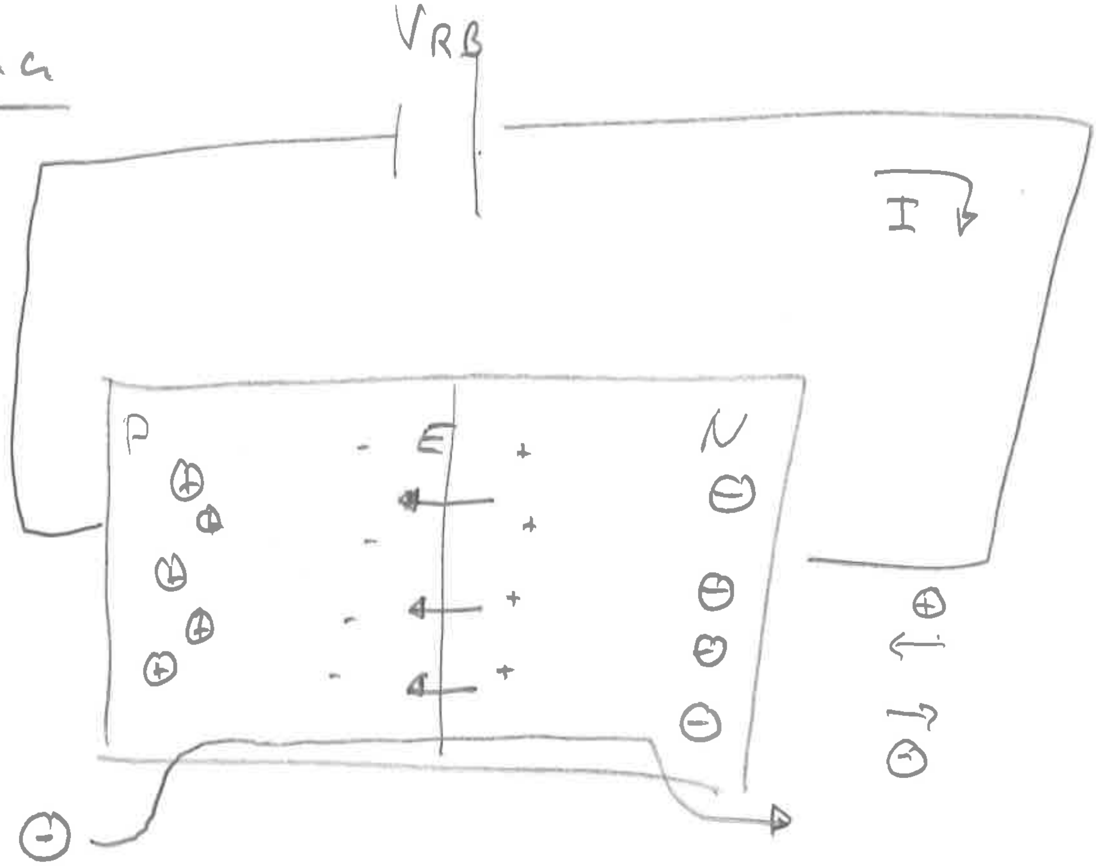
The

Transistor

(B model +
Basic Circuits)

(Needed for First
Transistor Lab)

Lemma



No current for majority carriers, because E-field fights pulling out any more.

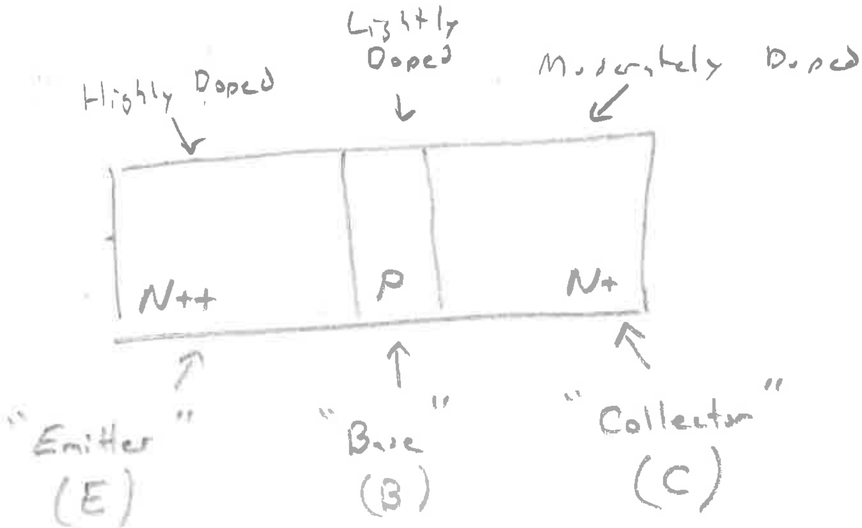
But an electron on P side sails right through.

RB for majority carriers

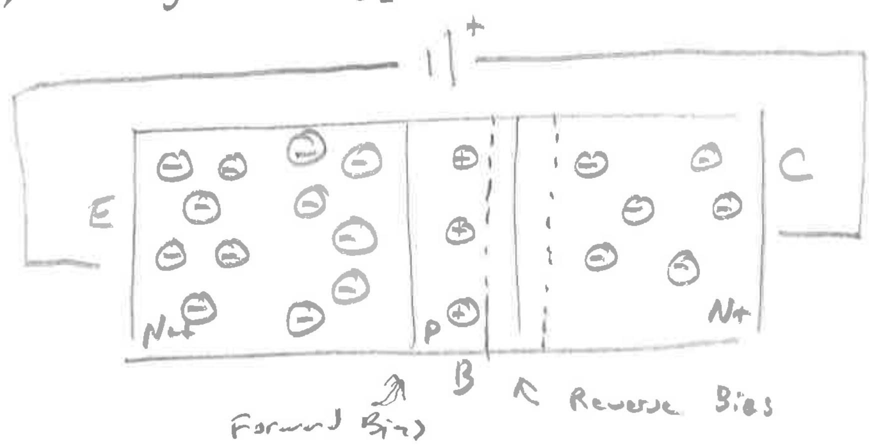
= FB for minority carriers

Bipolar Junction Transistor

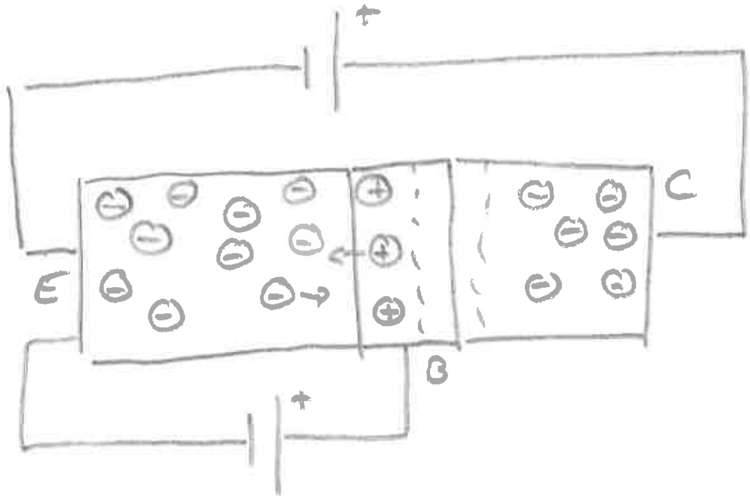
Design:



1) Apply voltage V_{CE}:

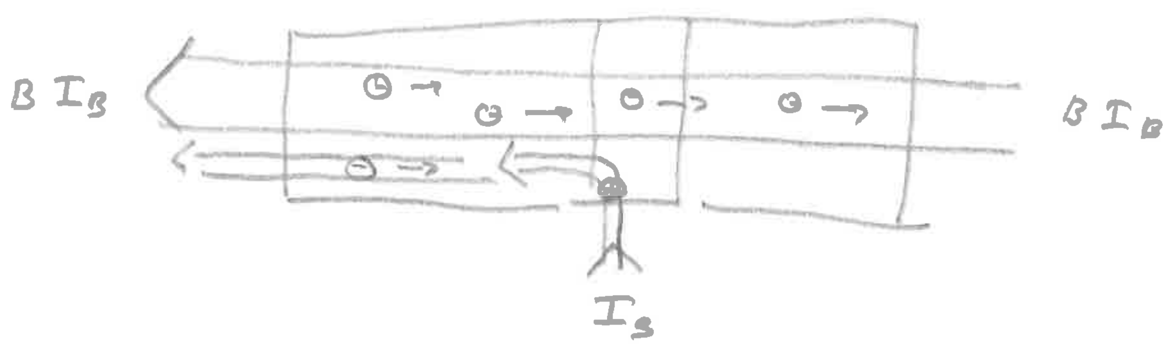


One junction is Forward Biased, but the other is reverse biased, so no current flows... until



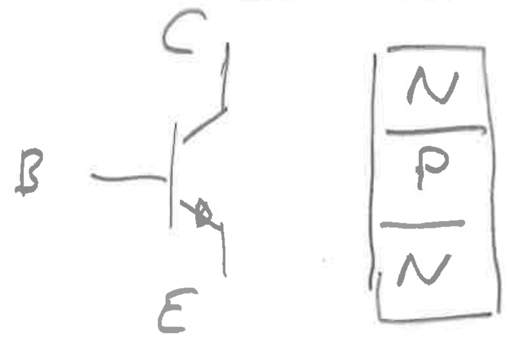
2) Apply voltage V_{BE} as well, now current flows through the forward biased diode made from N++ P in E B portion of transistor

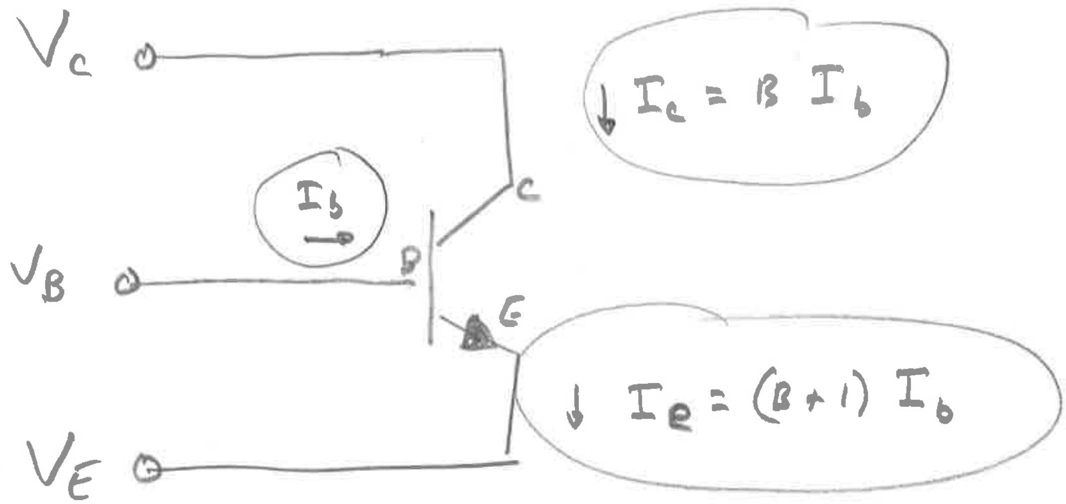
3) But! E is highly doped, compared to lightly doped, and thin, base. Electrons overwhelm holes and spill into the base. Minority carriers have no problem crossing the reverse biased junction (field accelerates them!)
Result:



Amplified current B I_B flows from C to E

Modelling Transistors for circuit design!





"Rules"

1) Keep $V_c > V_E$

2) "Usually" $B \to E$ is forward biased with diode drop V_d when transistor is <u>on</u>.

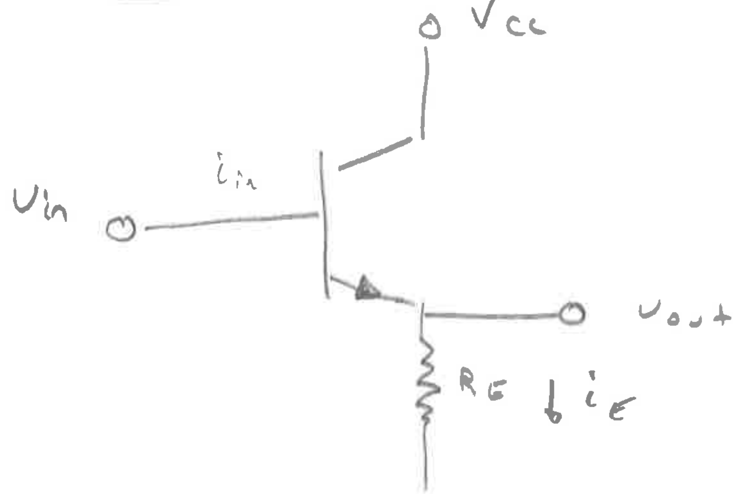
3) "Usually" $C \to B$ is reverse-biased, but only <u>technically</u>. Because I_b injects <u>minority</u> carriers at base an <u>amplified</u> current flows despite (or even <u>because</u>) of reverse bias:

$$\boxed{I_c = \beta I_b}$$

4) All devices have limits: Max V_{CE}, I_B, I_c

*** β is unreliable ***

Emitter Follower



$V_{out} = V_{in} - V_d$

What's the point? Why not just:

Input Impedance $= \dfrac{\Delta V_{in}}{\Delta i_{in}} = R$

But for emitter:

$$\Delta V_{in} = \Delta V_{out}$$

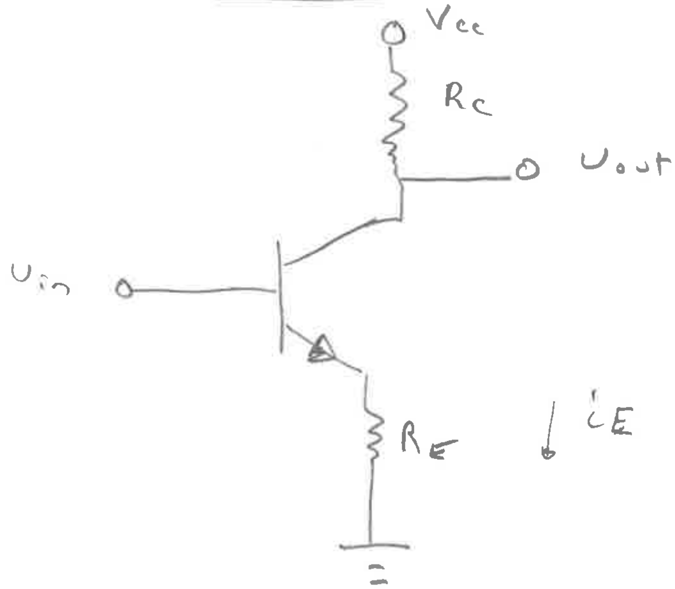
$$\Delta i_{in} = \Delta i_B = \frac{1}{(\beta+1)} \Delta i_E$$

$$\frac{\Delta V_{in}}{\Delta i_{in}} = (\beta+1) \frac{\Delta V_{out}}{\Delta i_E} = (\beta+1) R$$

Input impedance is $(\beta+1) R >> 1$

** Rely on β being <u>big</u> but not a certain value! ** $(\sim \beta R)$

Voltage Gain



$$i_E = \frac{V_{in} - V_d}{R_E} \qquad i_C = \frac{B}{B+1} i_E$$

$$V_{out} = V_{cc} - R_c i_C$$

$$= V_{cc} - R_c \frac{V_{in} - V_d}{R_E} \left(\frac{B}{B+1} \right)$$

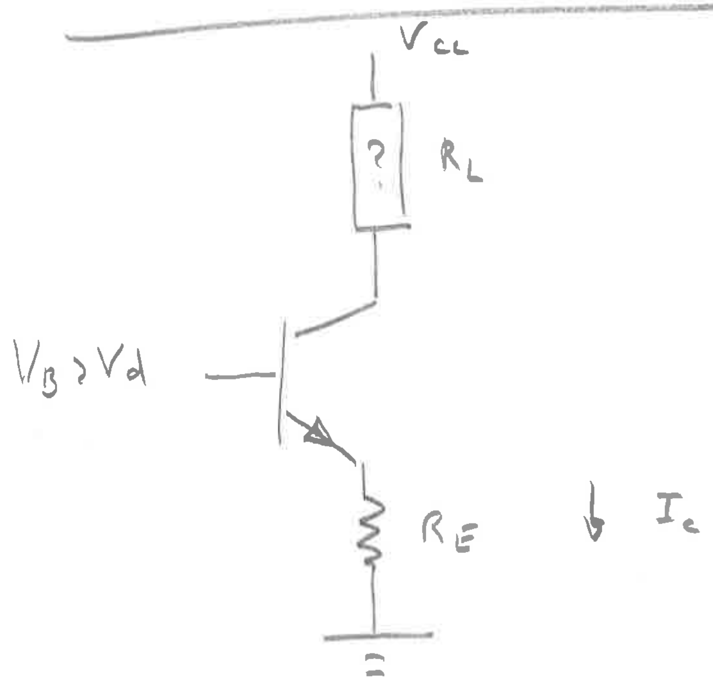
$$\frac{d V_{out}}{d V_{in}} = - \frac{R_c}{R_E} \left(\frac{B}{B+1} \right) \approx - \frac{R_c}{R_E}$$

Voltage Gain Factor $- \frac{R_c}{R_E}$

Inverting Amplifier

* $\left(\frac{B}{B+1} \right)$ factor shows good design ... doesn't depend on B! *

Transistor Current Source



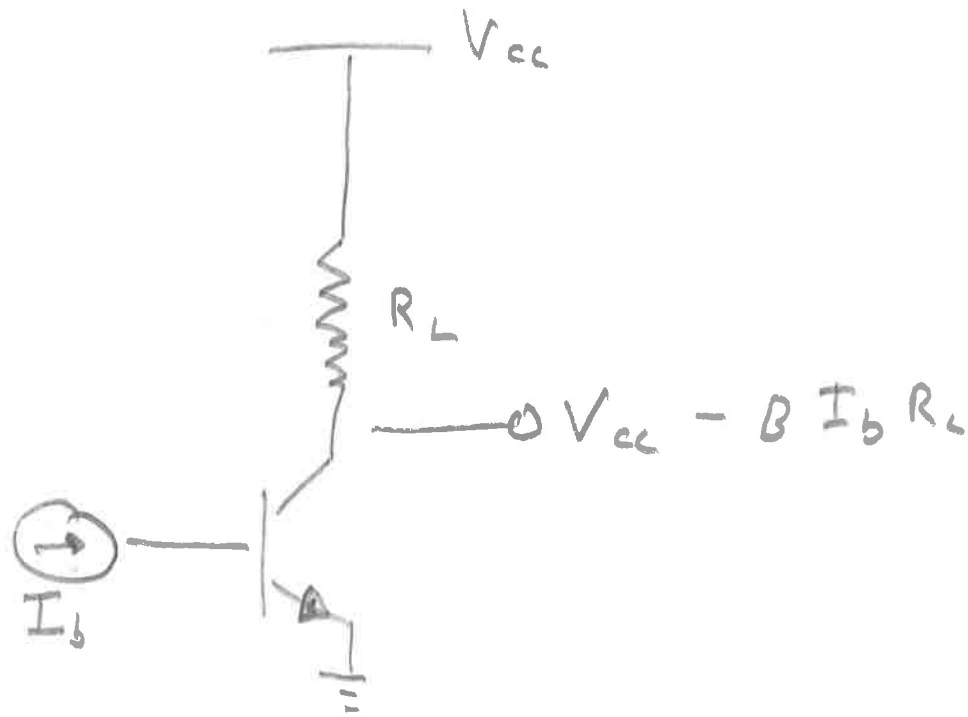
$$I_E = \frac{V_B - V_d}{R_E}$$

$$I_C = \frac{B}{(B+1)} \frac{V_B - V_d}{R_E}$$

Independent of $\underline{\underline{R_L}}$! (And β!)

A current source !

Saturation!



Suppose we make I_b very large, so drop on R_L is $\beta I_b R_L$

It seems for large enough I_b we can make

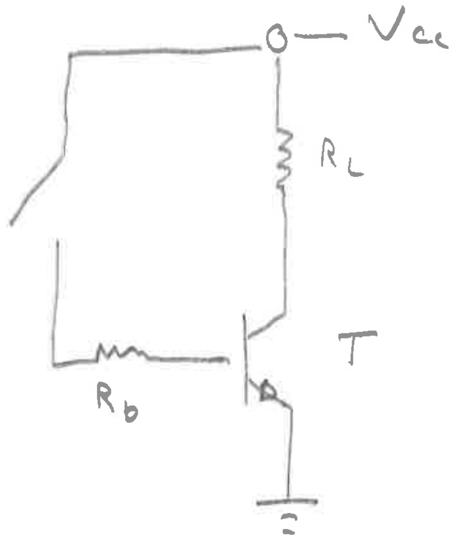
$$V_c = V_{cc} - \beta I_b R_L < 0.$$

But that breaks $V_c > V_E$. What happens

$V_c \sim V_E$ within less than a diode drop.

(Notice in this case, both PN junctions are forward biased, that's only way V_{CE} can be less than a diode drop!)

Transistor Switch



Want T to look like a switch $V_C = V_E$, i.e. in saturation.

In this case: $I_C = \dfrac{V_{cc}}{R_L}$

To provide this much current must insure

$$I_B > \frac{1}{\beta} I_C$$

$$R_B < \frac{V_{cc} - V_d}{I_B} = \beta \frac{V_{cc} - V_D}{I_C}$$

$$= \beta \frac{V_{cc} - V_D}{V_{cc}} \cdot R_L$$

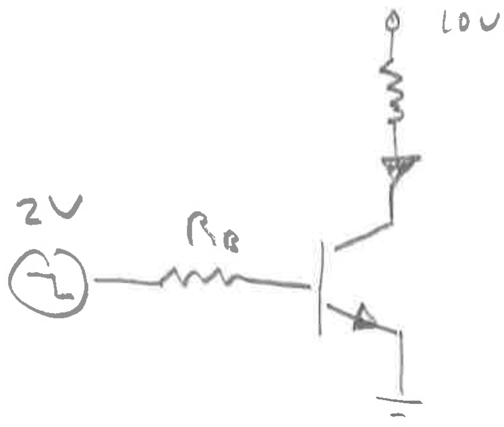
Choose lower than this, but without exceeding power limitations of diode.

(Use $\beta \sim 10$)

Transistor Switch

To burn bright, LED needs ~ 10 mA.

Use $R_1 \sim 1\,k\Omega$ (820Ω)



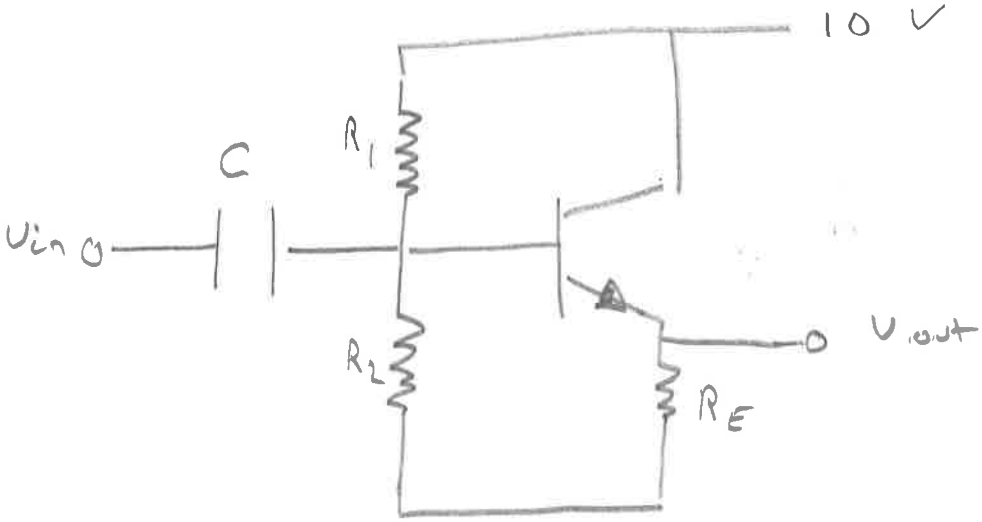
Near saturation $\beta \sim 10$, want $I_B \sim 1\,mA$

$$R_B = \frac{2V}{1mA} = 1\,k\Omega \qquad (820\,\Omega)$$

$$P = (2V)(1mA) = 2\,mW$$

(You will build in lab!)

Emitter Follower Design

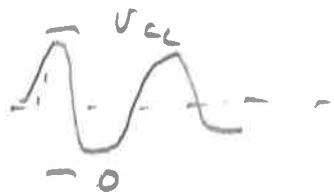


① Choose "quiescent bias" current $(I_E \sim I_C)$

$I_Q = 1\,mA$

② Choose DC point for Vout, usually

$\sqrt{\frac{1}{2}} V_{cc}$ for maximal swing



$V_E = \frac{1}{2} V_{cc}$

③ Calculate $R_E = \frac{V_E}{I_Q} = \frac{\frac{1}{2} V_{cc}}{I_Q} = \frac{5V}{1mA} \sim 5k\Omega \; (4.7k\Omega)$

④ Calculate (voltage divider) R_1/R_2 to set V_B

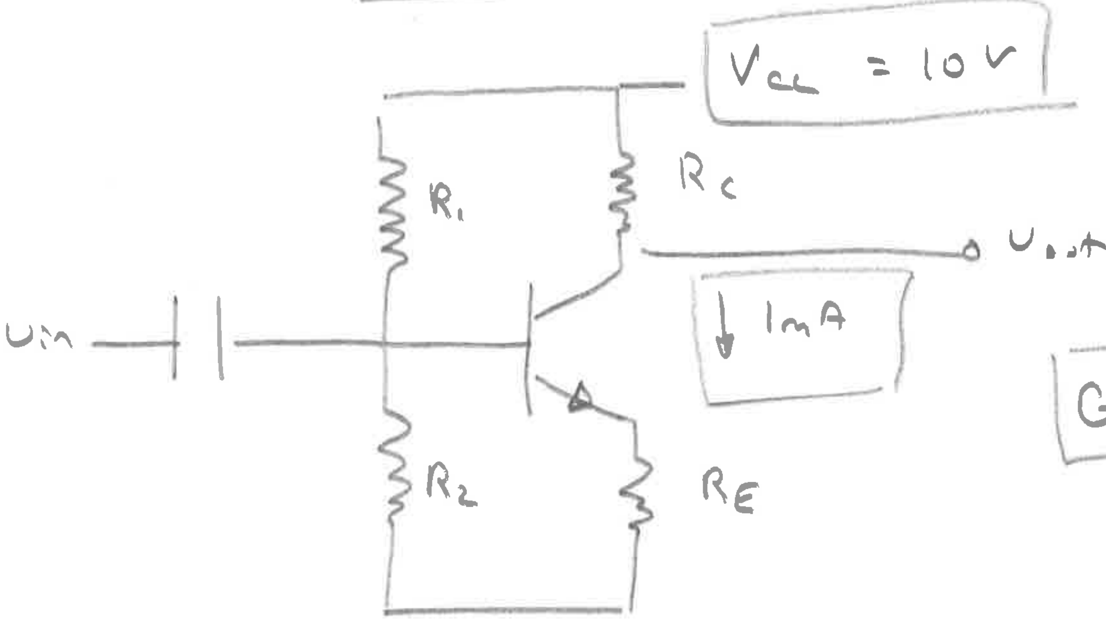
$V_B = \frac{R_2}{R_1+R_2} V_{cc} \qquad \frac{R_1}{R_2} = \frac{V_{cc}}{V_B} - 1 = \frac{10V}{5.6V} - 1$

$= 1.8$

⑤ Choose R_1, R_2 s.t. $R_1 // R_2 < \beta R_E = 100k\Omega$

$$\boxed{(R_1 = 5.6\,k\Omega \qquad R_2 = 8.2\,k\Omega)}$$

Common Emitter Amplifier



$\boxed{G \sim -5}$

① Choose $I_Q = 1\,mA$

② $V_c = \frac{1}{2} V_{cc} = 5\,V$

③ $R_c = V_c / I_Q = \frac{5V}{1mA} = 5\,k\Omega$ $(3.9\,k\Omega)$

④ Choose R_E to give correct gain:

$G = -\frac{R_c}{R_E}$ $\quad R_E \sim R_c/5 = 1\,k\Omega$ $(680\,\Omega)$

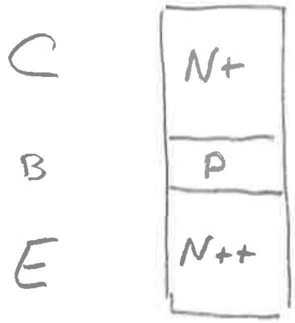
⑤ Calculate V_B, and find R_1/R_2 to provide it:

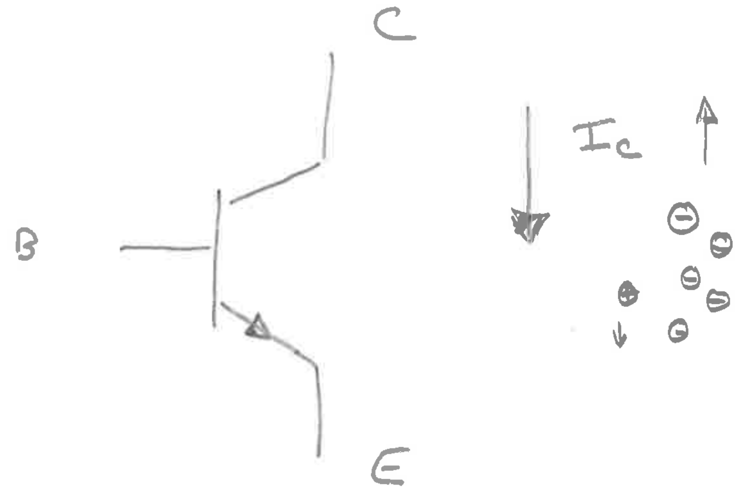
$V_B = R_E \cdot I_Q + V_0 = (1\,k\Omega)(1\,mA) + 0.6\,V$

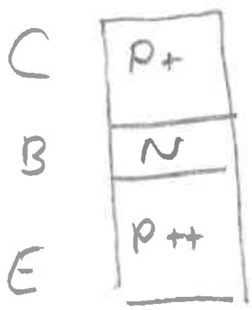
$= 1.6\,V$

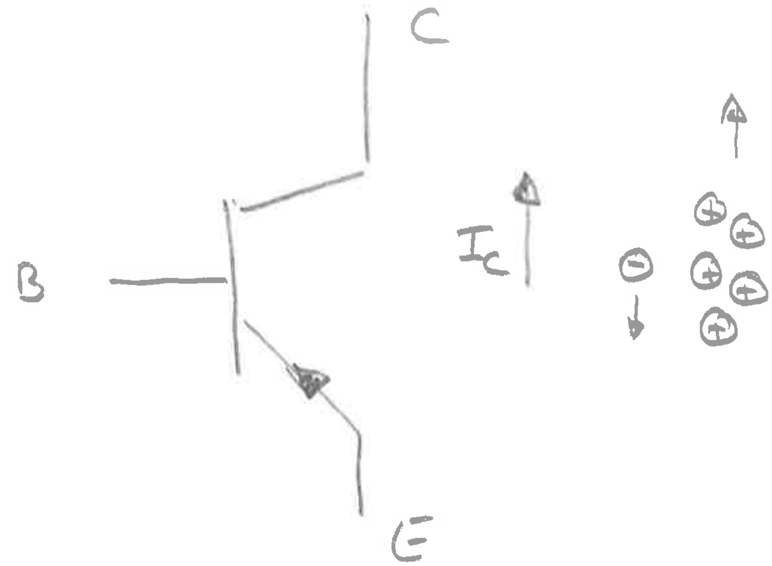
$\frac{R_1}{R_2} = \frac{V_{cc}}{V_B} - 1 = 5.25$

NPN / PNP

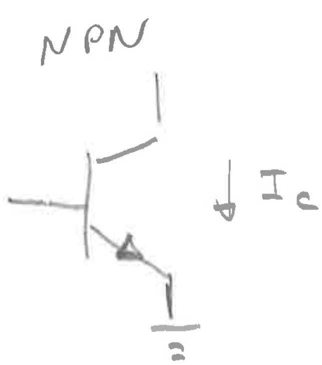




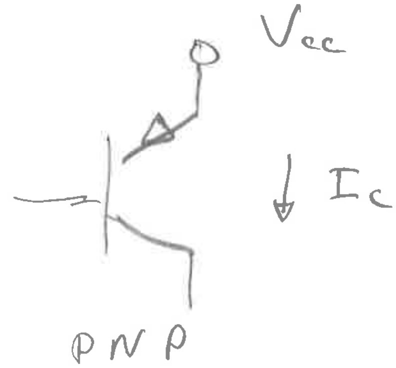




In circuits:

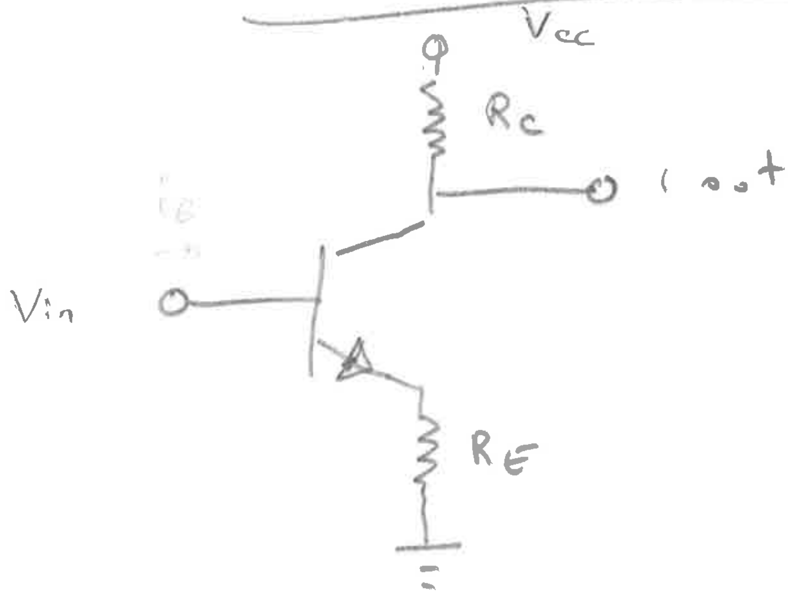


near ground
(or V_-)



near $V_{cc} = V_+$.

A Problem with Voltage Gain



$$I_B \sim V_{in} / \beta R_E$$

$$I_C \sim \beta I_B = \frac{V_{in}}{R_E}$$

$$V_{out} = V_{cc} - R_c I_c$$

$$= V_{cc} - R_c \left(\frac{1}{R_E} V_{in}\right)$$

$$\frac{\Delta V_{out}}{\Delta V_{in}} = - R_C \left(\frac{1}{R_E}\right)$$

If $R_E \to 0$ $\quad G \to -\infty$!