Lecture 1 : Emitter Follower

1. BJT Review
2. Emitter Follower Analysis
3. Emitter Follower Design

☆ minerva.union.edu/bumat

- PreLab 1 due next Thu (Sep 19)
- HW1 due next Fri (Sep 20)

Textbook Reading:

6-3	Transistor currents
6-8	Reading data sheets
6-10	Variations in current gain
7-11	pnp transistors
9-6	Darlington
9-7	Zener Follower

Analysis vs. Design

- ECE 248: Analyze circuits with diodes and transistors.

✲ ECE 363: **Design** circuits with op amps and transistors!

↳ "Accuracy"

[e.g. Stable voltage gain]

↳ "Heavy Lifting"

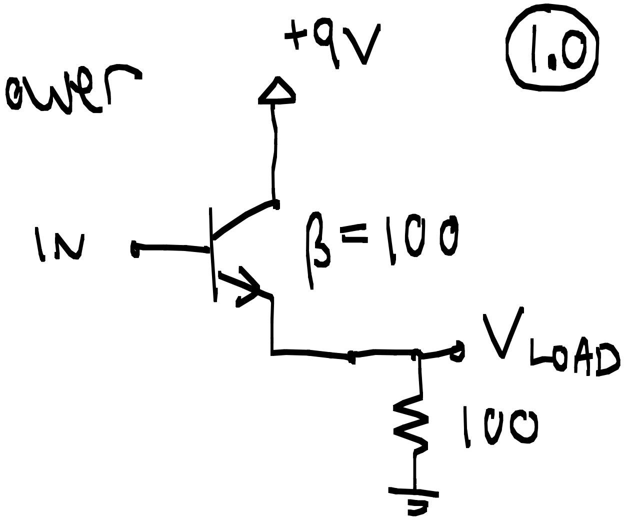
[e.g. Delivers load current]

op amps typically output < 25 mA

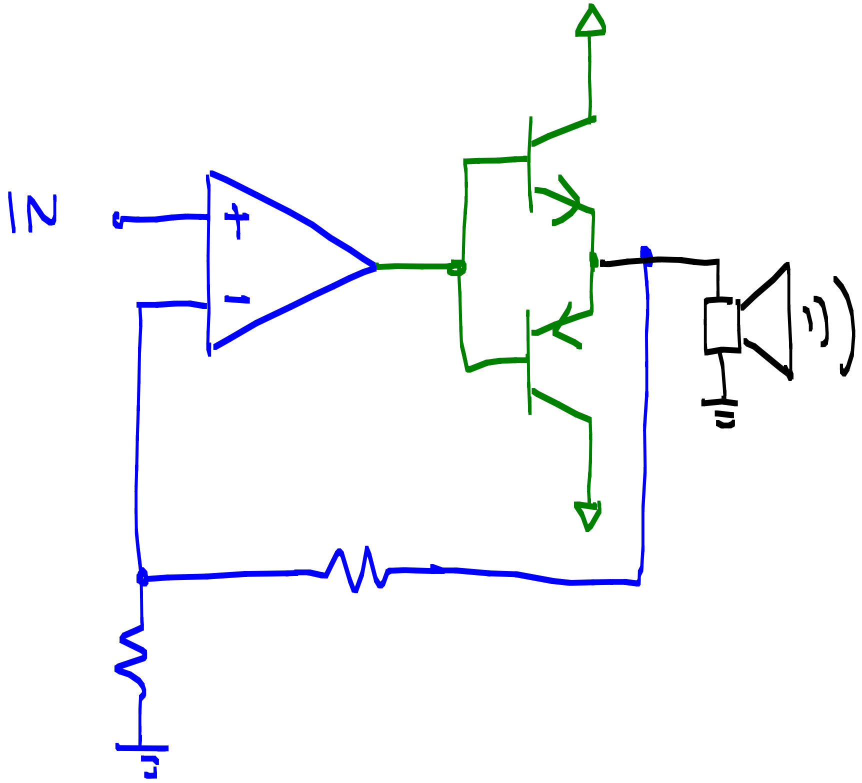
Small transistor (100 mA)

Power transistor (~5A)

Example Emitter Follower



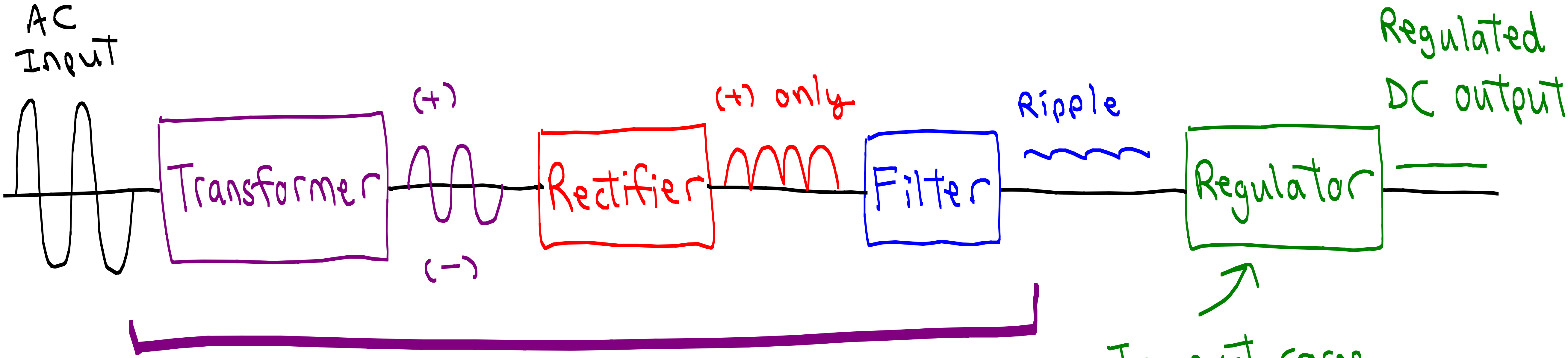
Example Audio Amplifier



1. Linear DC Supply

- Many electronic devices require a DC voltage. ← e.g. 12V
- Wall outlet provides AC voltage ($120V_{rms}$, 60Hz)
- Linear DC power supplies have the following:

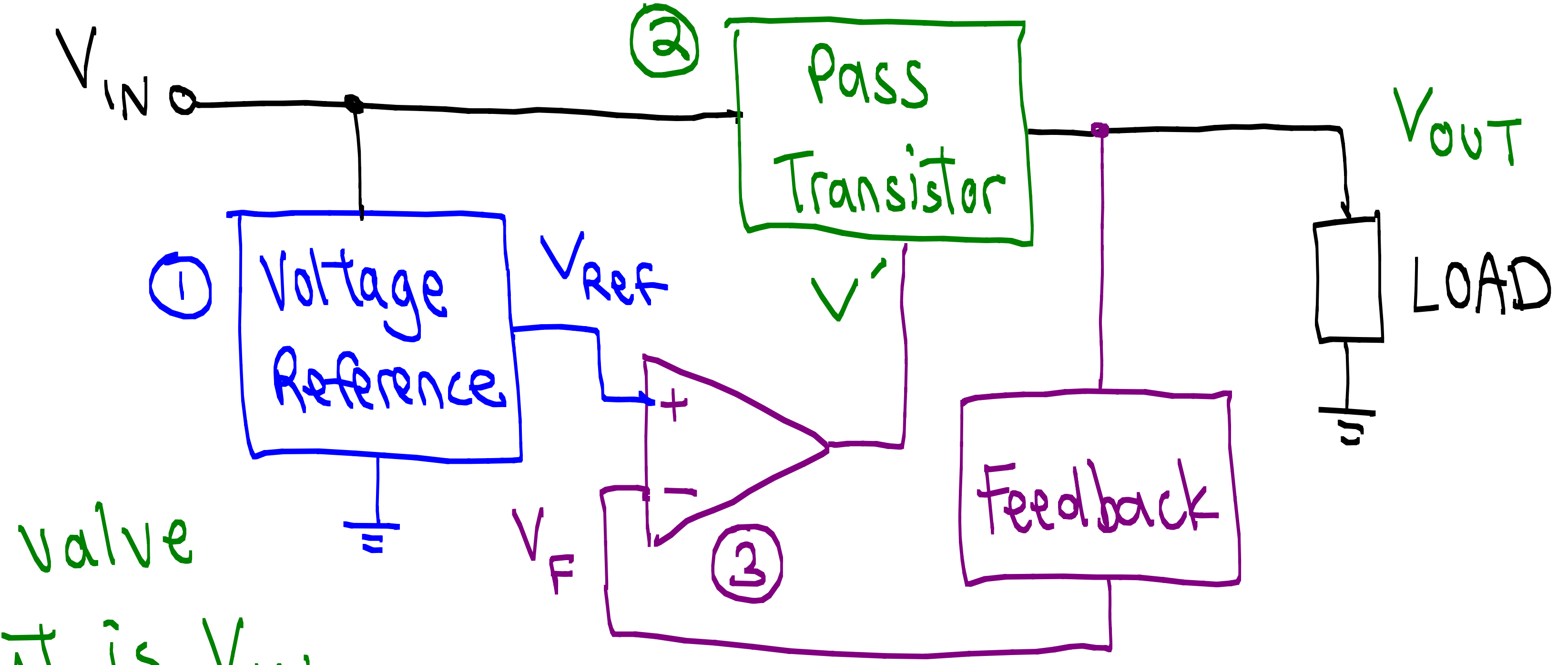
Benchtop Supply



Unregulated DC supply

In most cases, you would use an IC chip (e.g. LM7812)

Q: How to make a voltage regulator? → 3 key ingredients!



① Voltage reference
- Powered by V_{IN}
- Produces stable V_{Ref}

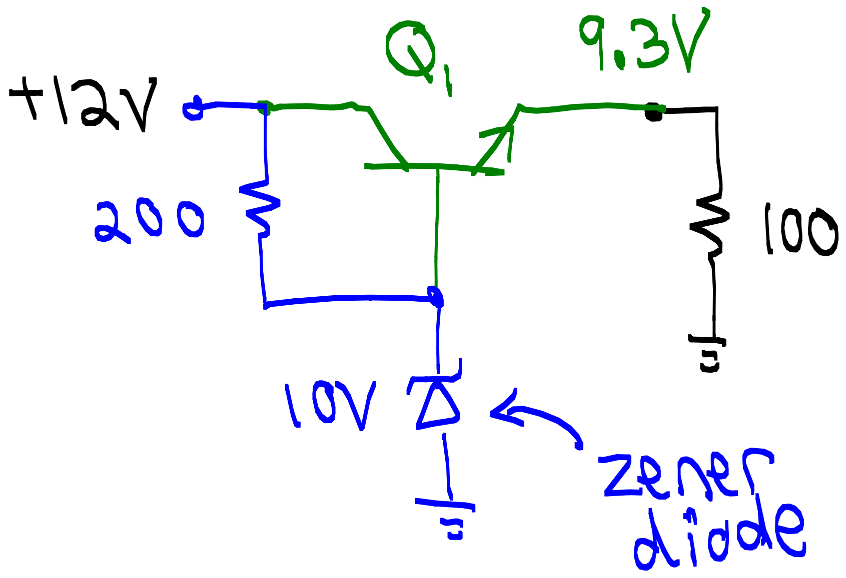
② Pass Transistor
- Acts like a pressure valve

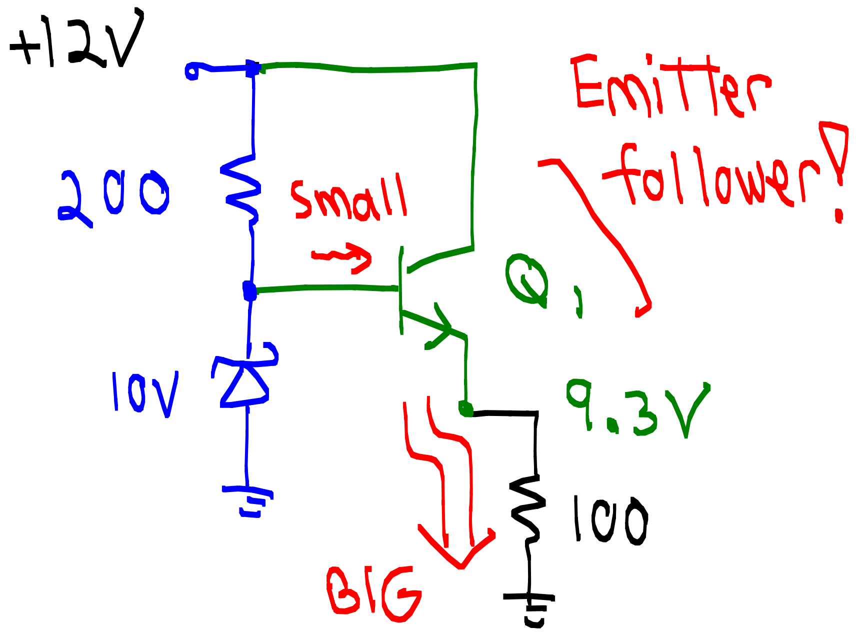
Control knob is V' $\left\{ \begin{array}{l} \text{Input is } V_{IN} \\ \text{Output } V_{OUT} < V_{IN} \end{array} \right.$

③ Negative Feedback
- Monitor V_{OUT} to adjust pass transistor $\left\{ \begin{array}{l} \text{If } V_{OUT} \text{ too high} \rightsquigarrow V_F > V_{ref} \rightsquigarrow V' \downarrow \rightsquigarrow V_{OUT} \downarrow ☺ \\ \text{If } V_{OUT} \text{ too low} \rightsquigarrow V_F < V_{ref} \rightsquigarrow V' \uparrow \rightsquigarrow V_{OUT} \uparrow ☺ \end{array} \right.$

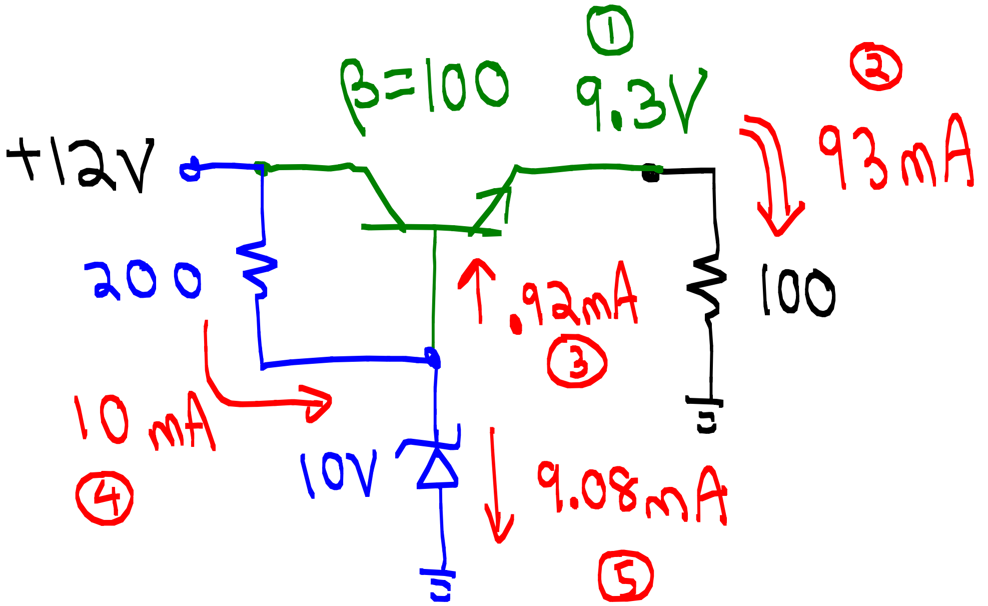
2. Emitter Follower Analysis

- Recall the zener follower from ECE248:





- "Quick" analysis (ECE 248 style):



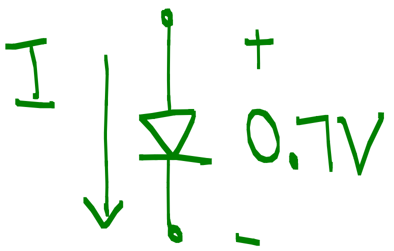
★ Problems with this circuit?

☹ ① Value of V_{OUT} ← Limited by available V_z

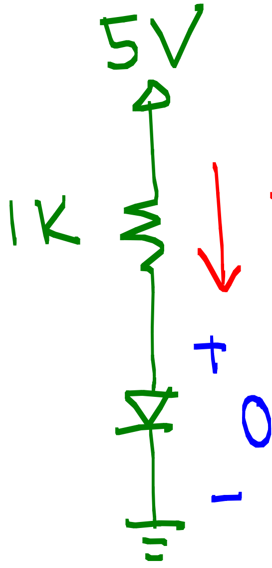
☹ ② No feedback! ← V_{OUT} is not actively stabilized

• Diode Review

"Typical" Diode



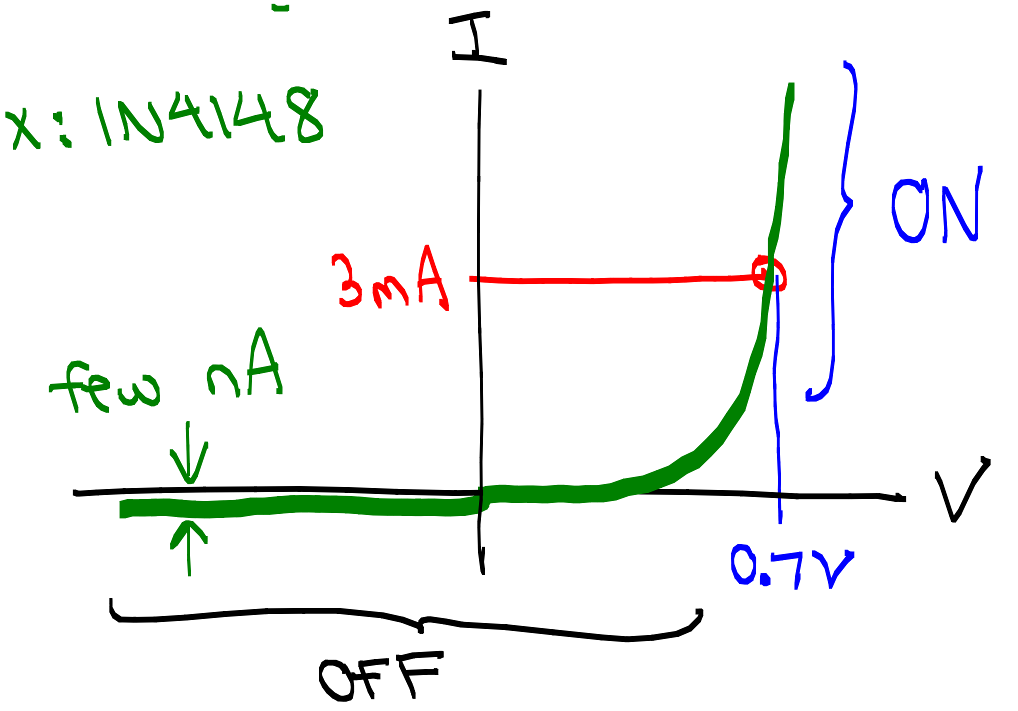
Ex:



$I = \frac{5-0.7}{1K} = 4.3mA$

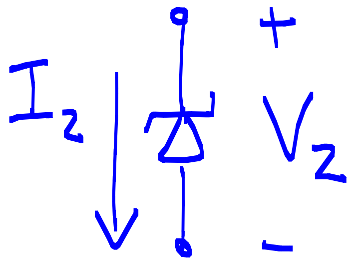
0.7V ← Not really true!

Ex: 1N4148

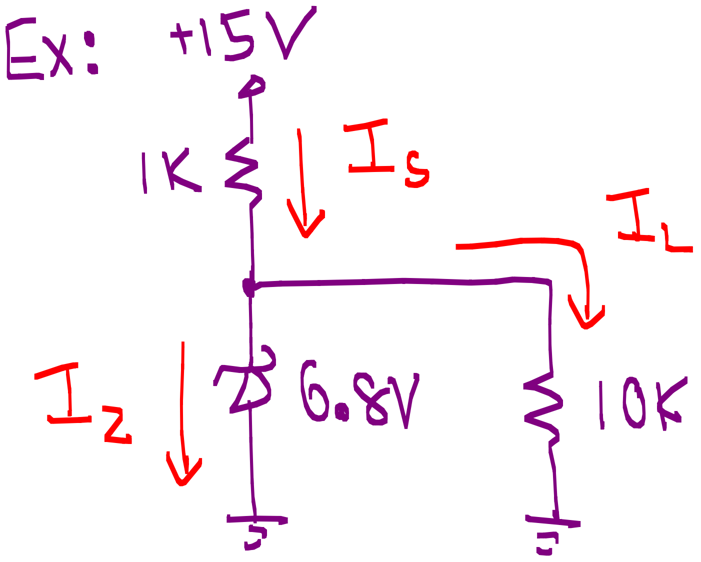


Zener Diode

← used "backwards"



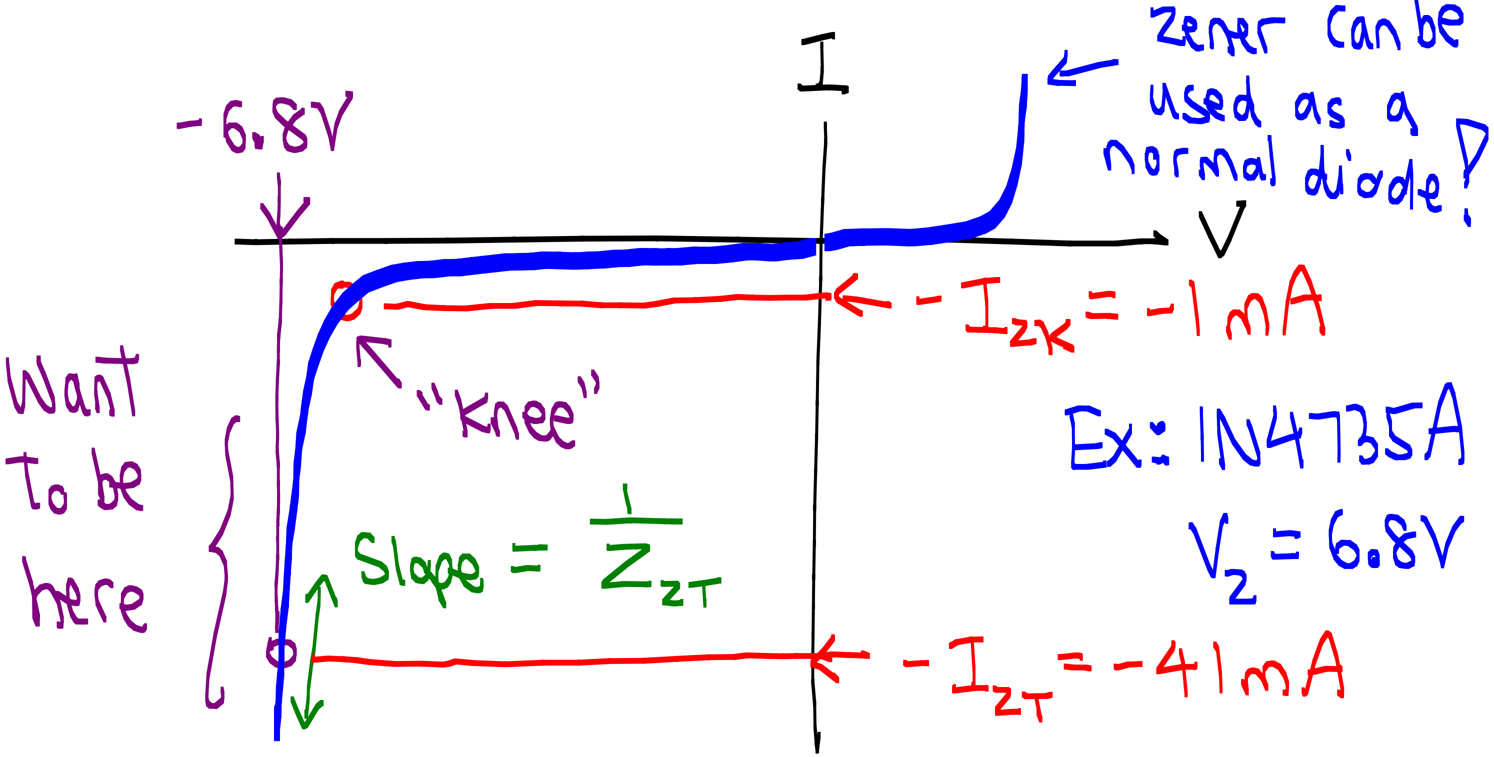
Ex:



$$I_Z = I_S - I_L$$

$$= \frac{15-6.8}{1K} - \frac{6.8-0}{10K}$$

$$= \underline{\underline{7.52mA}}$$



zener can be used as a normal diode!

Ex: 1N4735A

$V_Z = 6.8V$

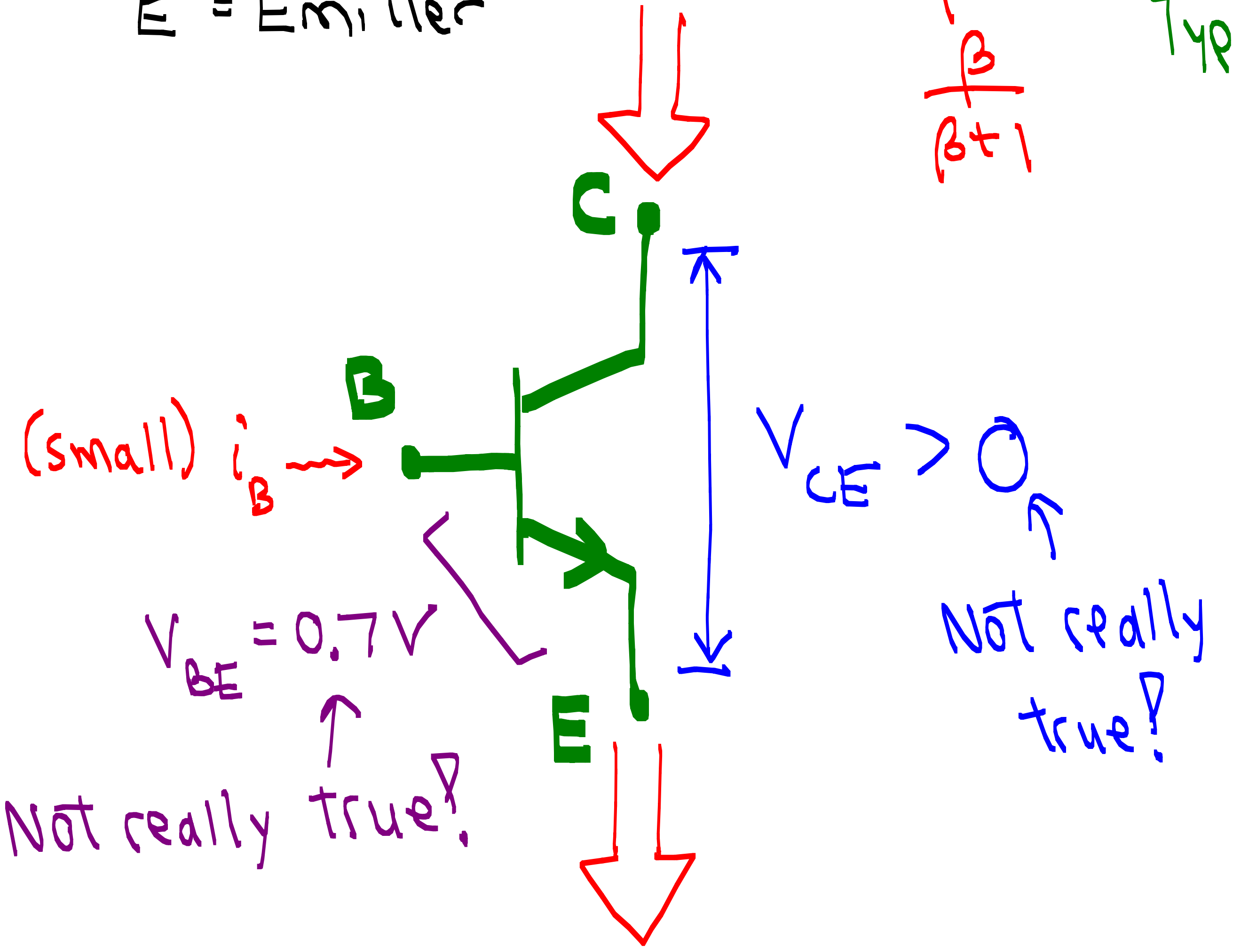
• Transistor Review (Active Mode)

C = Collector

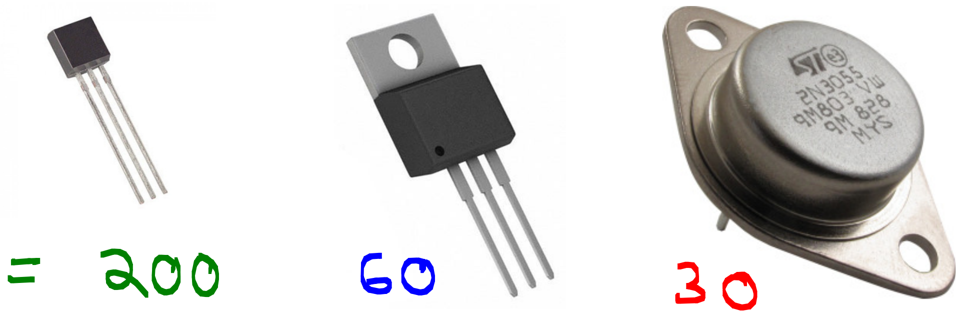
B = Base

E = Emitter

$$i_C = \overset{\surd}{\beta}\, i_B = \alpha\, i_E \qquad \alpha = \frac{\beta}{\beta+1}$$

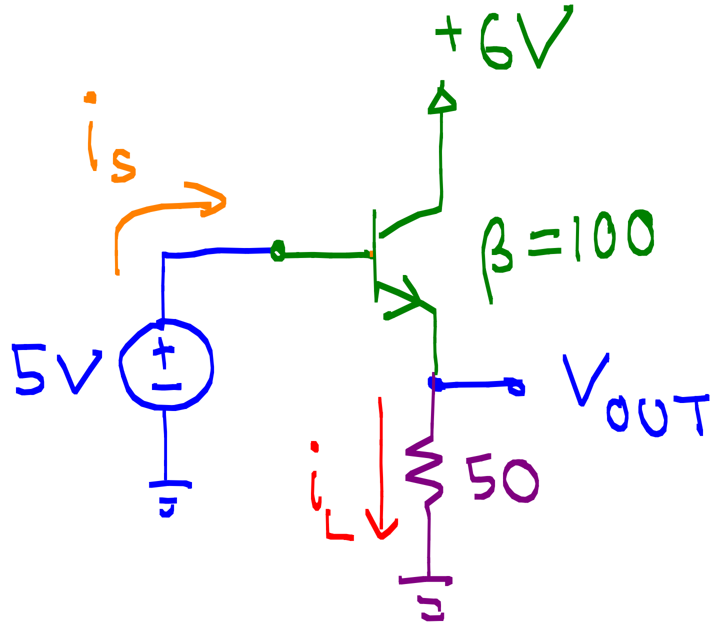


$$i_E = (\beta+1)\, i_B = i_C + i_B$$



	2N3904	TIP31	2N3055
Typical β =	200	60	30
Typical I_C =	.010A	1A	5A

Ex:



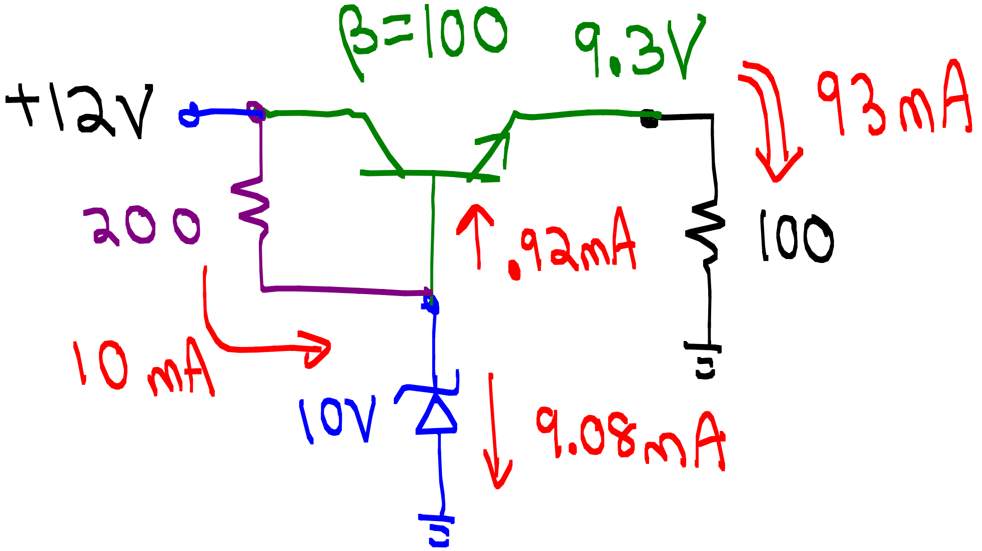
① $V_{OUT} = 5 - 0.7 = 4.3V$

② $i_L = 4.3/50\Omega = .086A = 86mA$

③ $i_S = \frac{86mA}{101} = 0.85mA$

• Power Dissipation

Device failure is usually due to thermal breakdown!



★ Rule of thumb: Stay below 50% of device's max power limit!

Ex: ¼W resistor

$P = I^2R = \frac{V^2}{R}$

$= (.01)^2 200 = \frac{(12-10)^2}{200}$

$= .02W = 20\,mW$ ✓

½W Zener

$P = I_Z V_Z$

$= (9.08mA)(10V)$

$= 90.8mW$ ✓

0.6W Transistor

$P = I_B V_{BE} + I_C V_{CE}$

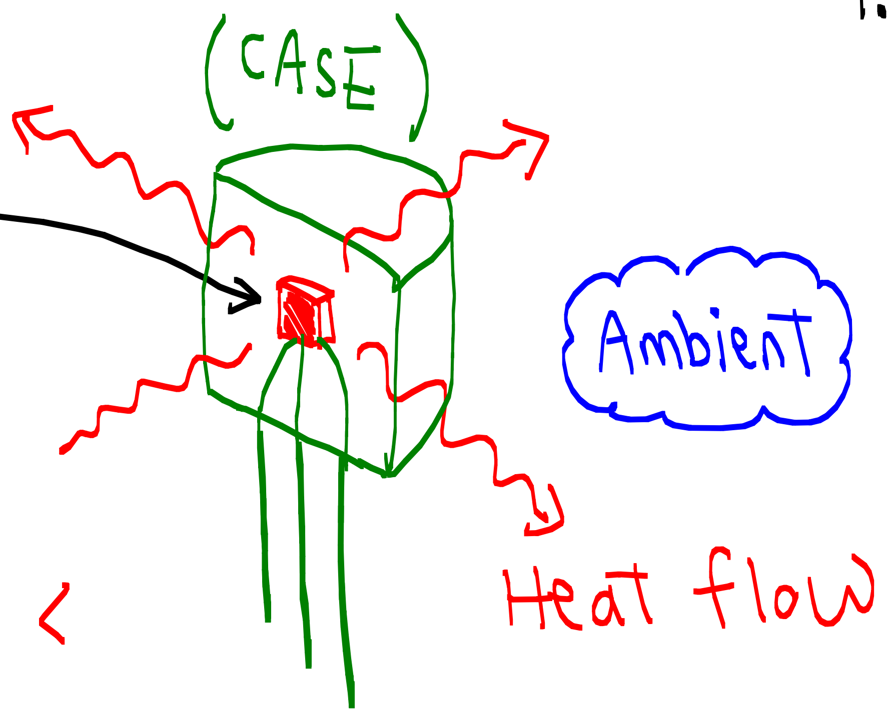
$= (.92mA)(0.7)$

$+ .99(93mA)(12-9.3)$

$= 249.2mW$ ✓

Q: What determines max power limit?

A: The temperature of the "junction" must not exceed a max value!
(BJT: 150°C , MOSFET: 175°C)

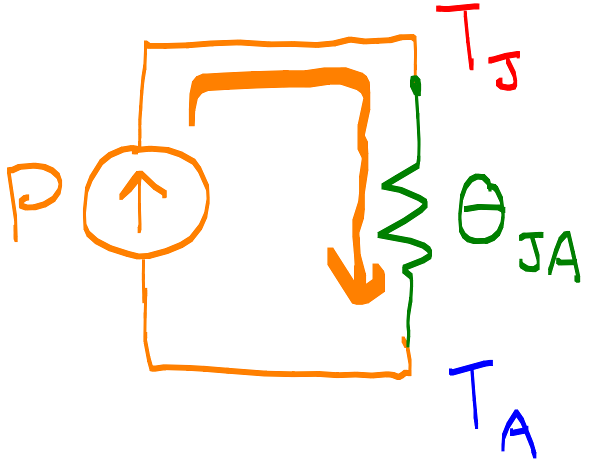


⇒ Can compute T_J with "thermal Ohm's Law"

$$\boxed{T_J - T_A = P \cdot \Theta_{JA}}$$

Thermal resistance from junction to ambient

Power dissipation acts like a current source →



① Power dissipation in junction creates heat

↓

Θ_{JA}

② Heat travels from junction to case

↓

③ Heat escapes from case to ambient

Thermal Characteristics $T_a = 25°C$ unless otherwise noted

For 2N3904 transistor

1.8

Symbol	Parameter	Max.			Units
		2N3904	*MMBT3904	**PZT3904	
P_D	Total Device Dissipation Derate above 25°C	625 5.0	350 2.8	1,000 8.0	mW mW/°C
$R_{\theta JC}$	Thermal Resistance, Junction to Case	83.3			°C/W
$R_{\theta JA}$	Thermal Resistance, Junction to Ambient	200	357	125	°C/W

$R_{\theta JA} = \Theta_{JA}$

For BJT, max $T_J = 150°C$!

$(T_A = 25°C)$ $P_{Rating} = \dfrac{T_J - T_A}{\Theta_{JA}}$

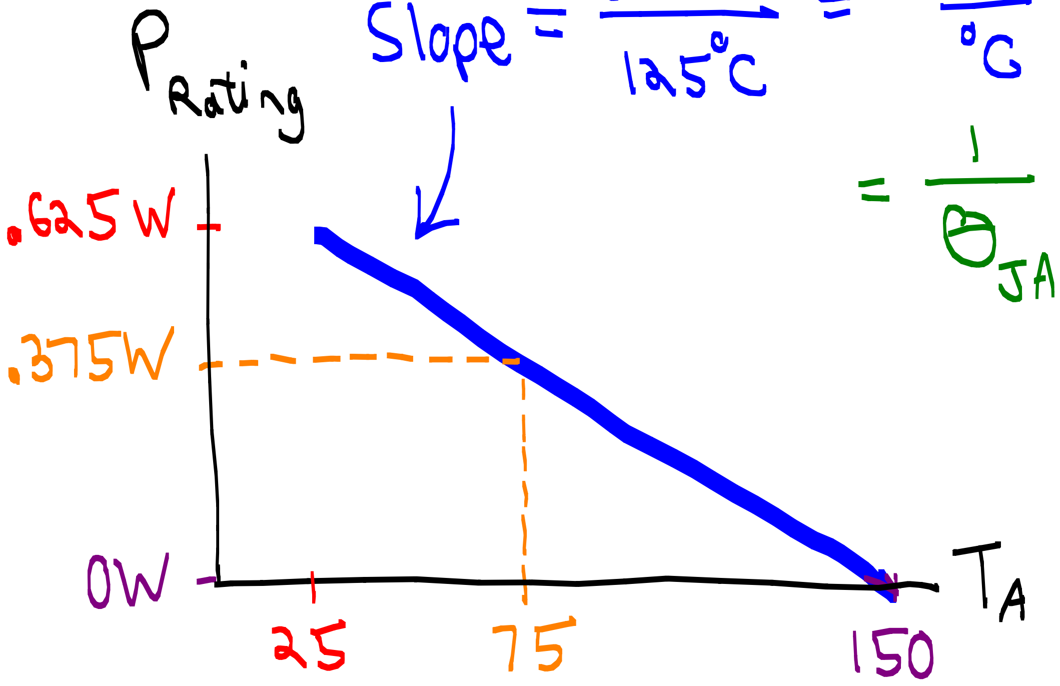
$= \dfrac{150 - 25°C}{200°C/W} = \underline{\underline{.625W}}$

$(T_A = 75°C)$ $P_{Rating} = \dfrac{150 - 75°C}{200°C/W} = \underline{\underline{.375W}}$

Derating Curve

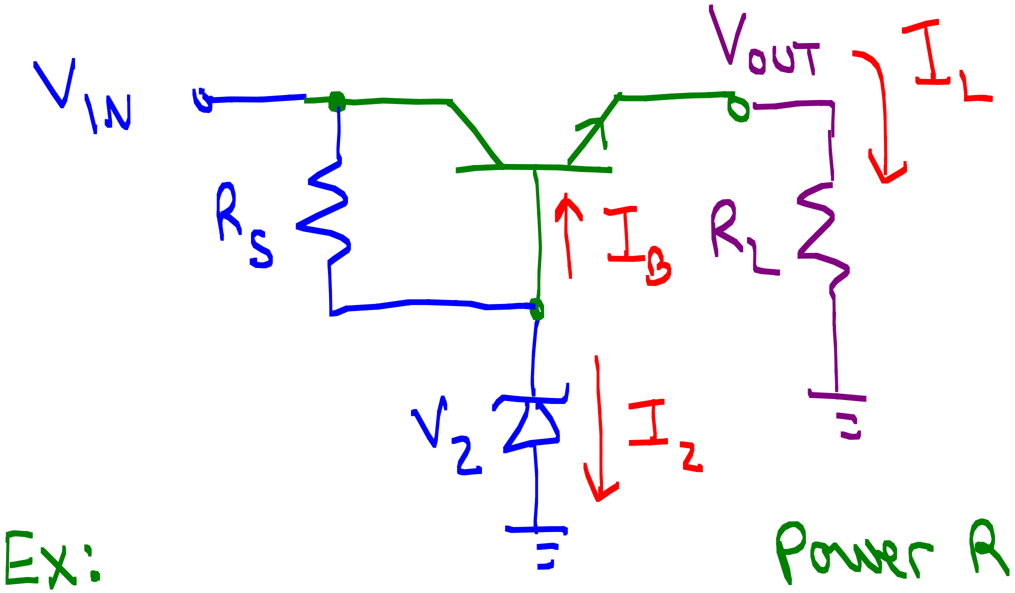
$\text{Slope} = \dfrac{625\,mW}{125°C} = 5\,\dfrac{mW}{°C}$

$= \dfrac{1}{\Theta_{JA}}$



3. Emitter Follower Design

Q: How to choose components?



★ Know your load: Greatest demand (e.g. max current)

★ Proper Transistor:

- Max I_C and V_{CE}

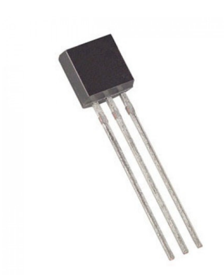
★ Zener: $I_Z \gtrsim 10\,mA$

★ Power rating for all components!

Ex:

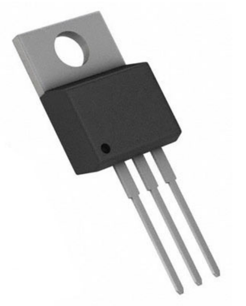
Transistor	Max I_C	Power Rating No heat sink $T_A = 25°C$	 With Heat sink $T_C = 25°C$
2N3904	200 mA ✗	625 mW	
2N4401	600 mA ✓	625 mW ✗	1.5W ✗
TIP31	3 A ✓	2 W ✗	40W ✓

2N3904

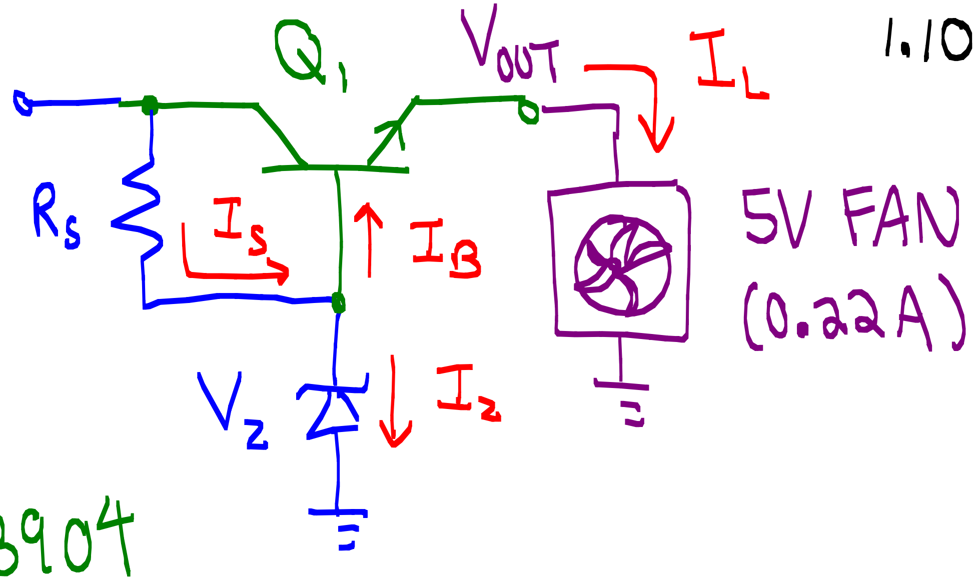


2N4401

TIP31



Design example



- $V_{OUT} = 5V = V_z - V_{BE} \sim V_z - 0.7$

  $\rightarrow V_z = 5.7V \Rightarrow$ Try $\boxed{5.6V \text{ Zener}}$ ← 1N4734A

- Q_1? We know $I_E = 0.22A$ ← Rules out 2N3904

  Estimate Max $P = I_B V_{BE} + I_C V_{CE} = \frac{.22A}{101}(0.7V) + \frac{100}{101}(.22A)(15-5) = \underline{\underline{2.18W}}$

  x2 safety factor

  Need > 4.36W rating

  $\boxed{\text{Choose TIP31 + Heat sink}}$

- R_s? Zener needs min $I_z > 10mA$

  min I_s - max $I_B > 10mA$

  $$\frac{12-5.6}{R_s} - \frac{.22A}{\beta+1} > .010A$$

  ← From TIP31 data sheet

- If designing for "typical" Q, properties:

5% tolerance

$\beta \sim \underline{\underline{120}}$ (See Appendix #1) $\rightarrow R_s < 541.5\Omega \xrightarrow{\times 0.95} 514.5\Omega \Rightarrow \boxed{\text{Choose } 510\Omega}$

Power rating? Max $P = \frac{(15-5.6)^2}{510\Omega} = .173W \xrightarrow{\times 2} .347W$ (½W rating ✓)

Zener? Max power $\cong \left(\frac{15-5.6}{510\Omega}\right)(5.6V) = .103W \xrightarrow{\times 2} \underline{\underline{.206W}}$ (¼W rating or higher)

- If designing for "worst case" Q, properties:

(430Ω probably ok)

$\beta = \underline{\underline{46}}$ (Appendix #1) $\rightarrow R_s < 436\Omega \xrightarrow{\times 0.95} 414\Omega \}$ Choose $\boxed{390\Omega}$

$P = \frac{(15-5.6)^2}{390} = .23W \xrightarrow{\times 2} .46W$ (½W rating)

Zener? Max power $\cong \left(\frac{15-5.6}{390}\right)(5.6V) = .135W \xrightarrow{\times 2} .27W$ (¼W rating or higher)

Appendix #1

- In reality, β depends on I_c!

→ To obtain "typical" value, use graph of β vs I_c in datasheet

TIP31

~220 mA

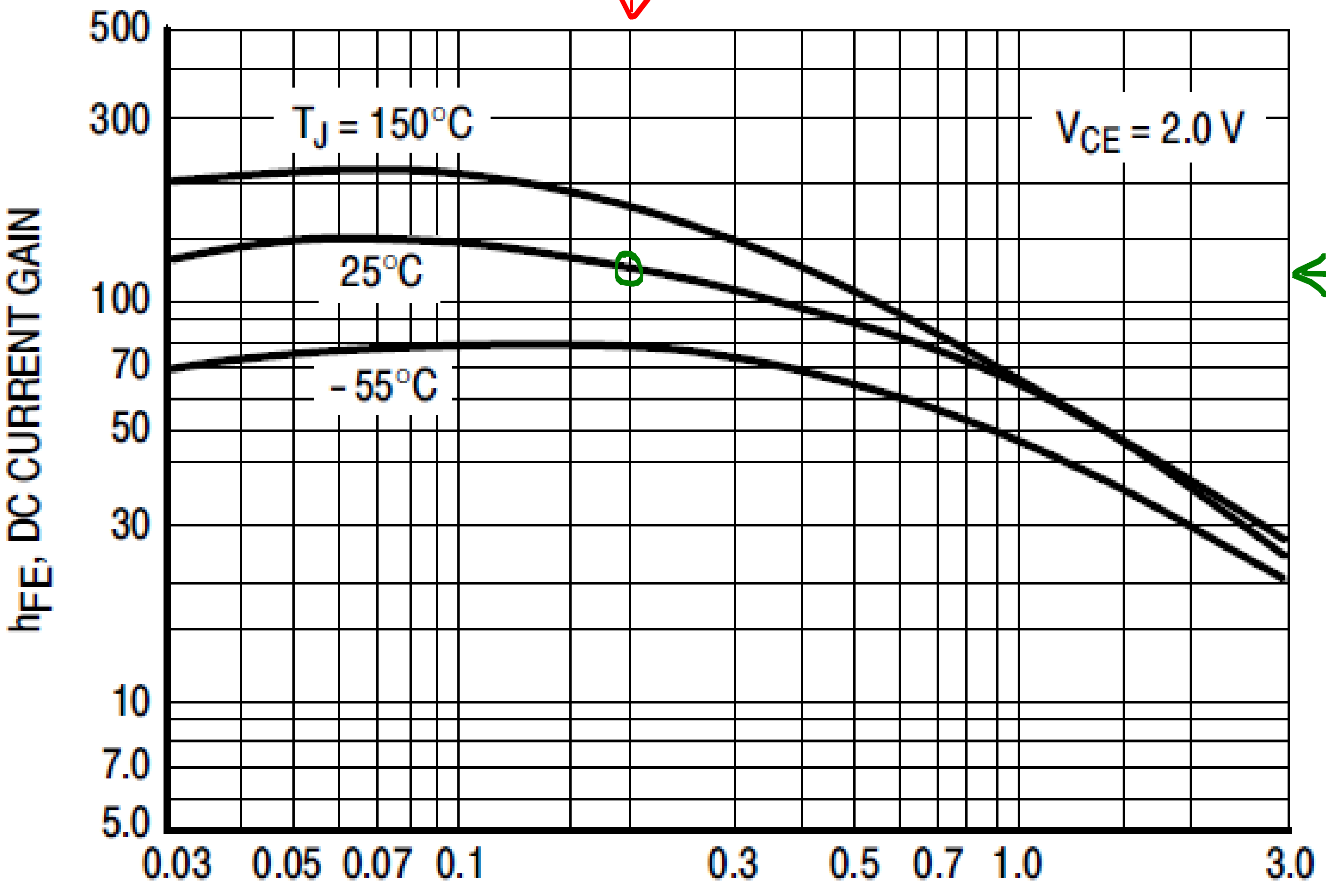


Figure 9. DC Current Gain

STEP 1 Estimate I_c using "quick" analysis or known load parameters

→ I_c ~ 0.22A

STEP 2 Use plot to find β

(same as h_{FE})

h_{FE} ~ 120

Not the same as h_{fe}

For RF applications

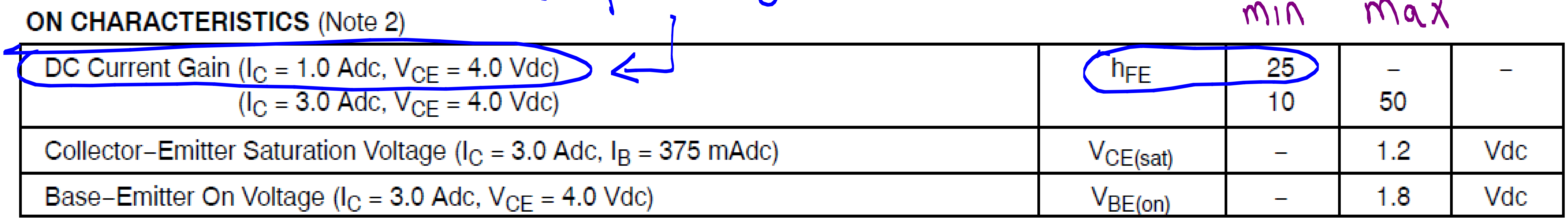
called "DC" or "pulsed" current gain.

- Any device parameter has "typical" and "worst case" values!

use the <u>table</u> of "On Characteristics"

TIP31

Only for $I_c = 1A$!



ON CHARACTERISTICS (Note 2)

		min	max	
DC Current Gain (I_C = 1.0 Adc, V_{CE} = 4.0 Vdc)	h_{FE}	25	–	–
(I_C = 3.0 Adc, V_{CE} = 4.0 Vdc)		10	50	
Collector–Emitter Saturation Voltage (I_C = 3.0 Adc, I_B = 375 mAdc)	$V_{CE(sat)}$	–	1.2	Vdc
Base–Emitter On Voltage (I_C = 3.0 Adc, V_{CE} = 4.0 Vdc)	$V_{BE(on)}$	–	1.8	Vdc

- Table only has β_{min} for $I_c = 1A$.
  → But we need $I_c \sim 220$ mA.

☆ OK to assume $\frac{\beta_{min}}{\beta_{typ}} \approx$ constant:

@ 1A, 25°C @ .22A

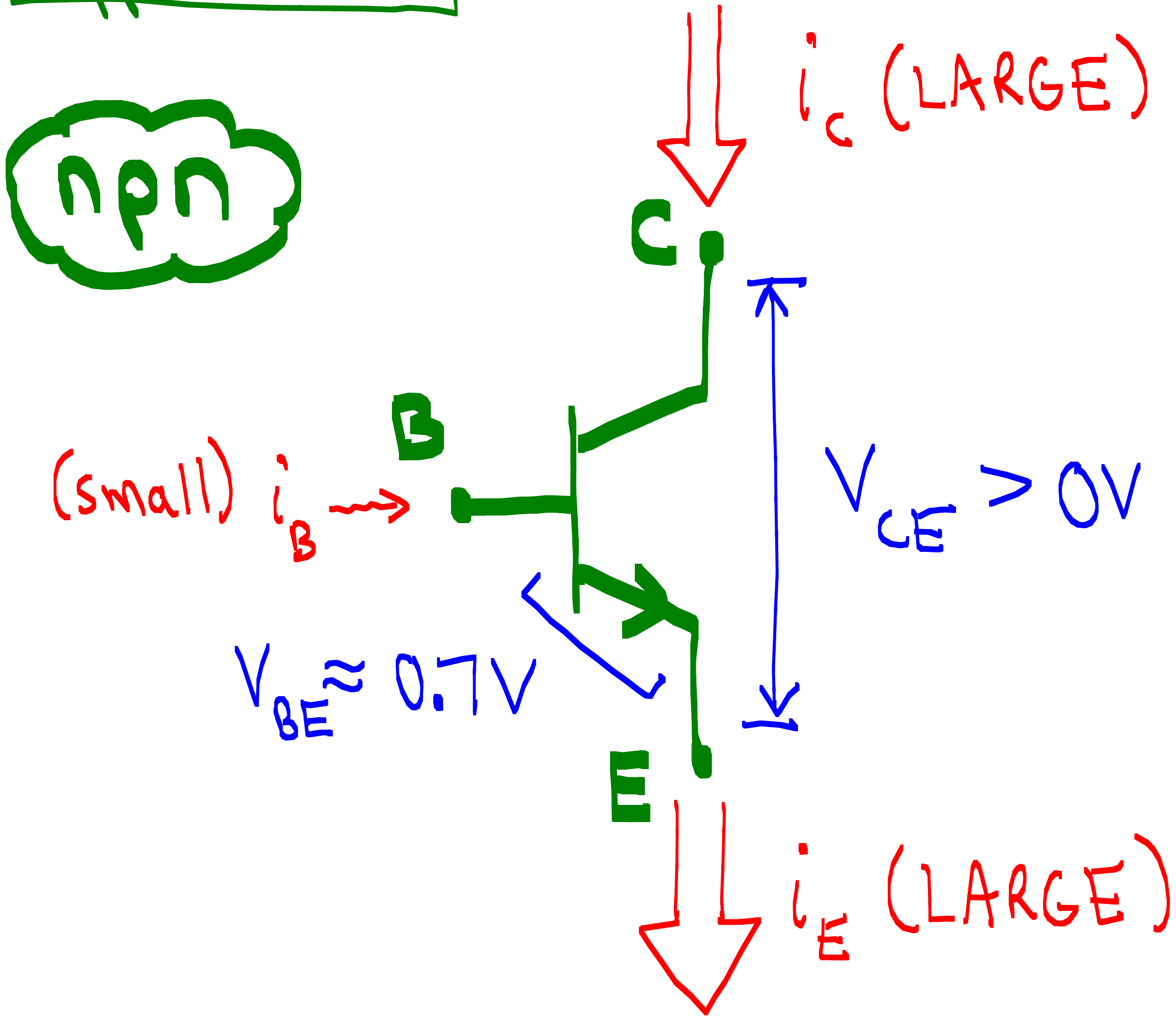
$$\frac{25}{65} \approx \frac{\beta_{min}}{120}$$

From graph

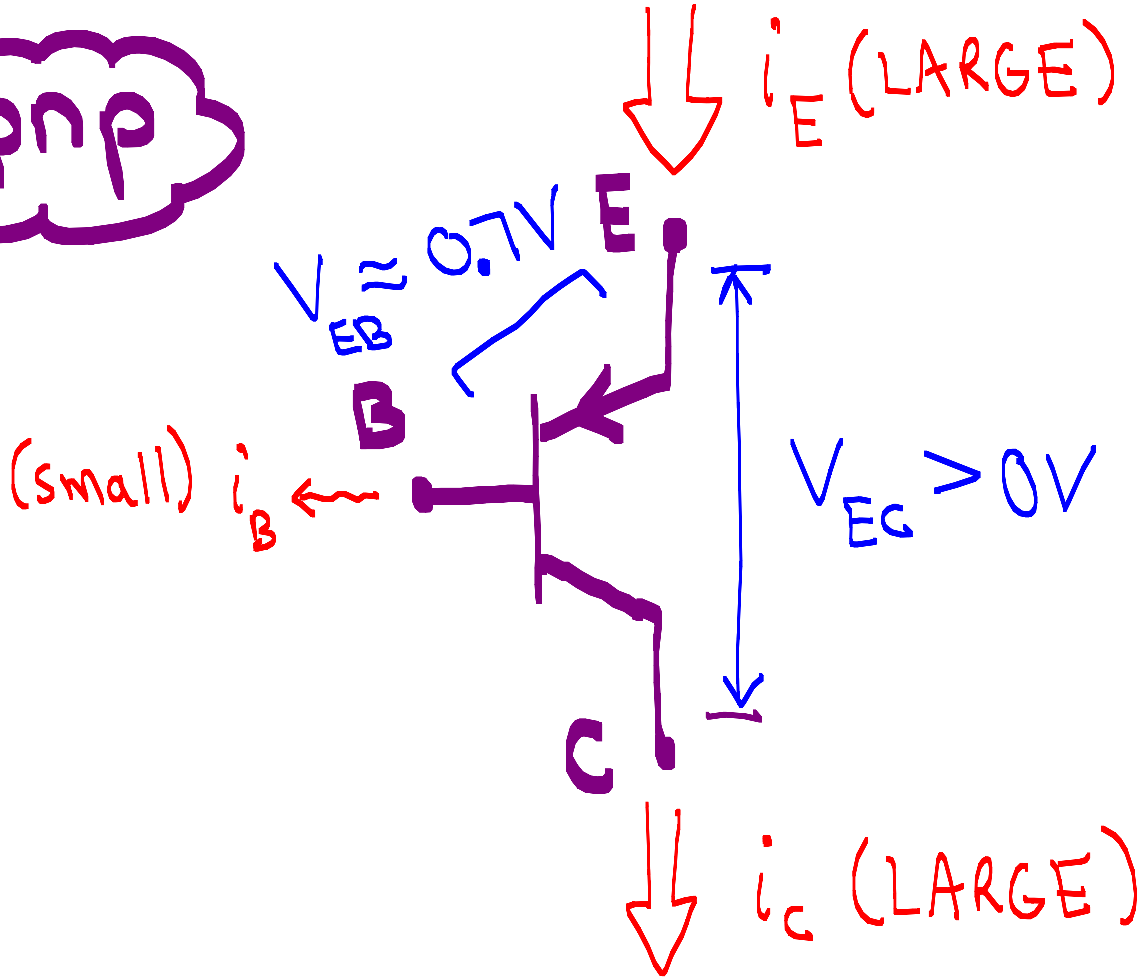
$\Rightarrow \beta_{min} = \underline{\underline{46}}$ @ .22 A

Appendix #2

npn



pnp



☆ For both npn + pnp $\Longrightarrow$

Always true!

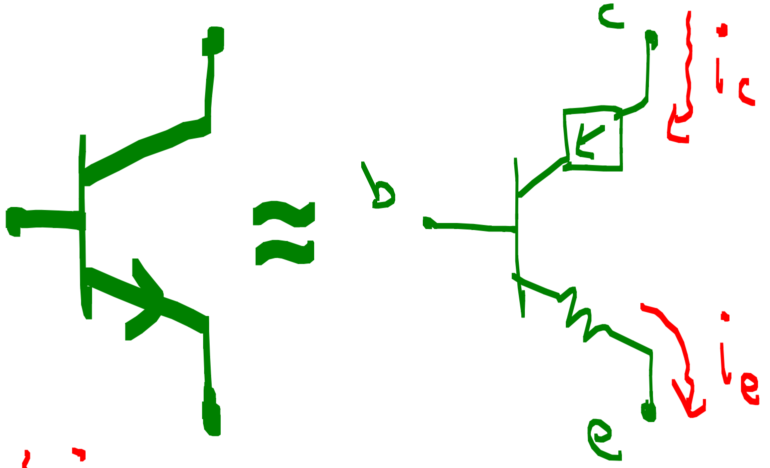
$$\boxed{i_B + i_C = i_E}$$

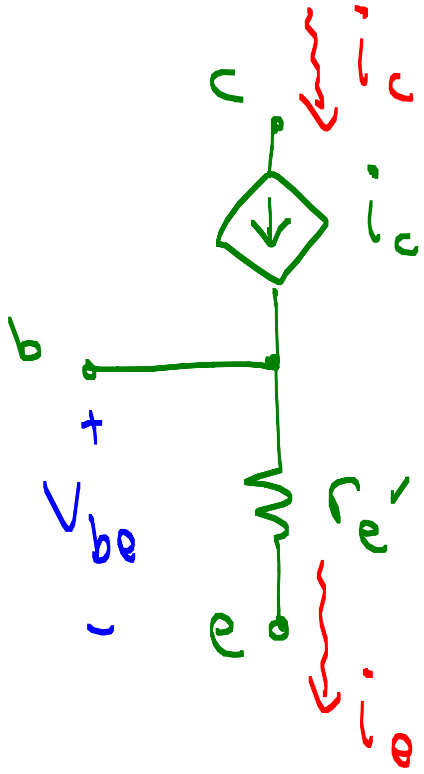
Only true for Active Mode

$$\boxed{i_C = \beta i_B = \alpha i_E \text{ AND } i_E = (\beta+1)\, i_B}$$

- **T-model** ← useful for understanding amplifier gain and input/output impedance

npn

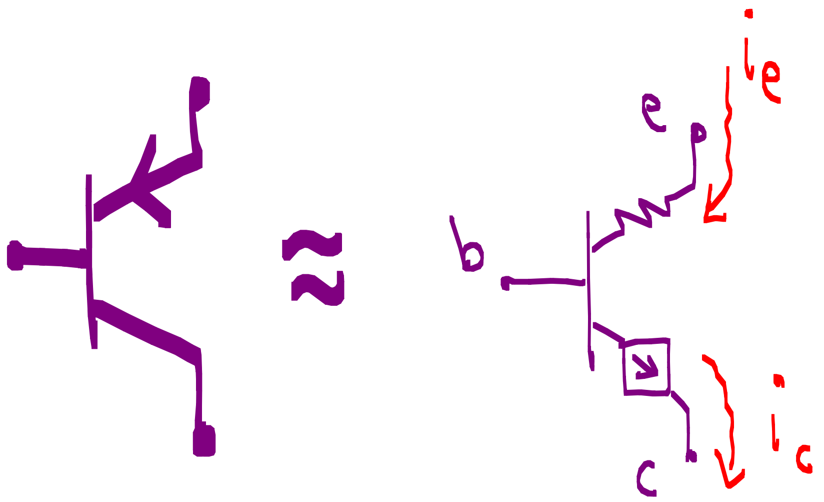


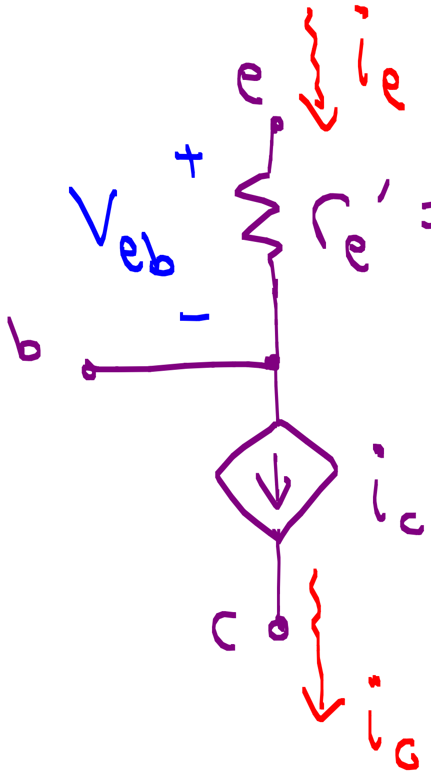


$$i_c = \alpha i_e = \alpha \frac{V_{be}}{r_e'}$$

$$r_e' = \frac{.026V}{I_{EQ}}$$

pnp





$$r_e' = \frac{.026V}{I_{EQ}}$$

$$i_c = \alpha i_e = \alpha \frac{V_{eb}}{r_e'}$$

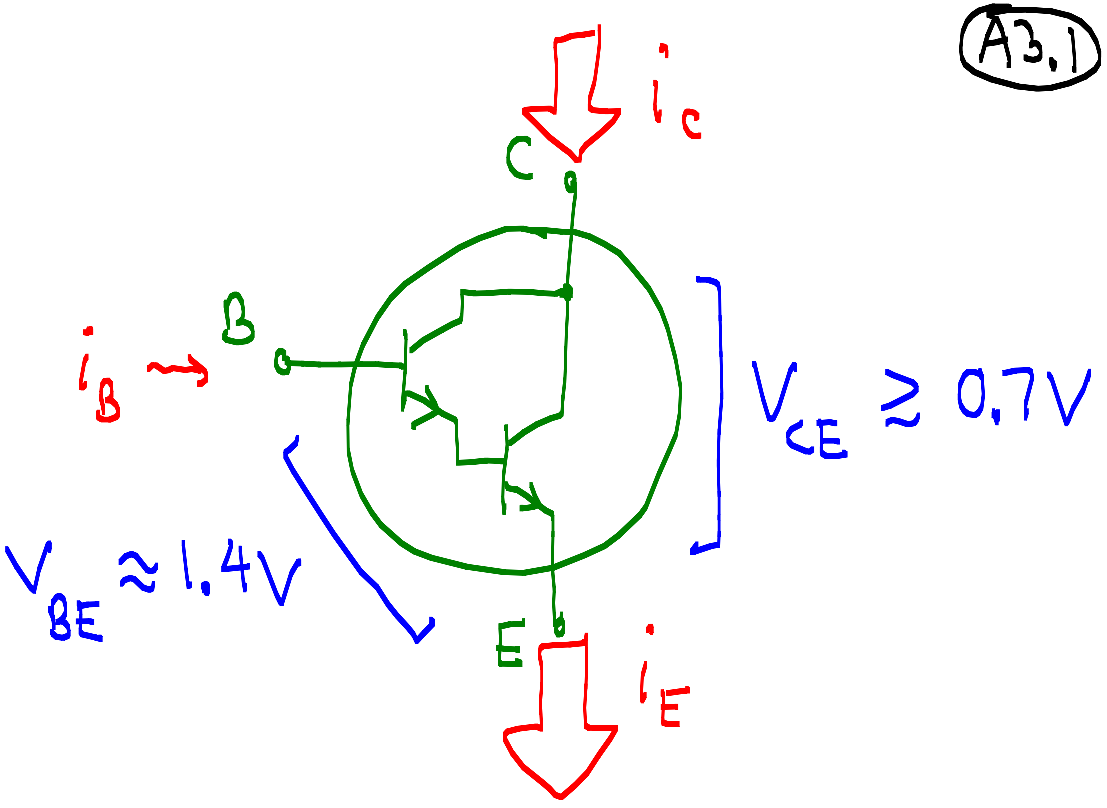
Appendix #3

$\beta \approx 2500$

- Extra high current gain is possible with a Darlington!

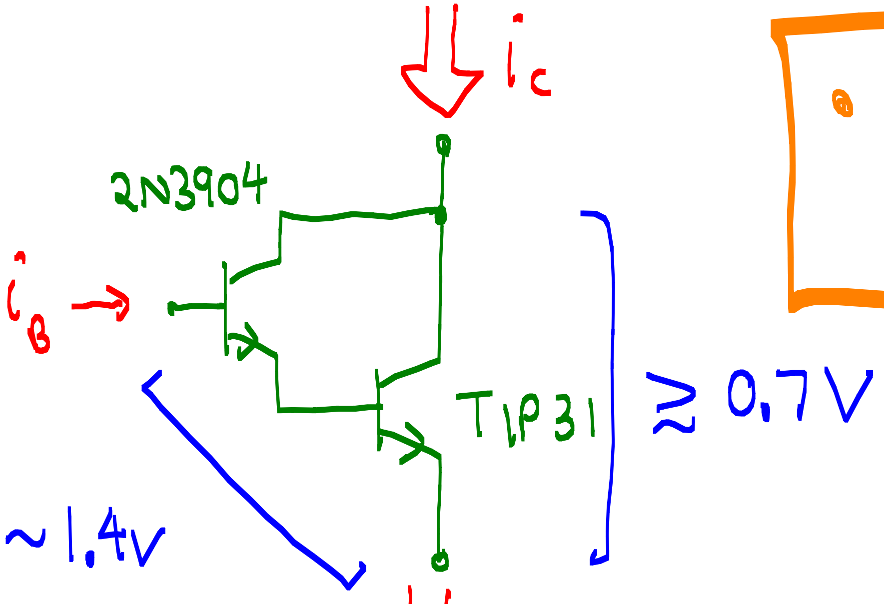
(a) Darlington Transistor

→ single device containing both transistors (e.g. KSP14, TIP120)



(b) Darlington Pair

→ two separate transistors connected to each other (e.g. 2N3904 + TIP31)



$\beta \approx \beta_1 \beta_2$

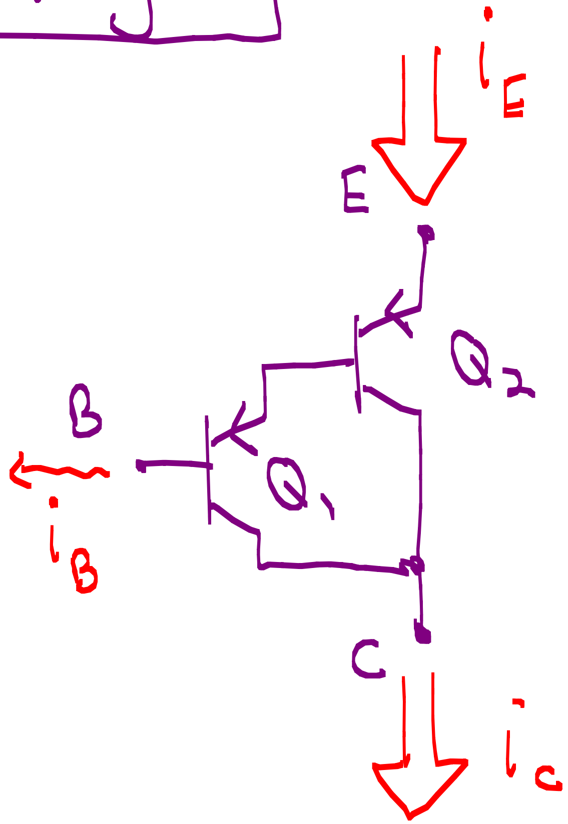
- For Darlington "quick" analysis,

$V_{BE} = 1.4V$
$\beta = 2500$
$V_{CE(sat)} = 0.7V$

pnp Darlington

Method 1

Two pnp's

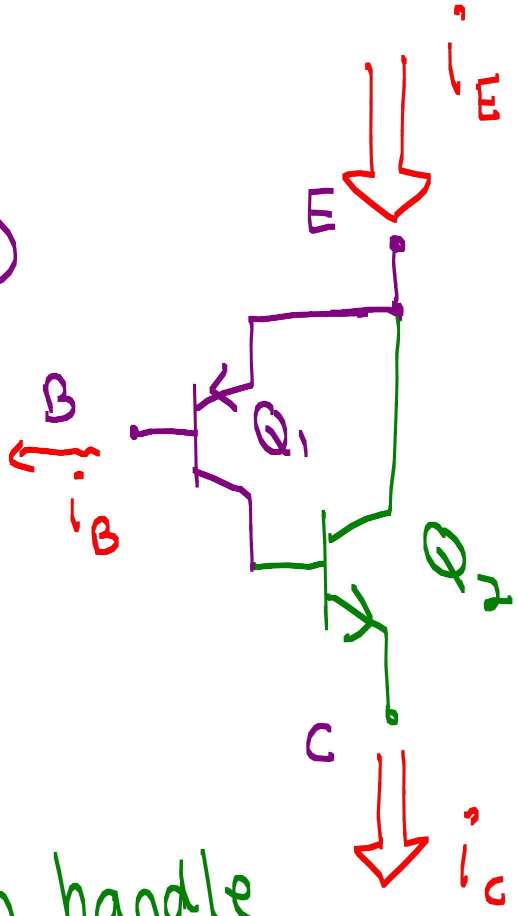


Method 2

$Q_1 = pnp$

$Q_2 = npn$

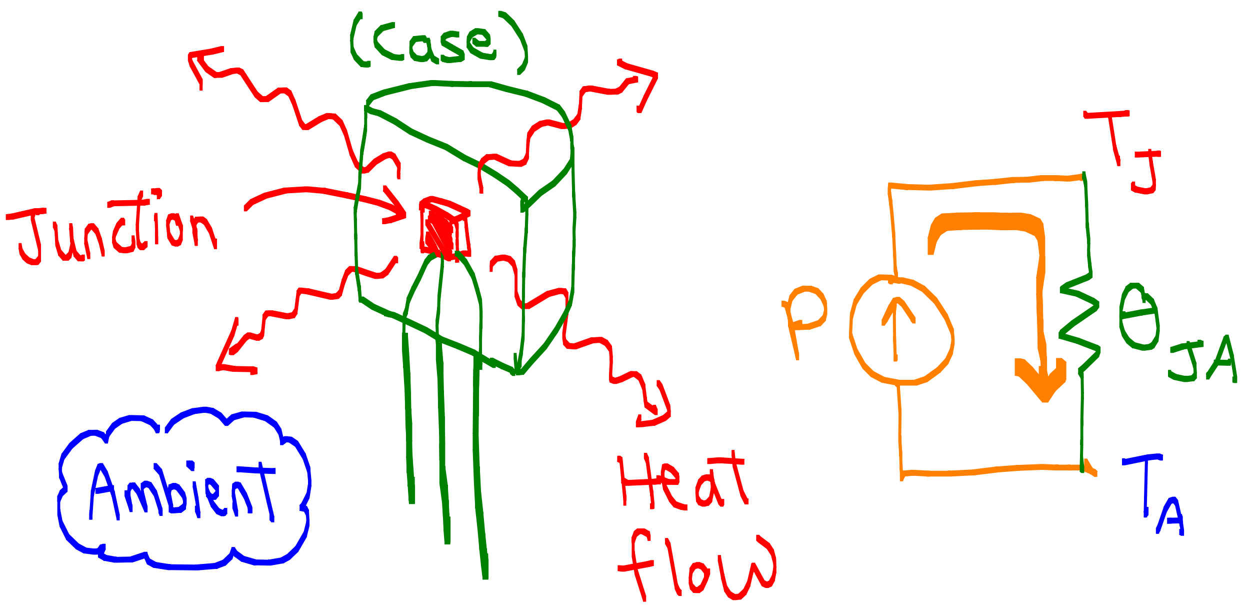
npn can handle higher currents than pnp



Called "Complementary" or "Sziklai" Pair

Appendix #4 Heat sink formulas

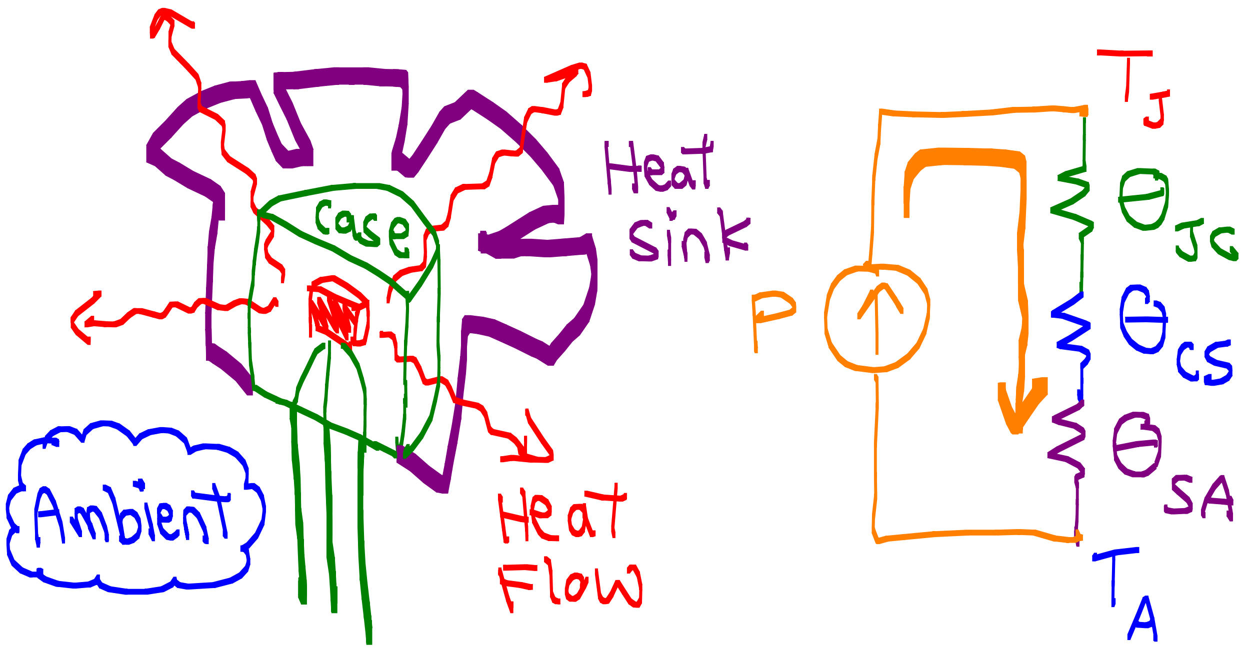
• NO heat sink



$$T_J = T_A + P \times \overset{\text{Junction to Ambient}}{\Theta_{JA}}$$

$$= T_A + P \times \left[\underbrace{\Theta_{JC}}_{\text{Junction to case}} + \underbrace{\Theta_{CA}}_{\text{Case to Ambient}}\right]$$

• WITH heat sink



$$T_J = T_A + P \times \overbrace{\left[\underbrace{\Theta_{JC}}_{\text{Junction to case}} + \underbrace{\Theta_{CS}}_{\text{Case to Sink}} + \underbrace{\Theta_{SA}}_{\text{sink to Ambient}}\right]}^{\text{"new" }\Theta_{JA}}$$