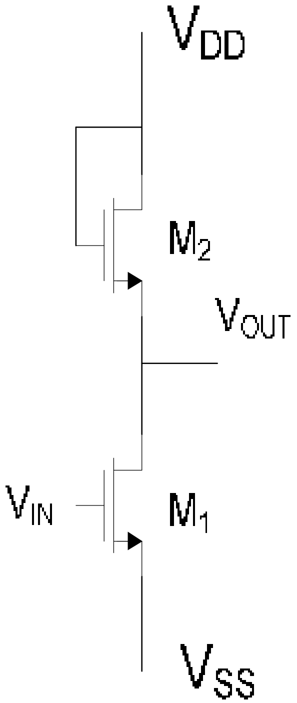
Have neglected bulk effect for M2 which introduces small nonlinearity

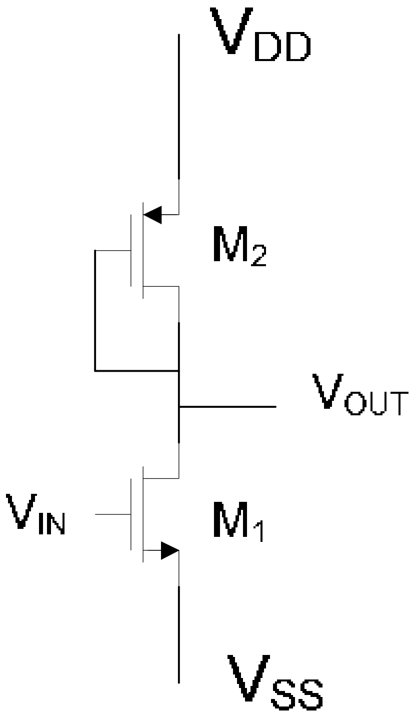
Have also neglected λ effects which introduce some more nonlinearity

Dependent upon square-law model which may not be good enough

Overall, good linearity and accurate control of gain but not perfect

MOS Amplifier Determine the small signal voltage gain for the following circuit. Assume M_1 and M_2 operating in the saturation region

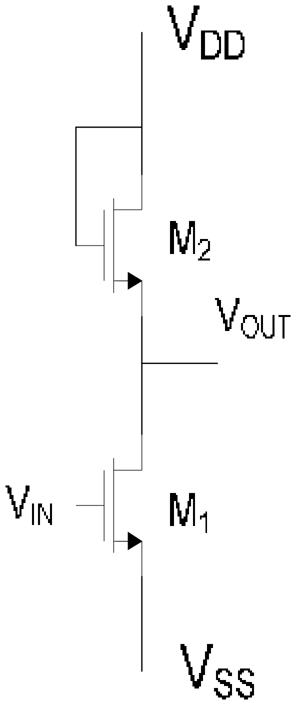


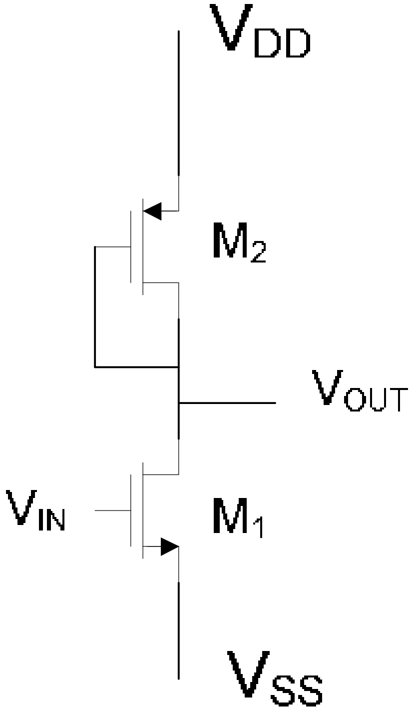


How do these two amplifiers compare?

$$A_V = -\frac{\sqrt{\cancel{2}m_1 C_{OX1}\frac{W_1}{L_1}\cancel{I}_{DQ1}}}{\sqrt{\cancel{2}m_2 C_{OX2}\frac{W_2}{L_2}\cancel{I}_{DQ2}}} \cong \sqrt{\frac{m_1}{m_2}\frac{W_1}{W_2}\frac{L_2}{L_1}}$$

MOS Amplifier   Determine the small signal voltage gain for the following circuit. Assume M_1 and M_2 operating in the saturation region





How do these two amplifiers compare?

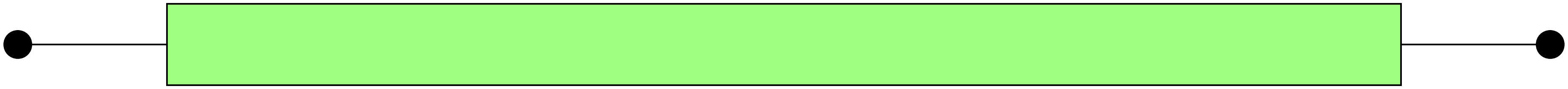
g_{mb} effects are removed for one on right !

Gain can not be as accurately controlled

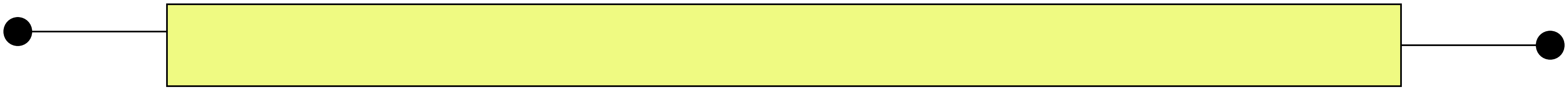
Bipolar Junction Transistors

- Operation
- Modeling

Carriers in Doped Semiconductors

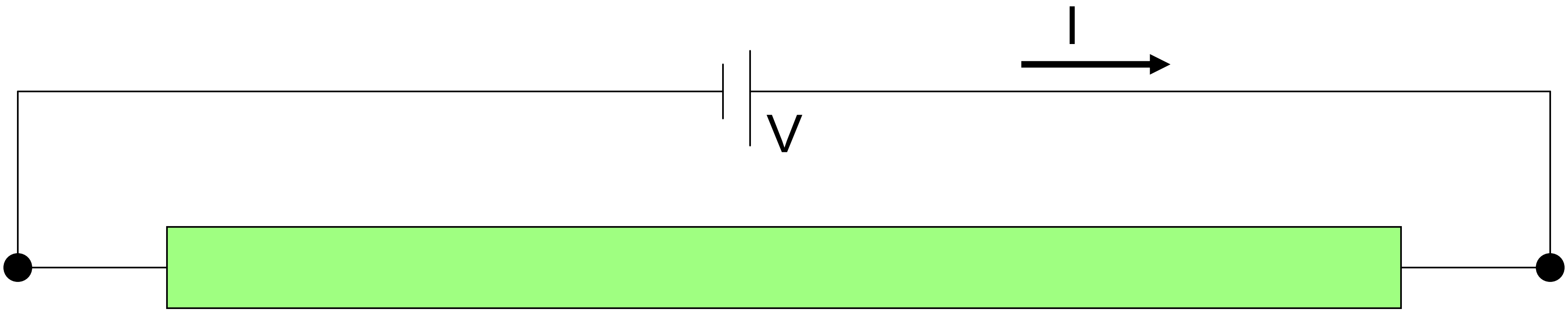


n-type



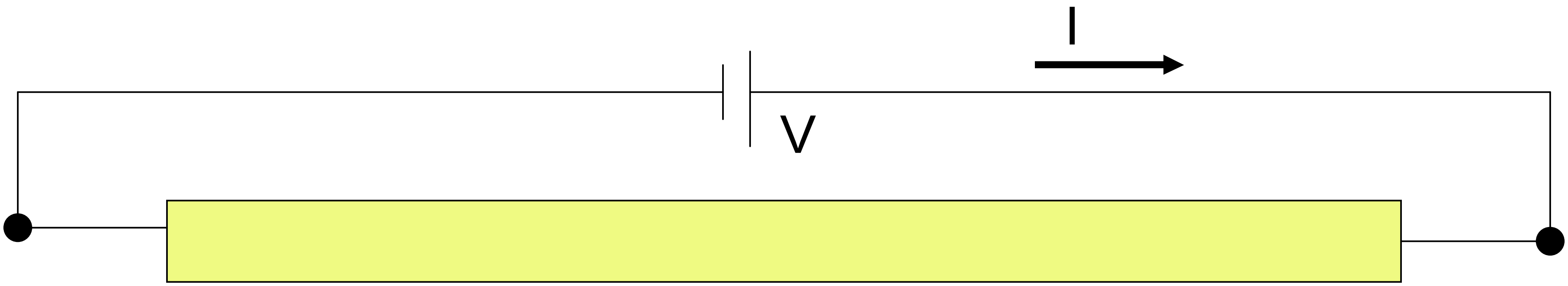
p-type

Carriers in Doped Semiconductors



Current carriers are dominantly electrons

Small number of holes are short-term carriers



Current carriers are dominantly holes

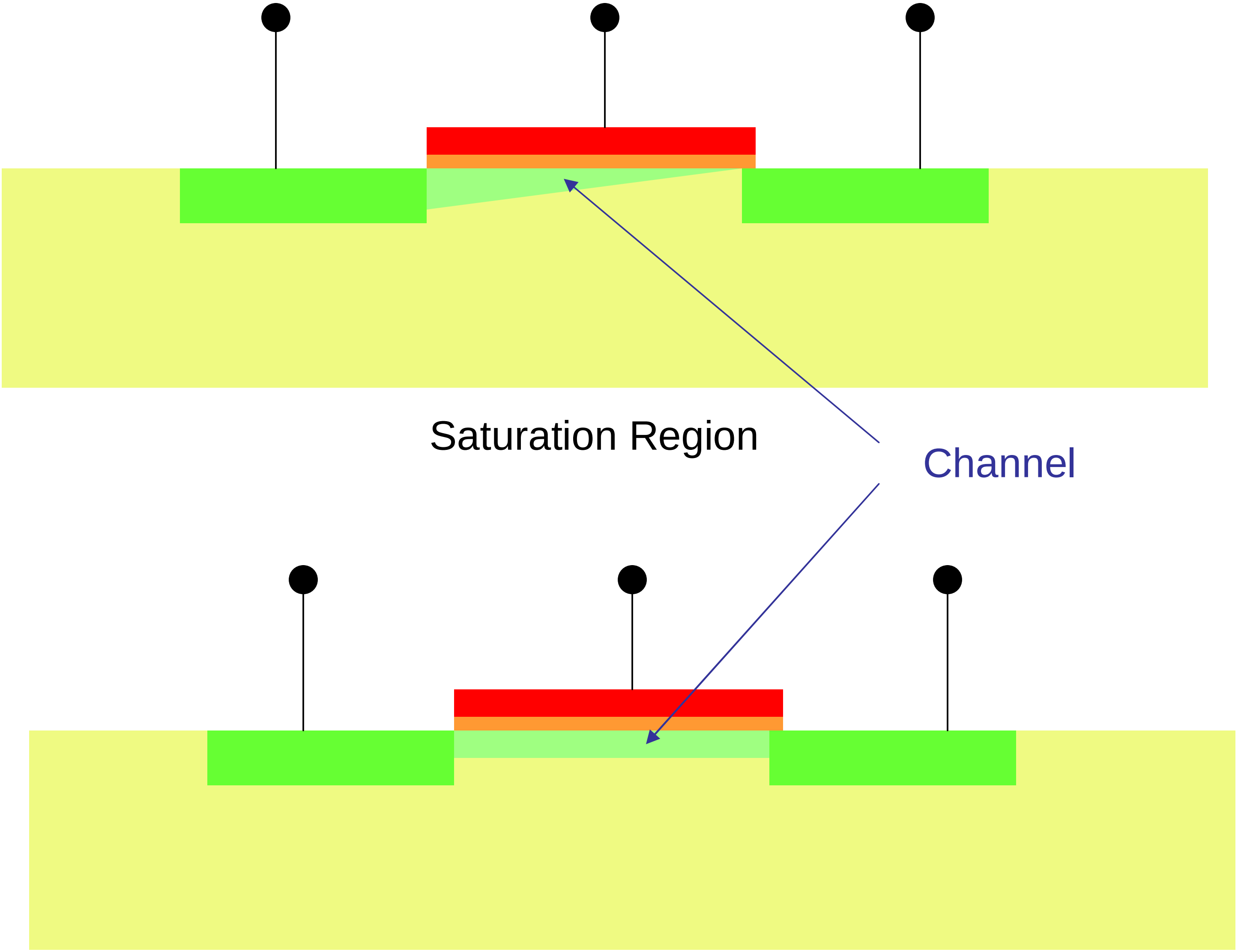
Small number of electrons are short-term carriers

Carriers in Doped Semiconductors

	Majority Carriers	Minority Carriers
n-type	electrons	holes
p-type	holes	electrons

Carriers in MOS Transistors

Consider n-channel MOSFET



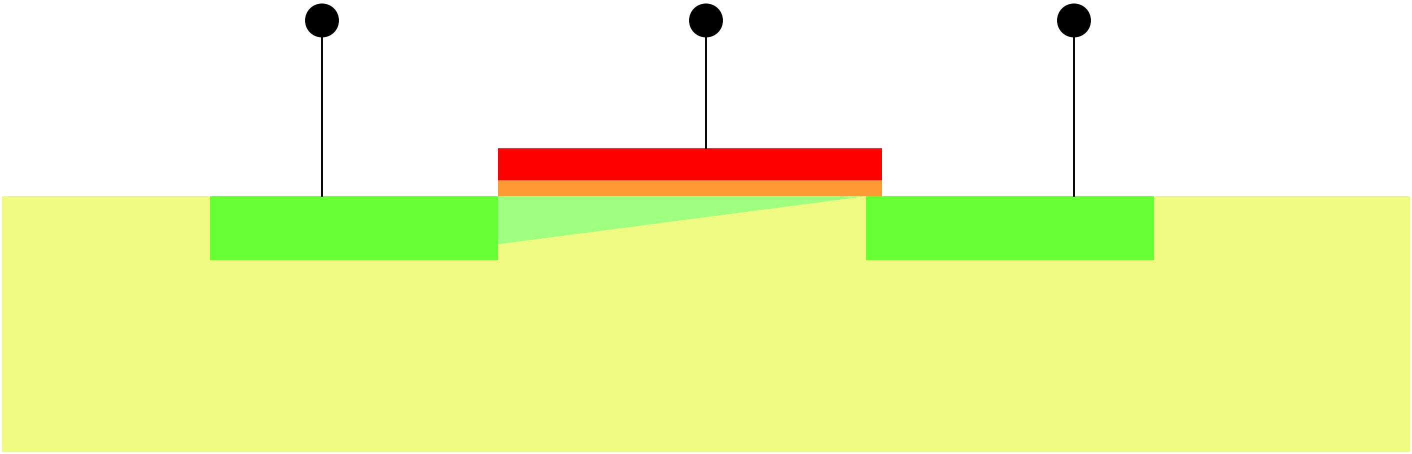
Saturation Region

Channel

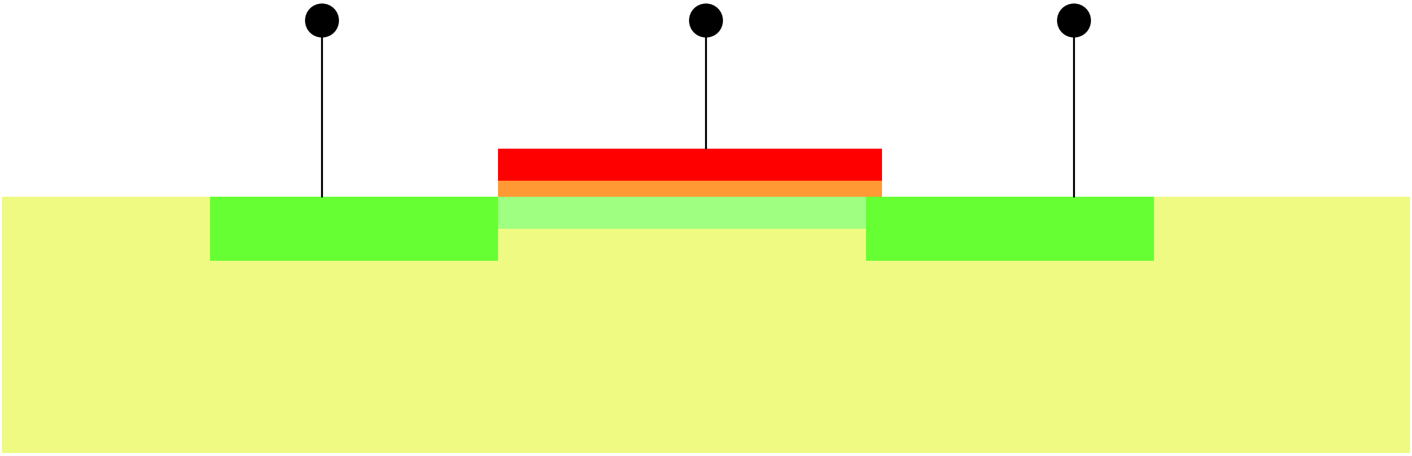
Triode Region

Carriers in MOS Transistors

Consider n-channel MOSFET



Saturation Region

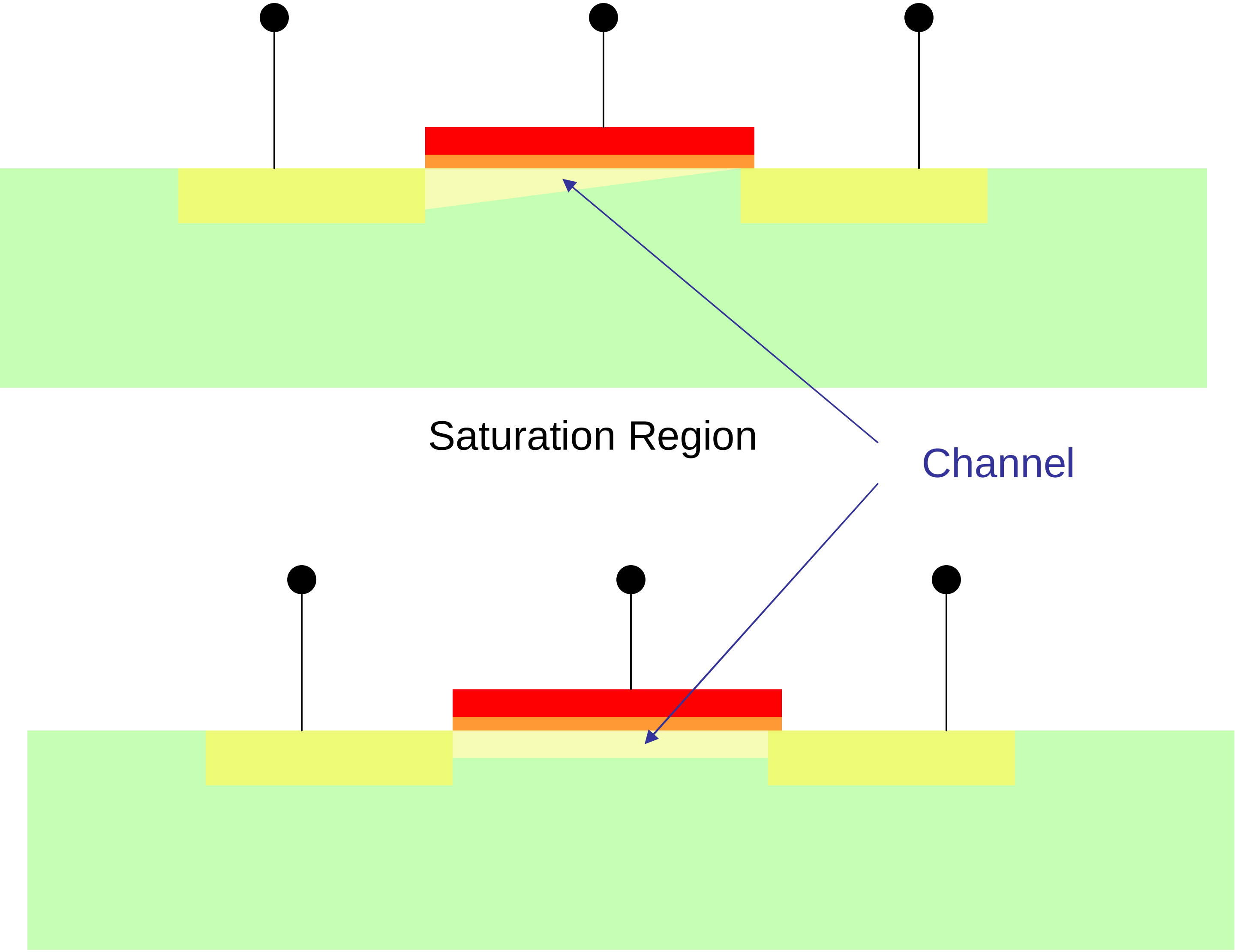


Triode Region

Carriers in electrically induced n-channel are electrons

Carriers in MOS Transistors

Consider p-channel MOSFET



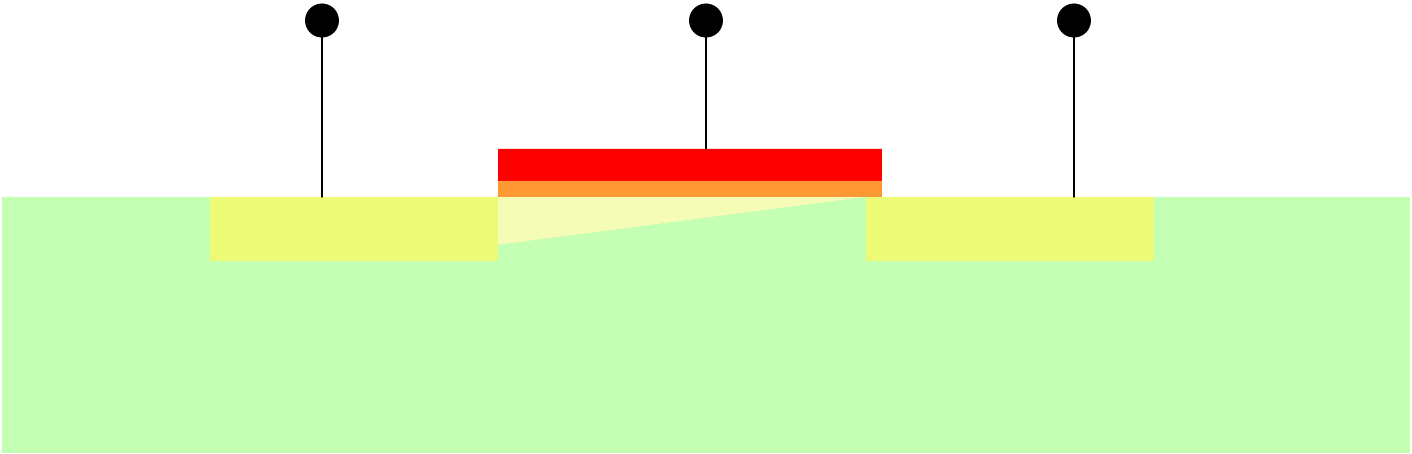
Saturation Region

Channel

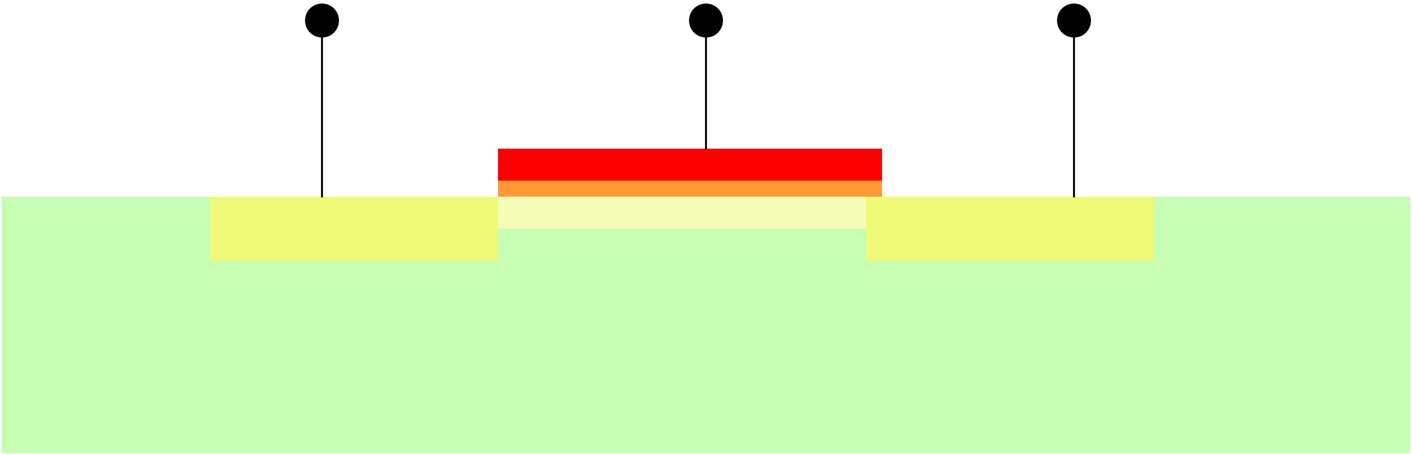
Triode Region

Carriers in MOS Transistors

Consider p-channel MOSFET



Saturation Region



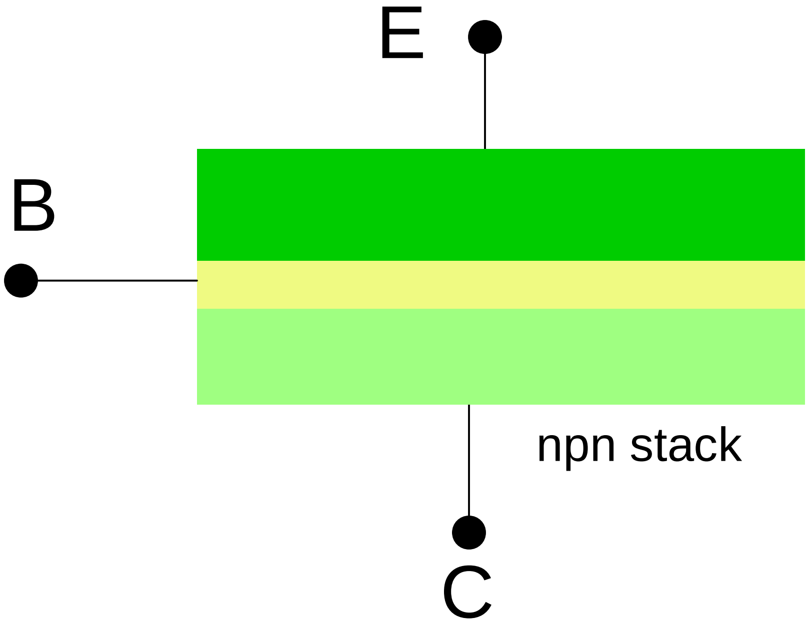
Triode Region

Carriers in electrically induced p-channel are holes

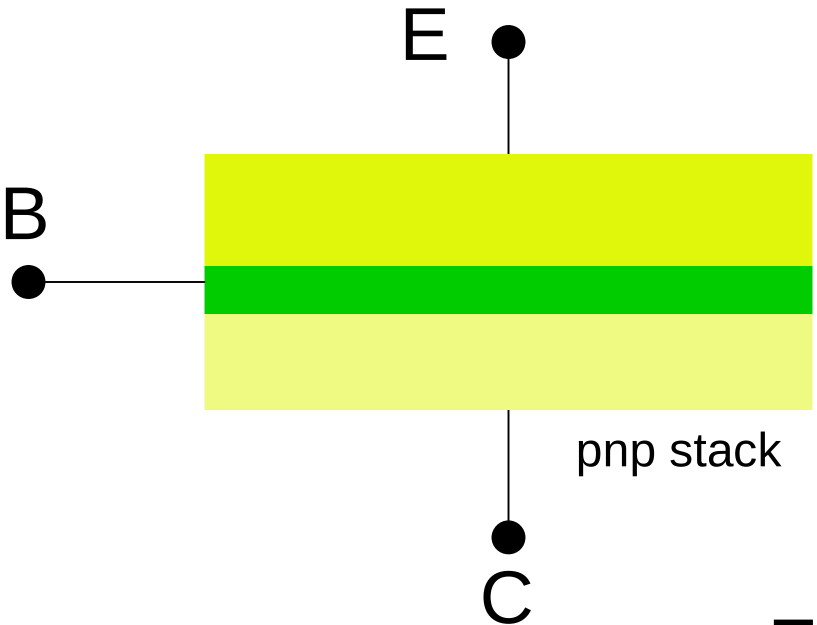
Carriers in MOS Transistors

Carriers in channel of MOS transistors are Majority carriers

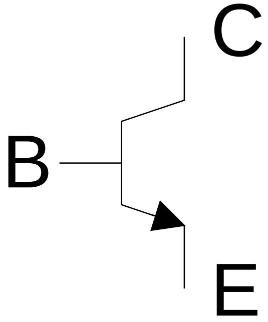
Bipolar Transistors



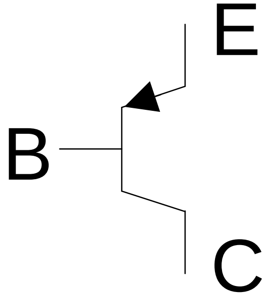
npn stack



pnp stack



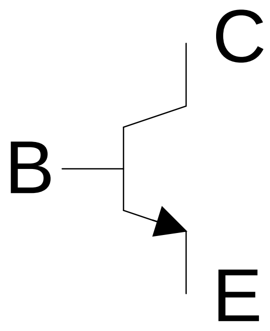
npn transistor



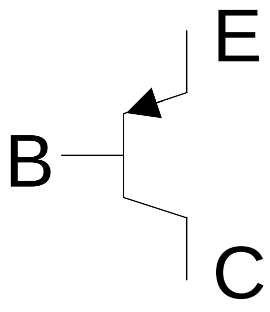
pnp transistor

With proper doping and device sizing these form Bipolar Transistors

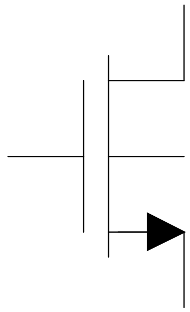
Bipolar Transistors



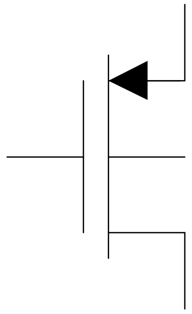
npn transistor



pnp transistor



n-channel MOSFET

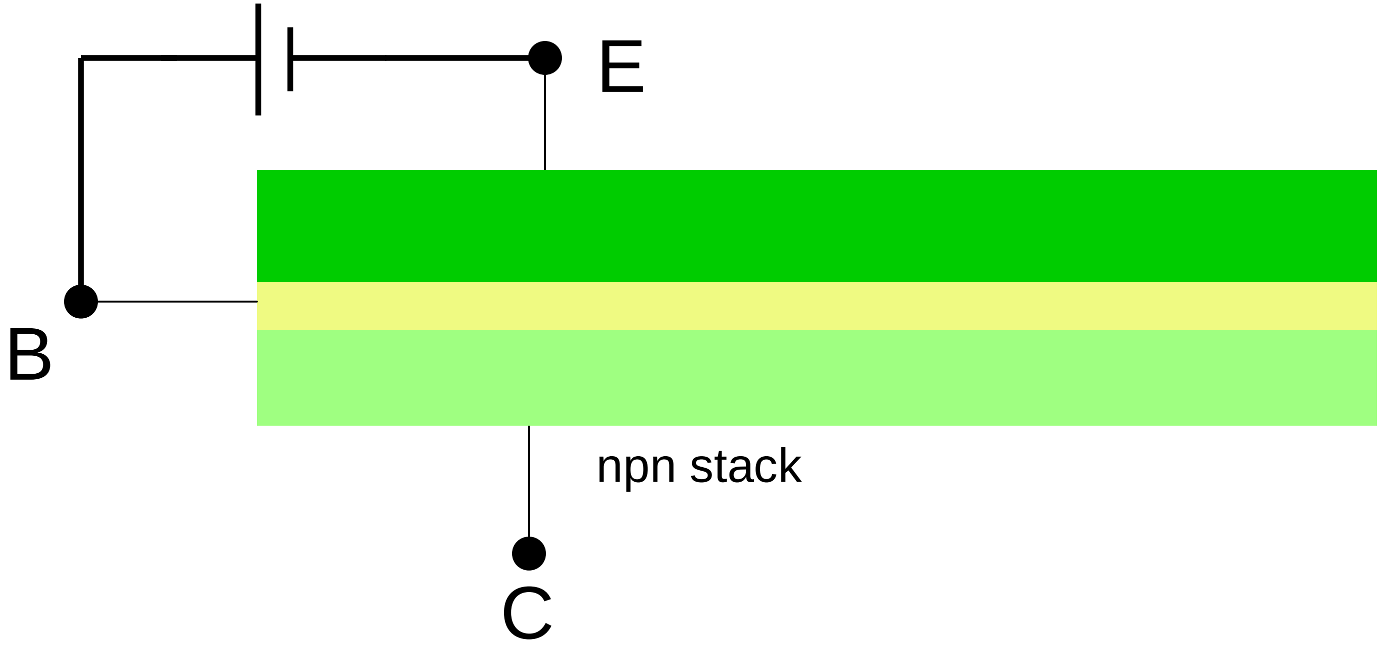


p-channel MOSFET

In contrast to a MOSFET which has 4 terminals, a BJT only has 3 terminals

Bipolar Operation

Consider npn transistor



Under **forward bias** current flow into base and out of emitter

Current flow is governed by the diode equation

Carriers in emitter are electrons (majority carriers)

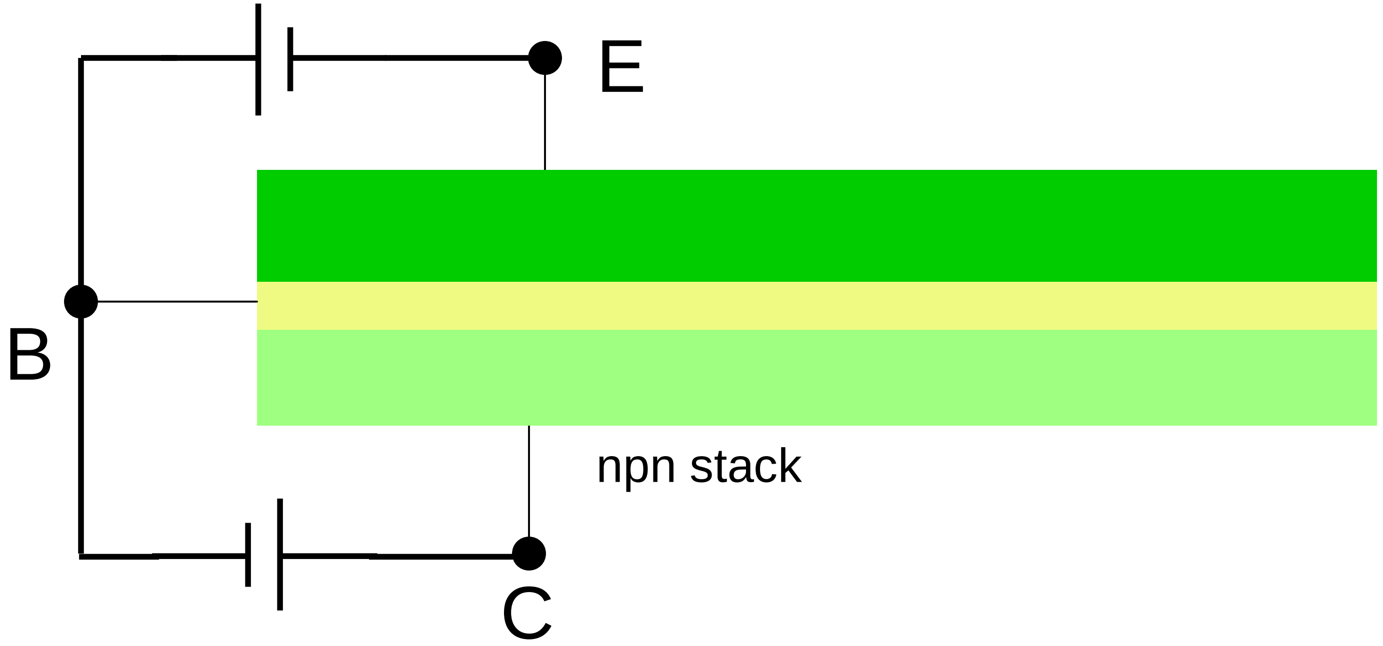
When electrons pass into the base they become minority carriers

Quickly recombine with holes to create holes base region

Dominant current flow in base is holes (majority carriers)

Bipolar Operation

Consider npn transistor



Under forward BE bias and reverse BC bias current flows into base **region**

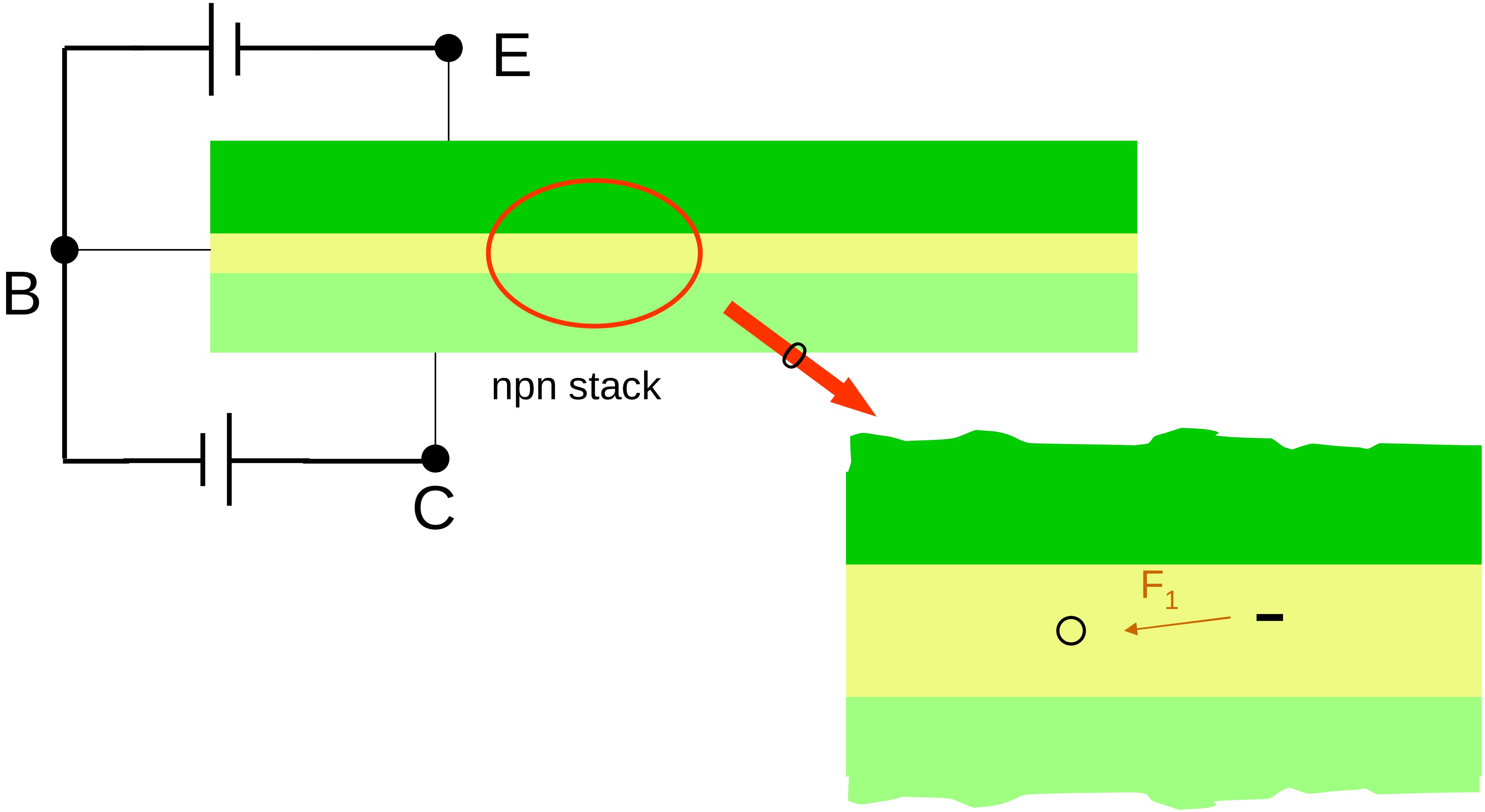
Carriers in emitter are electrons (majority carriers)

When electrons pass into the base they become minority carriers

When minority carriers are present in the base they can be attracted to collector

Bipolar Operation

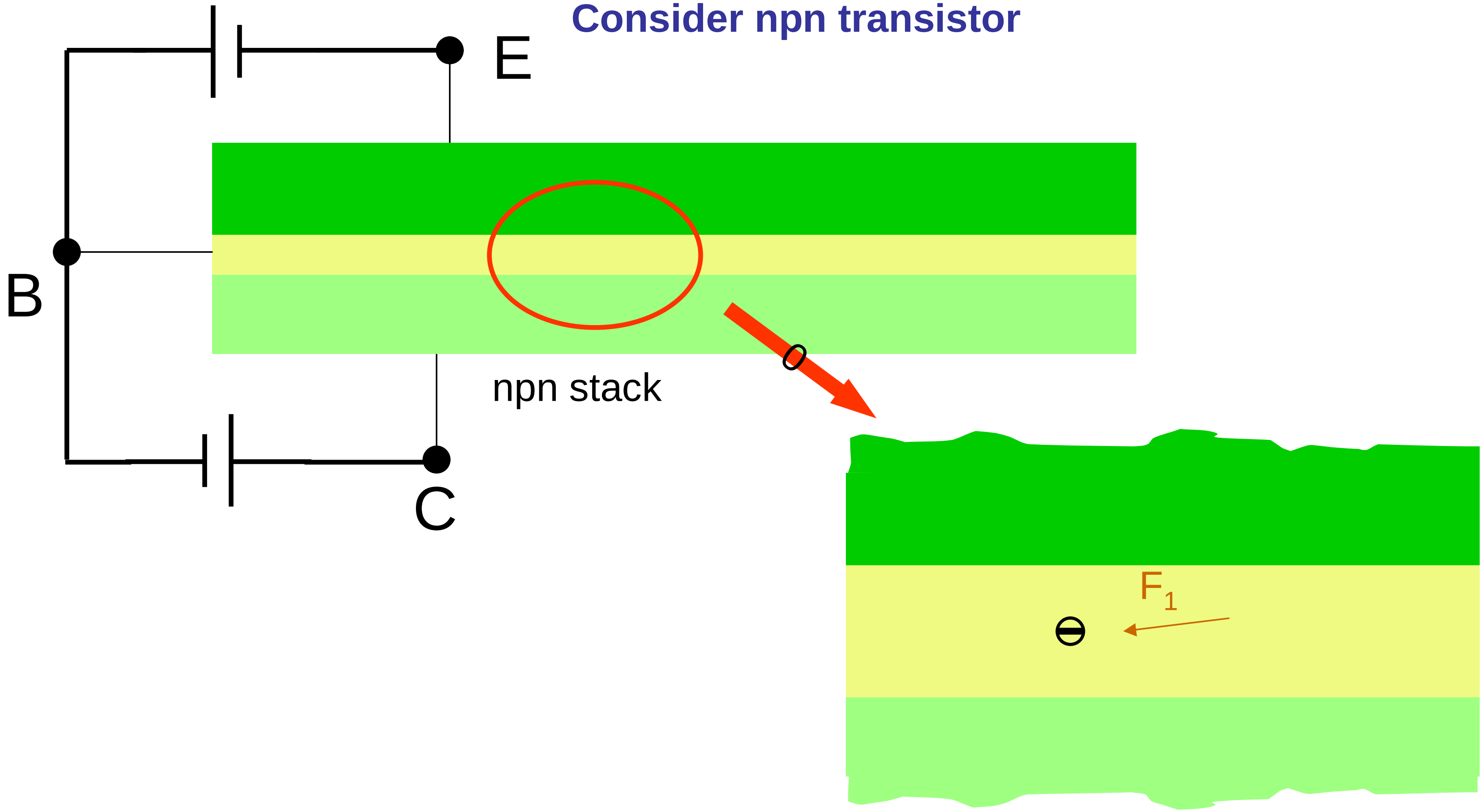
Consider npn transistor



If no force on electron is applied by collector, electron will contribute to base current

Bipolar Operation

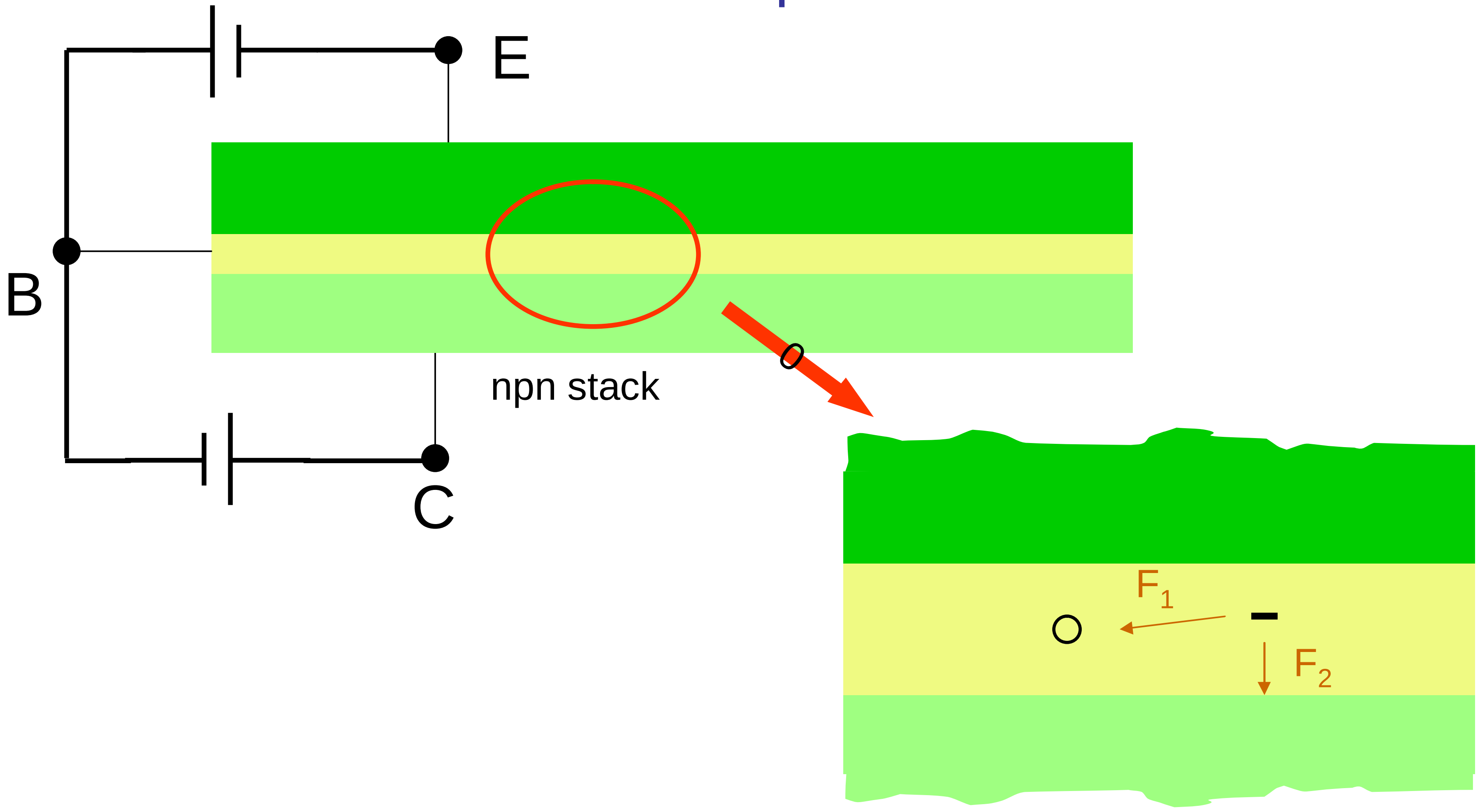
Consider npn transistor



If no force on electron is applied by collector, electron will contribute to base current
Electron will recombine with a hole so dominant current flow in base will be by majority carriers

Bipolar Operation

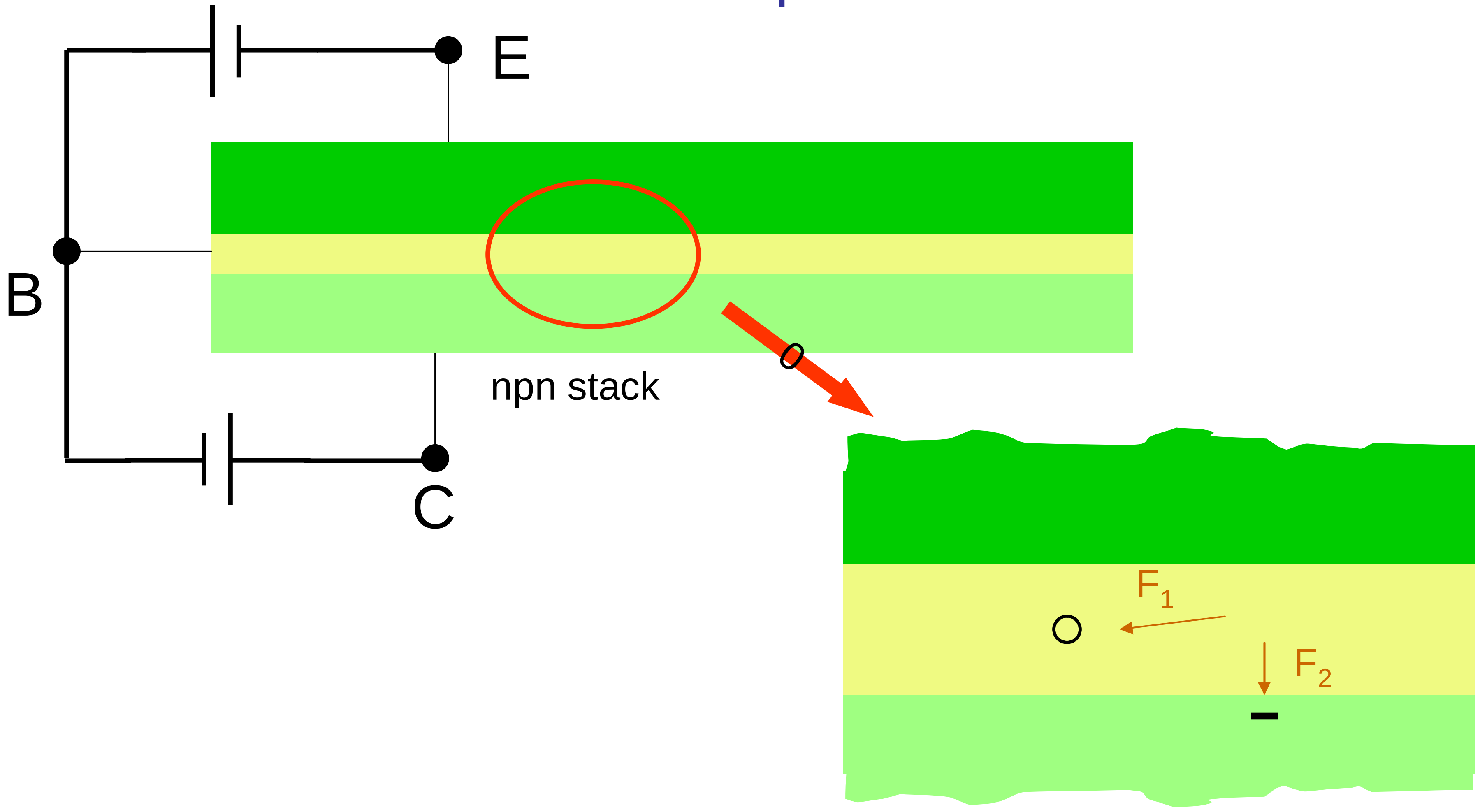
Consider npn transistor



When minority carriers are present in the base they can be attracted to collector with reverse-bias of BC junction and can move across BC junction

Bipolar Operation

Consider npn transistor

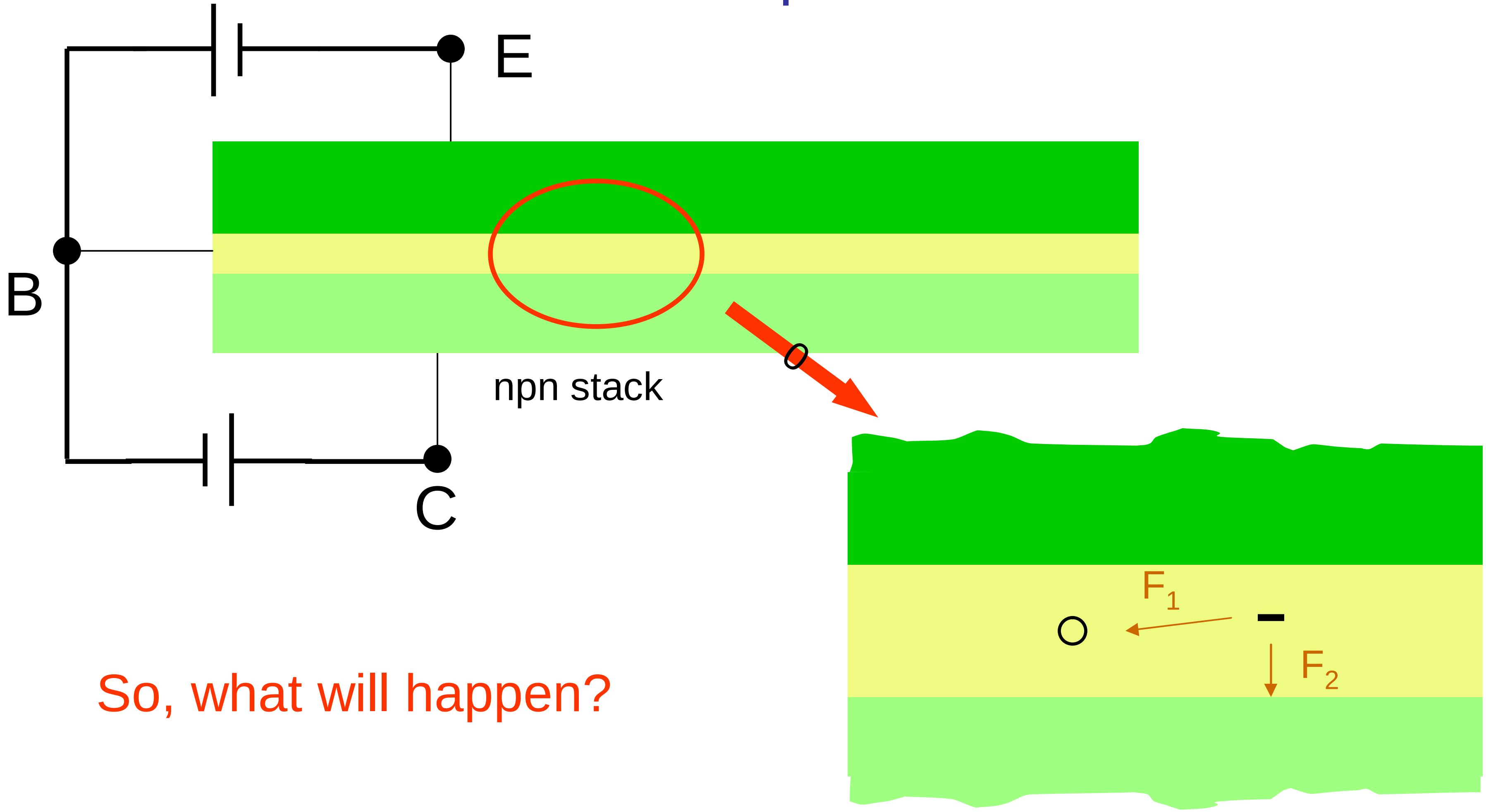


When minority carriers are present in the base they can be attracted to collector with reverse-bias of BC junction and can move across BC junction

Will contribute to collector current flow as majority carriers

Bipolar Operation

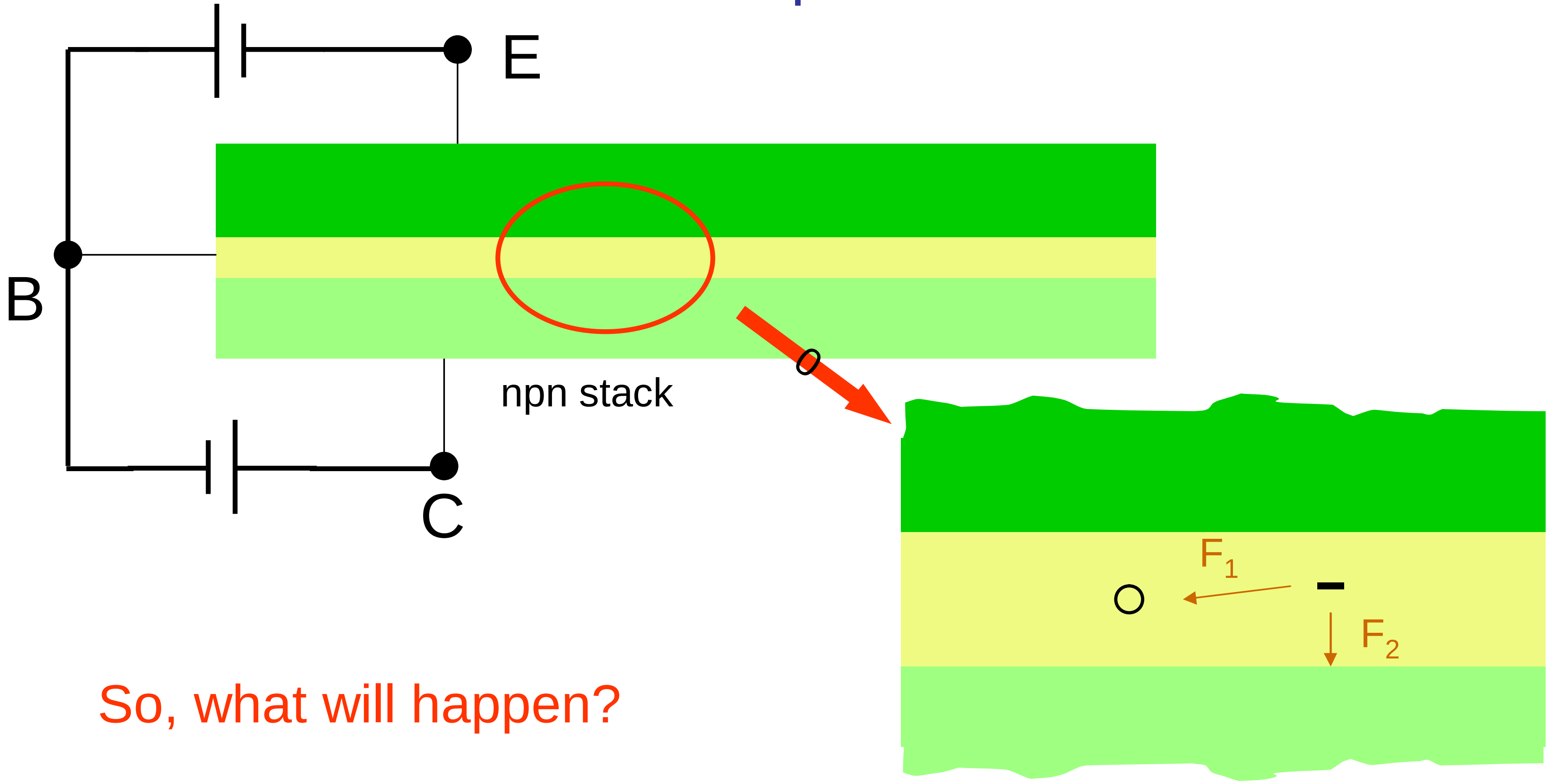
Consider npn transistor



So, what will happen?

Bipolar Operation

Consider npn transistor



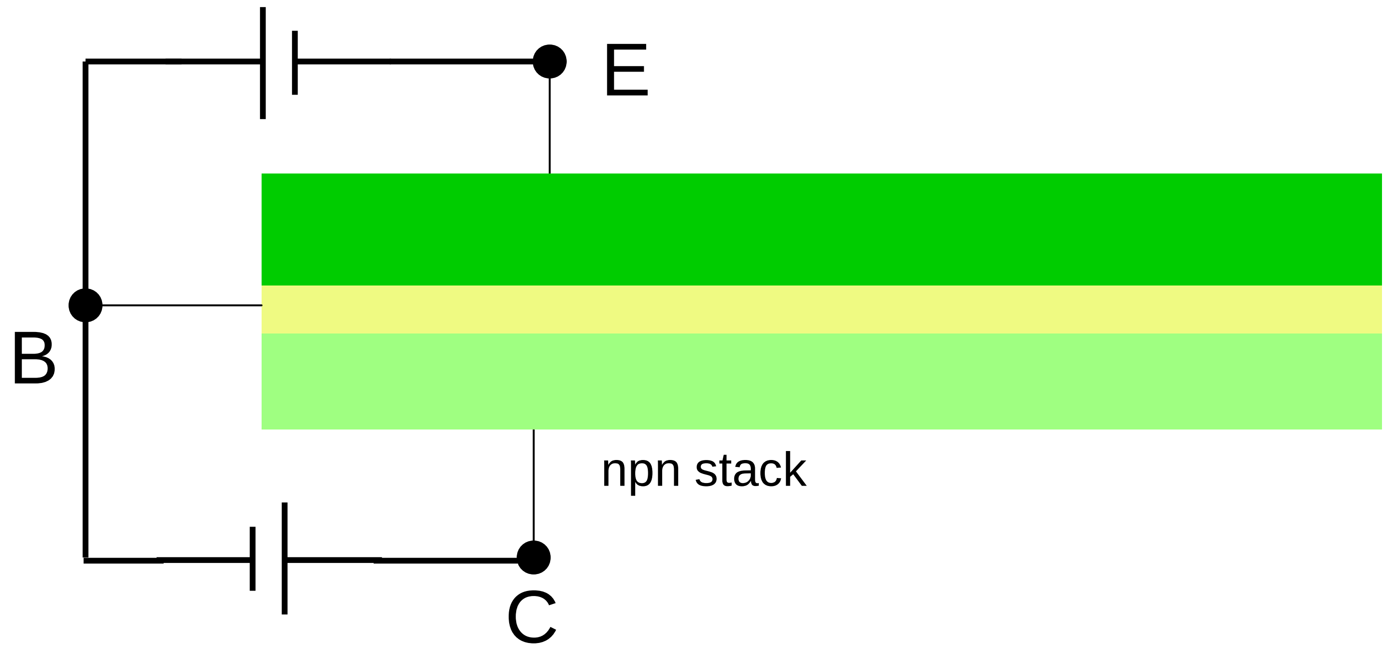
So, what will happen?

Some will recombine with holes and contribute to base current and some will be attracted across BC junction and contribute to collector

Size and thickness of base region and relative doping levels will play key role in percent of minority carriers injected into base contributing to collector current

Bipolar Operation

Consider npn transistor



Under forward BE bias and reverse BC bias current flows into base **region**

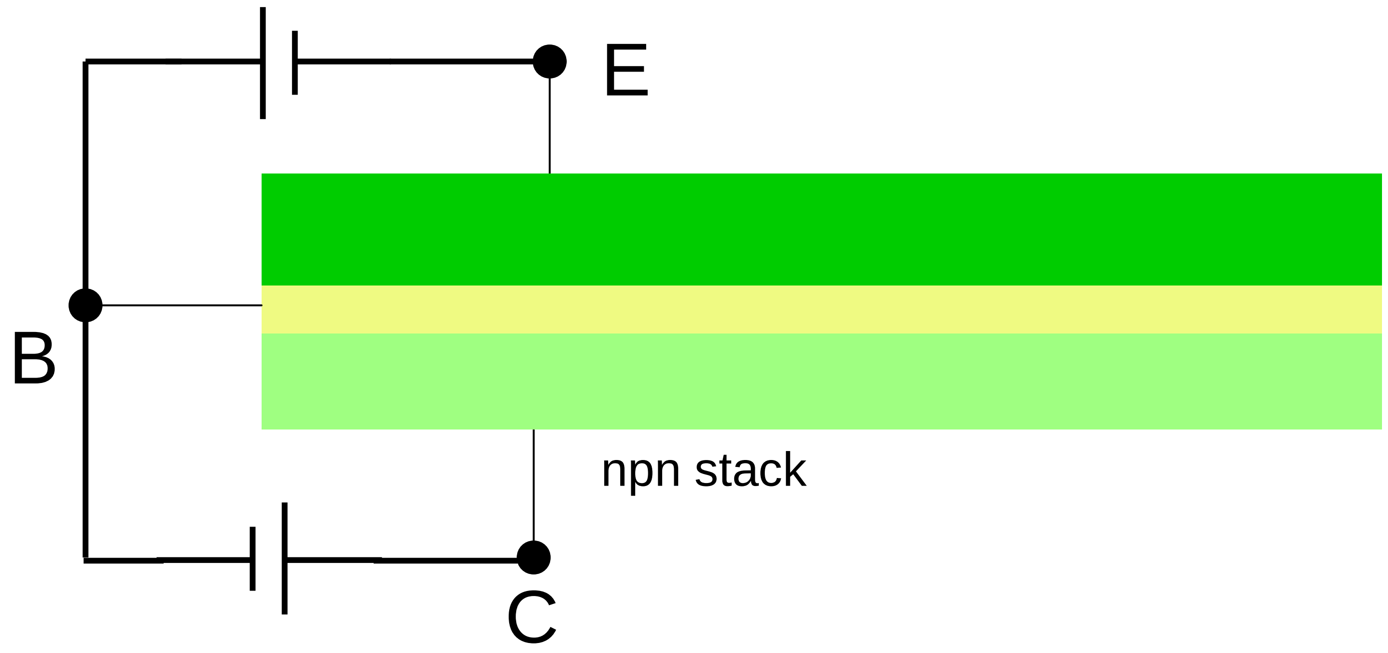
Carriers in emitter are electrons (majority carriers)

When electrons pass into the base they become minority carriers

When minority carriers are present in the base they can be attracted to collector
Minority carriers either recombine with holes and contribute to base current
or are attracted into collector region and contribute to collector current

Bipolar Operation

Consider npn transistor



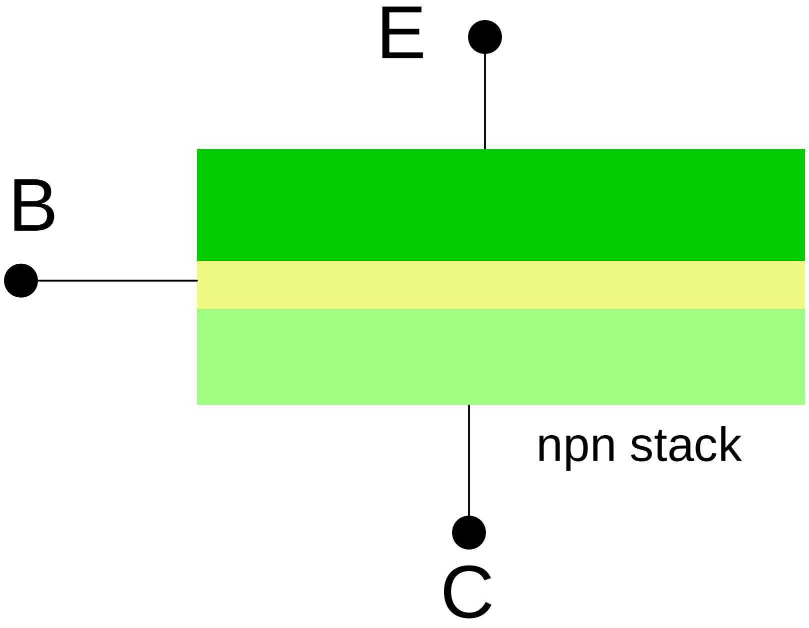
Under forward BE bias and reverse BC bias current flows into base **region**

Efficiency at which minority carriers injected into base region and contribute to collector current is termed α

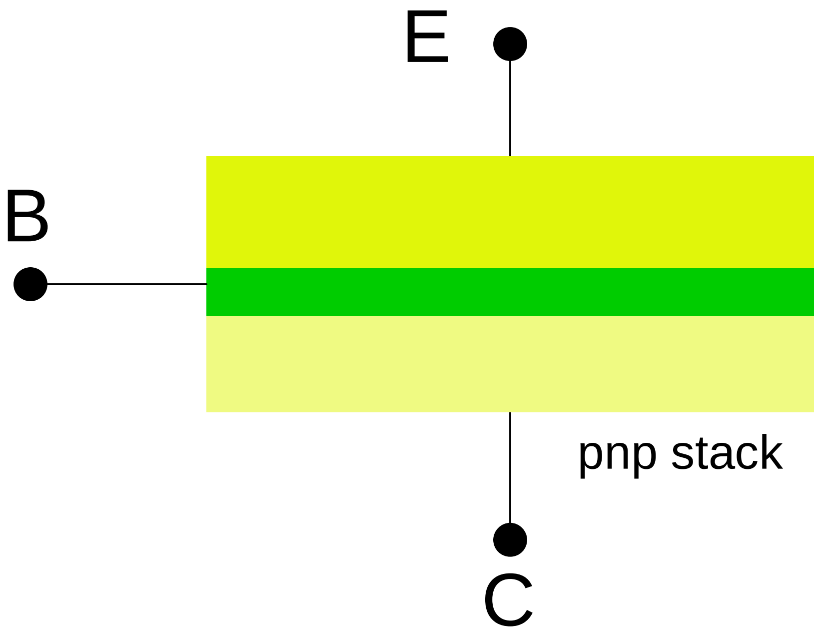
α is always less than 1 but for a good transistor, it is very close to 1

For good transistors $.99 < \alpha < .999$
Making the base region very thin makes α large

Bipolar Transistors



npn stack



pnp stack

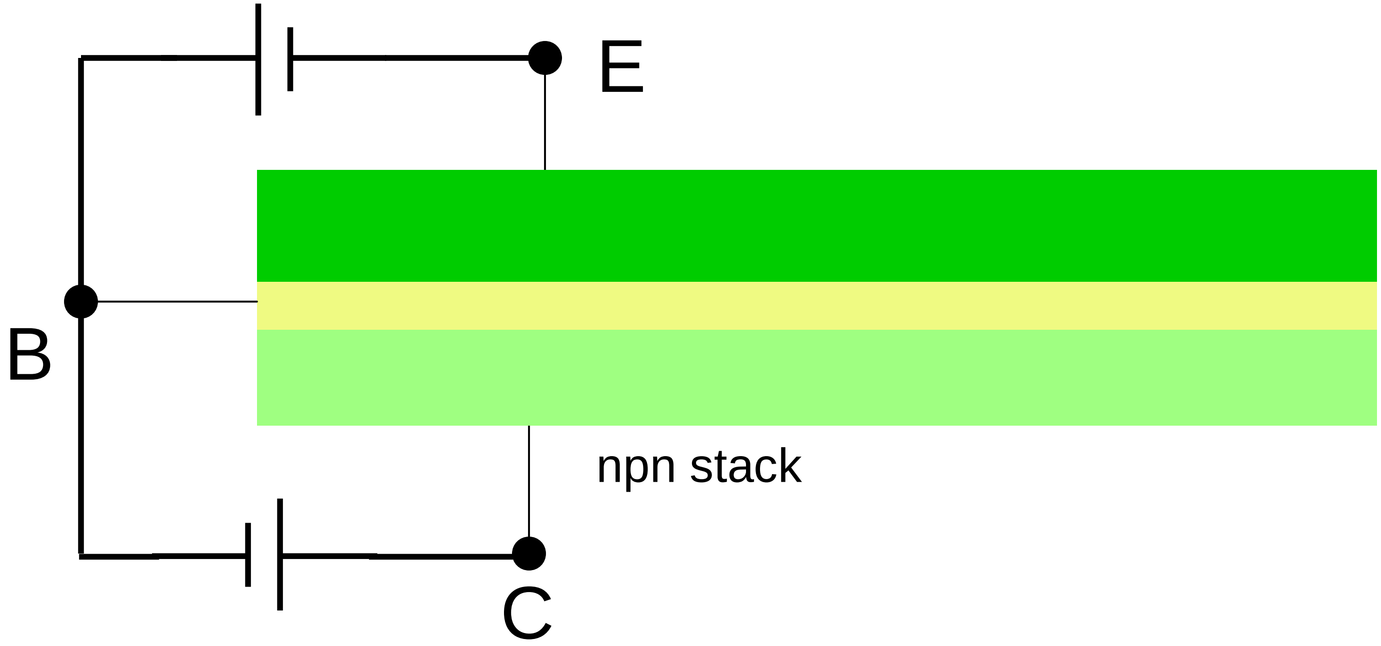
principle of operation of pnp and npn transistors are the same

minority carriers in base of pnp are holes

npn usually have modestly superior properties because mobility of electrons
Is larger than mobility of holes

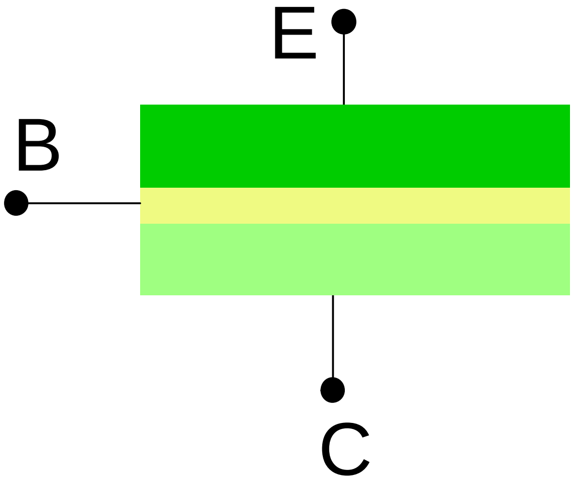
Bipolar Operation

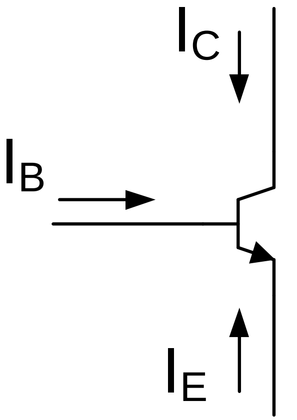
Consider npn transistor



In contrast to MOS devices where current flow in channel is by majority carriers, current flow in the critical base region of bipolar transistors is by minority carriers

Bipolar Operation





$$\left.\begin{aligned} I_C + I_B &= -I_E \\ I_C &= -\alpha I_E \end{aligned}\right\}$$

$$I_C = \frac{a}{1-a} I_B$$

$$b \overset{defn}{=} \frac{a}{1-a}$$

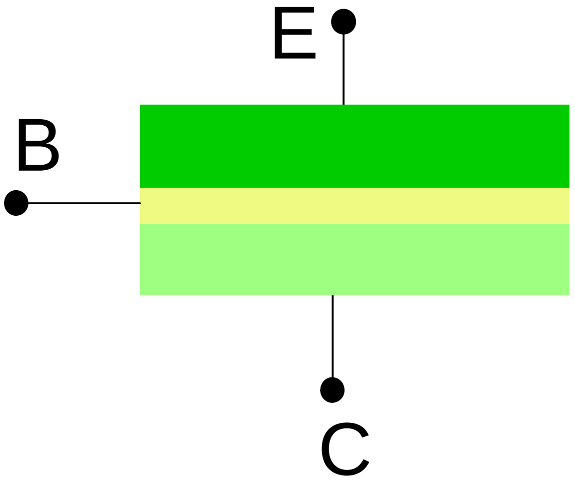
$$I_C = b\, I_B$$

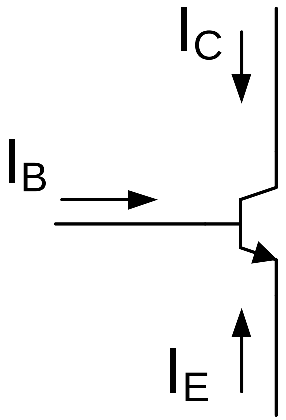
β is typically very large

often 50<β<999

$I_C = b\, I_B$

Bipolar Operation





$$I_C = b\, I_B$$

β is typically very large

Bipolar transistor can be thought of a current amplifier with a large current gain

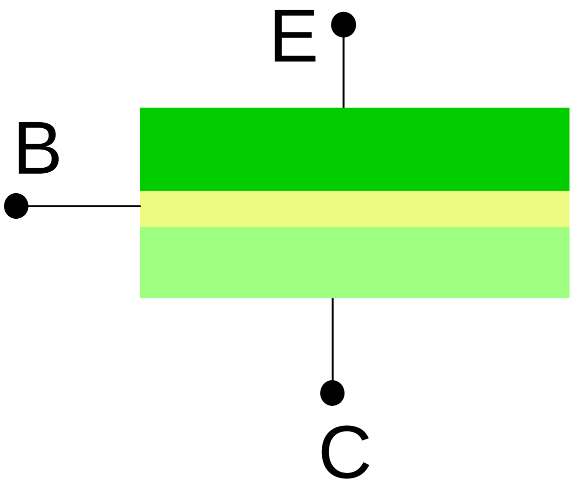
In contrast, MOS transistor is inherently a tramsconductance amplifier

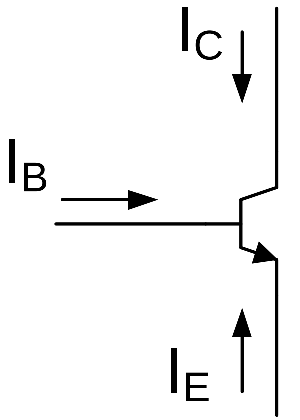
Current flow in base is governed by the diode equation $$I_B = \tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$

Collector current thus varies exponentially with V_{BE} $$I_C = b\tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$

$I_C = b\, I_B$

Bipolar Operation





$$I_C = b\, I_B$$

β is typically very large

Collector current thus varies exponentially with V_{BE}

$$I_C = b\tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$

This exponential relationship (in contrast to the square-law relationship for the MOSFET) provides a very large gain for the BJT and this property is very useful for many applications !!