Lecture 2: Linear Regulator

0. Review
1. Op amp feedback
2. Design example
3. Current limiting

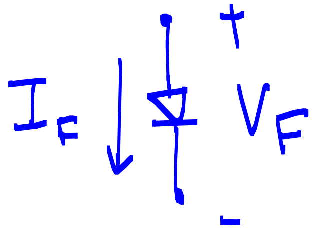
- PreLab1 due Thu (Sep 19) at lab session
- HW1 due Fri (Sep 20)
  → leave in box outside my office
- Quiz1 next Tue (Sep 24)

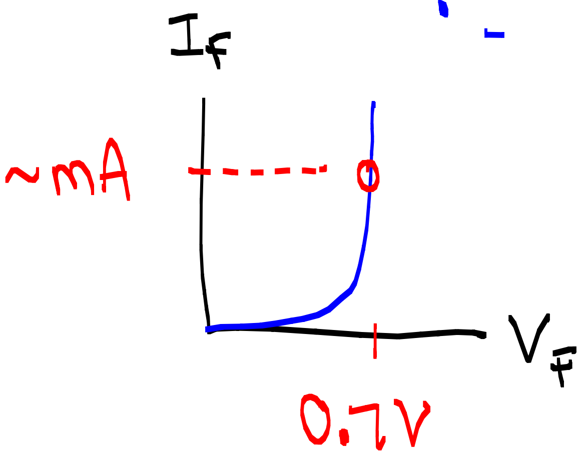
Helpful textbook reading:

Ch 22-1 Power Supply Characteristics
22-3 Series regulators
22-4 Monolithic Linear regulators

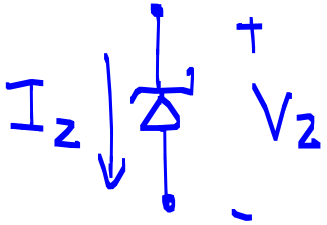
0. Review

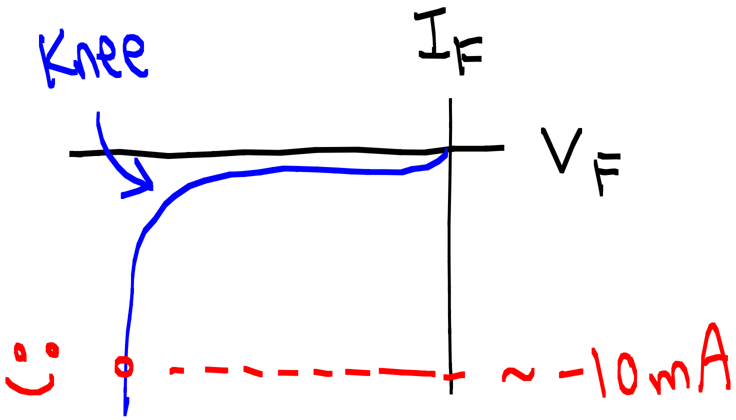
- **Diode**



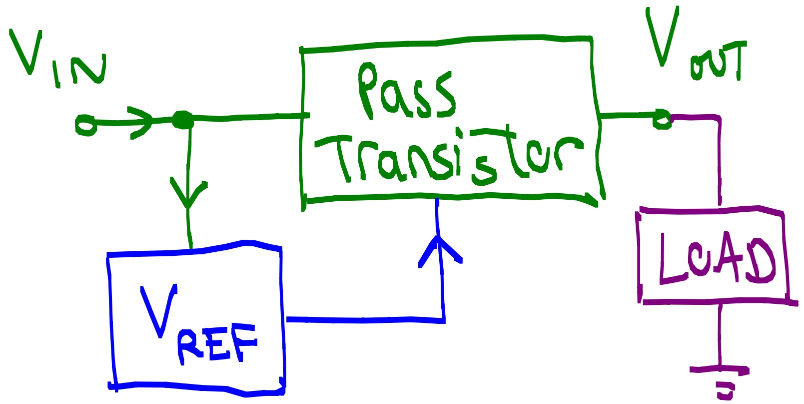


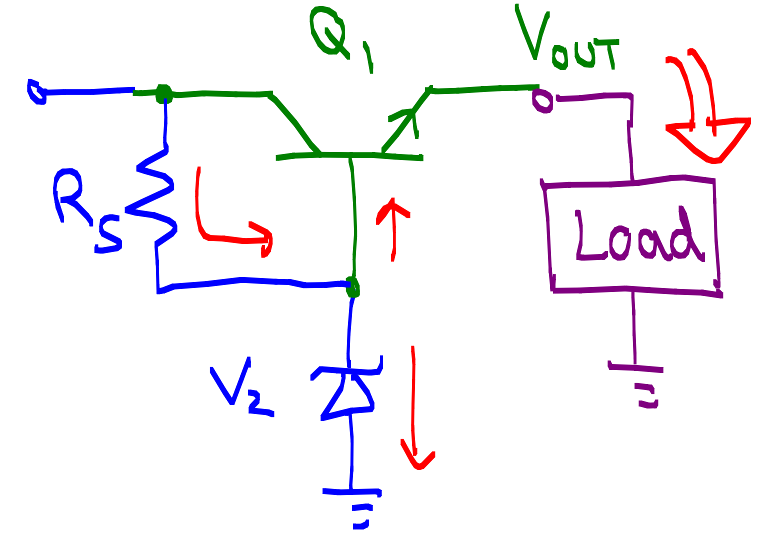
- **Zener**





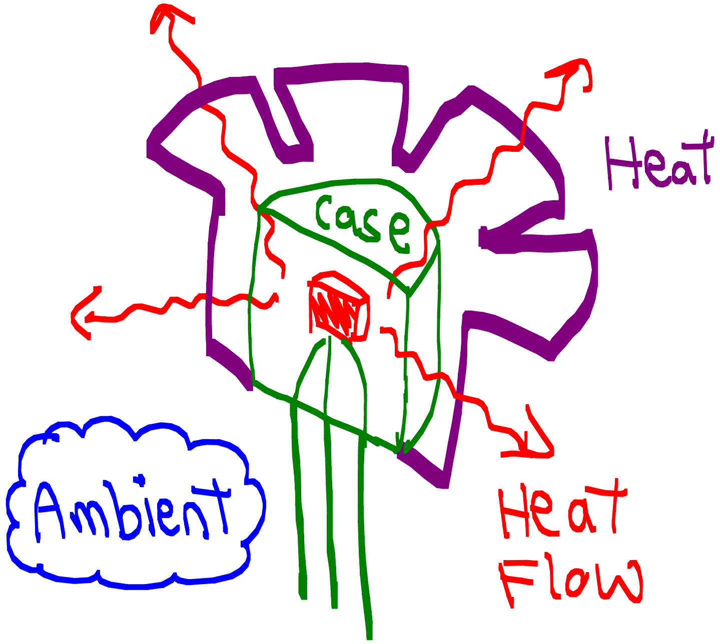
Zener Follower





$$\boxed{V_{OUT} = V_Z - V_{BE}}$$

- Heat Sinks



$$T_J = T_A + P \times \overbrace{\left[\theta_{JC} + \theta_{CS} + \theta_{SA}\right]}^{\theta_{JA} \text{ w/ heat sink}}$$

Junction to case

Case to sink

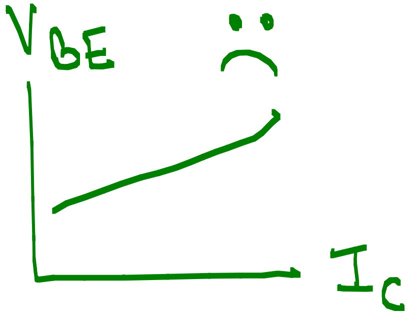
Sink to Ambient

1. Negative Feedback

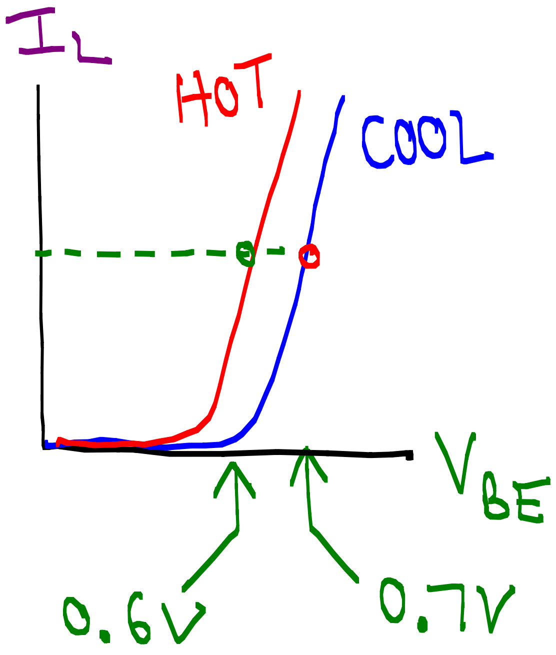
- Zener follower problems:

① Limited selection of zener values (e.g. 5.6V, 8.2V)

② V_{BE} varies with current



③ V_{BE} varies with temp!

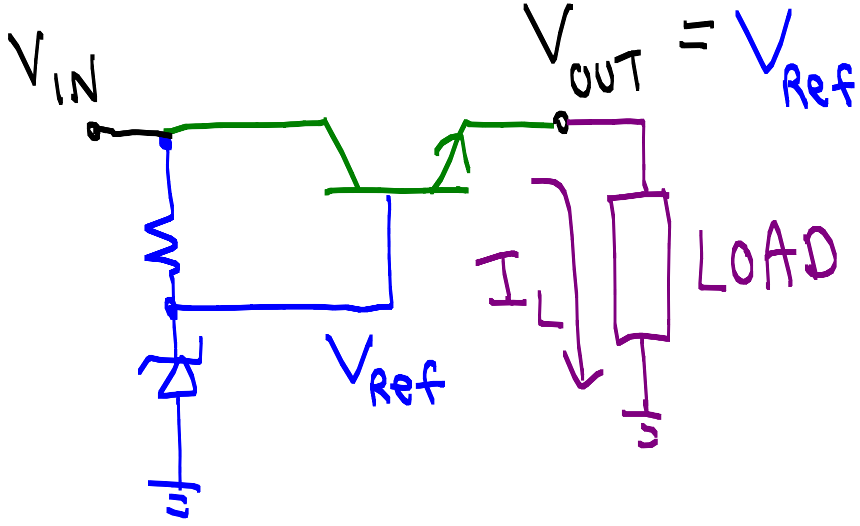


$$\boxed{\frac{\Delta V_{BE}}{\Delta T} = -2\ \frac{mV}{°C}}$$

Ex: $V_{BE} = \begin{cases} 0.7V\ @\ 25°C \\ 0.6V\ @\ 75°C \end{cases}$

① ②③

$V_{OUT} = V_{Ref} - V_{BE}$



- A voltage regulator actively stabilizes V_{out} using negative feedback!

(a) Sample a portion of V_{OUT}

(b) Create error signal

(c) Adjust V_{OUT}

Q: How to do this?

★ Use an op amp with negative feedback!

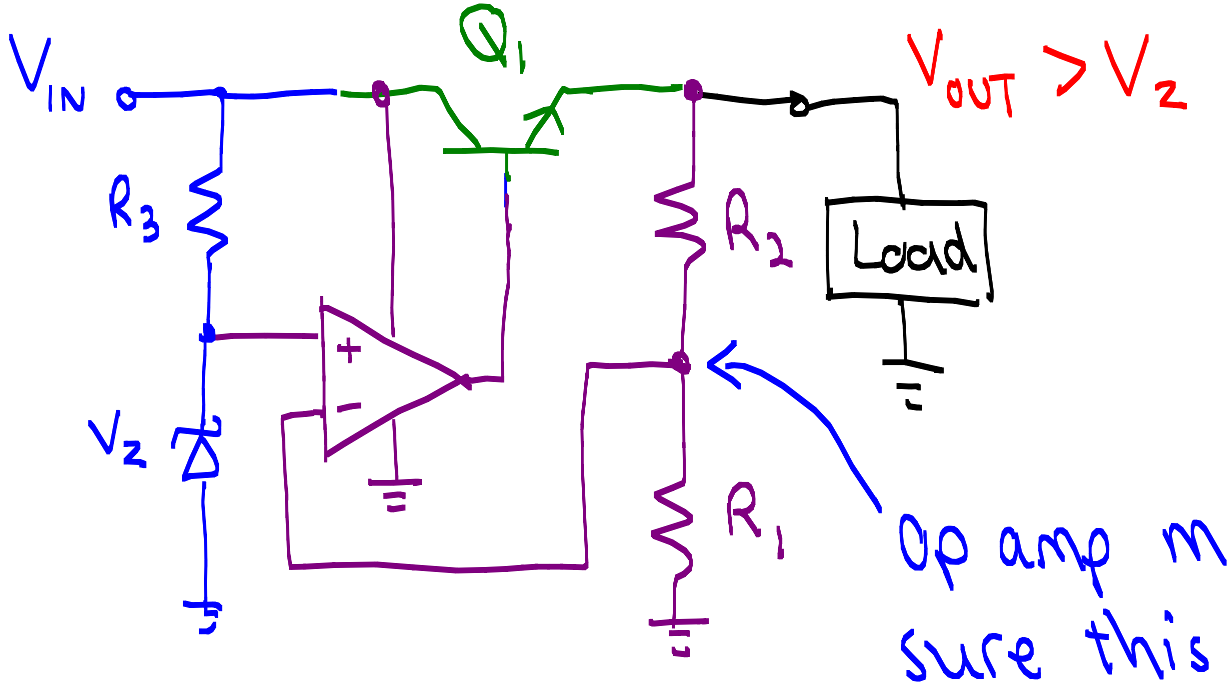
→ An op amp makes $V_- = V_+$

$V_{OUT}\frac{R_1}{R_1+R_2} \nearrow \qquad \nwarrow V_Z$

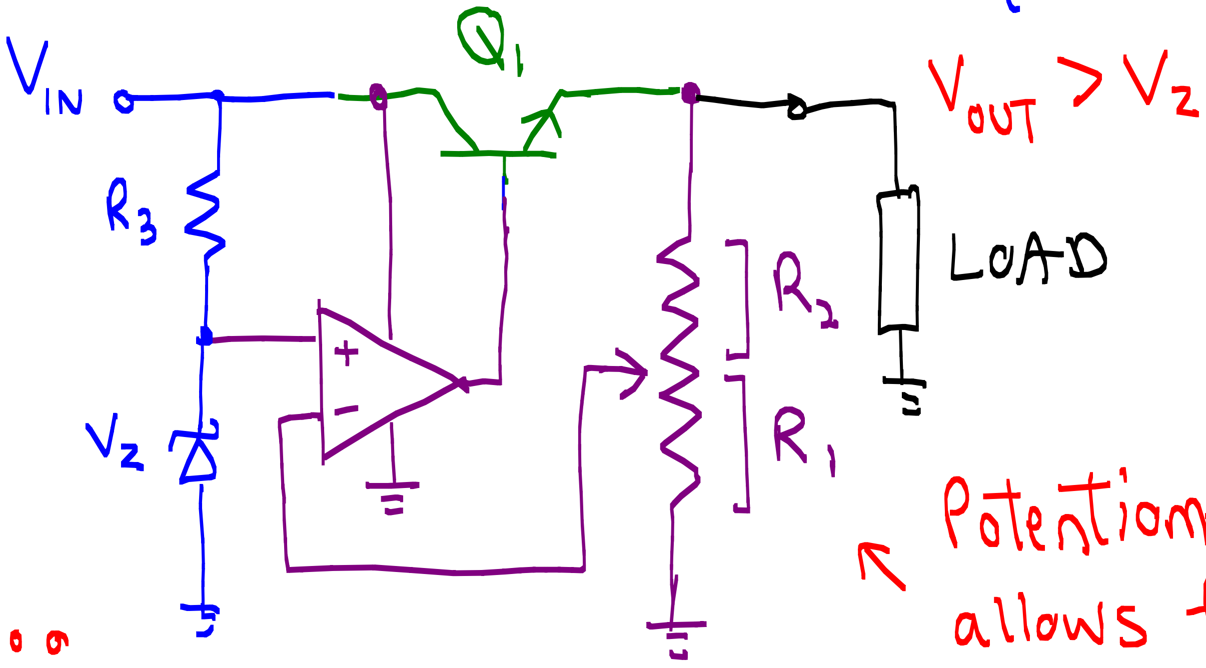
SO, $\boxed{V_{out} = V_Z \times \left(1+\frac{R_2}{R_1}\right)}$

→ Can achieve any V_{OUT} by choosing R_2/R_1

→ V_{OUT} does NOT depend on V_{BE}, so Q_1 variation don't matter! ☺



Op amp makes sure this is equal to V_Z!



↖ Potentiometer allows fine adjustment

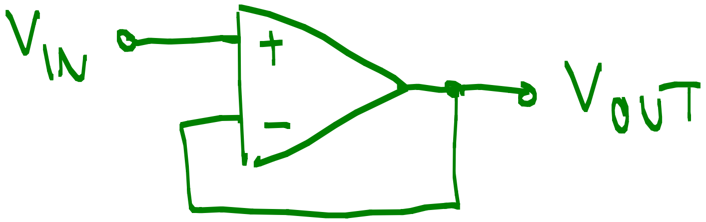
• Op Amp Review

Ideal op amp with (−) feedback obeys two Golden Rules: "virtual short"

① The two input terminals are at the same voltage. ← $V_- = V_+$

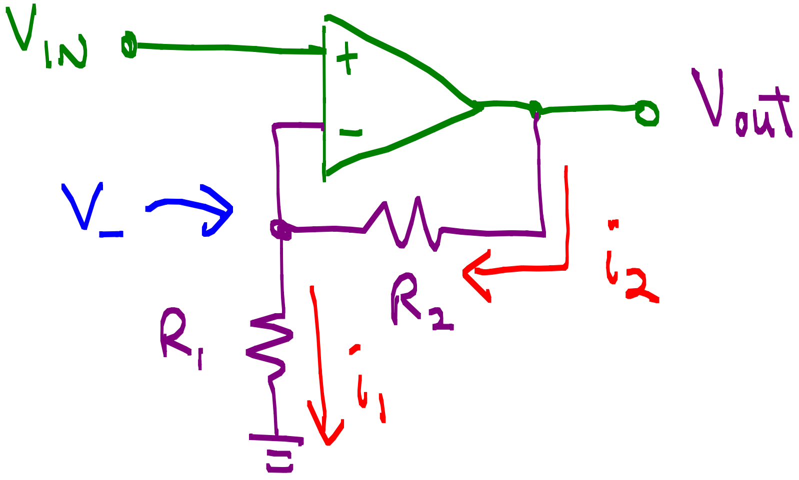
② The two input terminals draw no current.

Ex.1 Voltage Buffer



$V_- = V_+$ → $\boxed{V_{OUT} = V_{IN}}$

Ex.2 Non-inverting Amplifier



Golden Rule #1 → V_{IN}

Golden Rule #2 → KCL at node V_-: $i_2 = i_1$

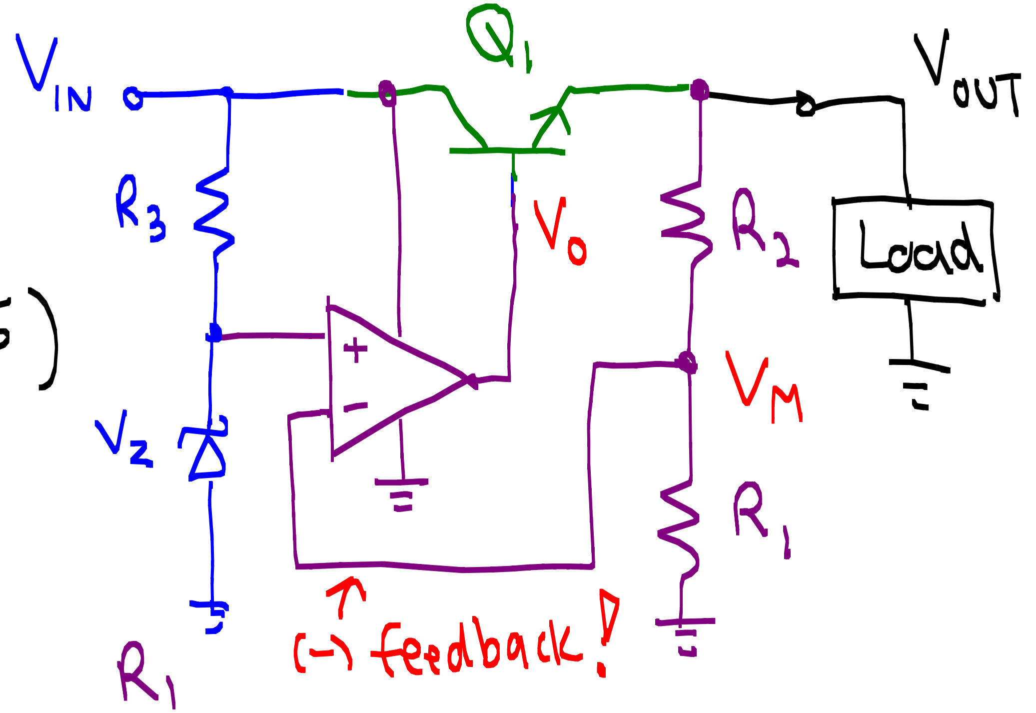
$$\frac{V_{OUT}-V_-}{R_2} = \frac{V_- - 0}{R_1} \Rightarrow V_{OUT} = \left(1+\frac{R_2}{R_1}\right)V_-$$

$$\Rightarrow \boxed{\frac{V_{OUT}}{V_{IN}} = 1 + \frac{R_2}{R_1}}$$

:)

NOTE: $\left.\begin{array}{l} R_2 = 0 \\ R_1 = \infty \end{array}\right\}$ $V_{OUT} = V_{IN}$! (buffer)

Q: How does the op amp do this?



An op amp is basically a <u>differential amplifier</u> with <u>super high gain</u> (~10^5)

$$\underbrace{V_0}_{V_{OUT}+V_{BE}} = A\times(V_+ - V_-) = A\times(V_Z - \underbrace{V_M}_{\uparrow\, V_{OUT}\frac{R_1}{R_1+R_2}})$$

SO, $V_{OUT} + V_{BE} = AV_Z - A\frac{R_1}{R_1+R_2}V_{OUT}$

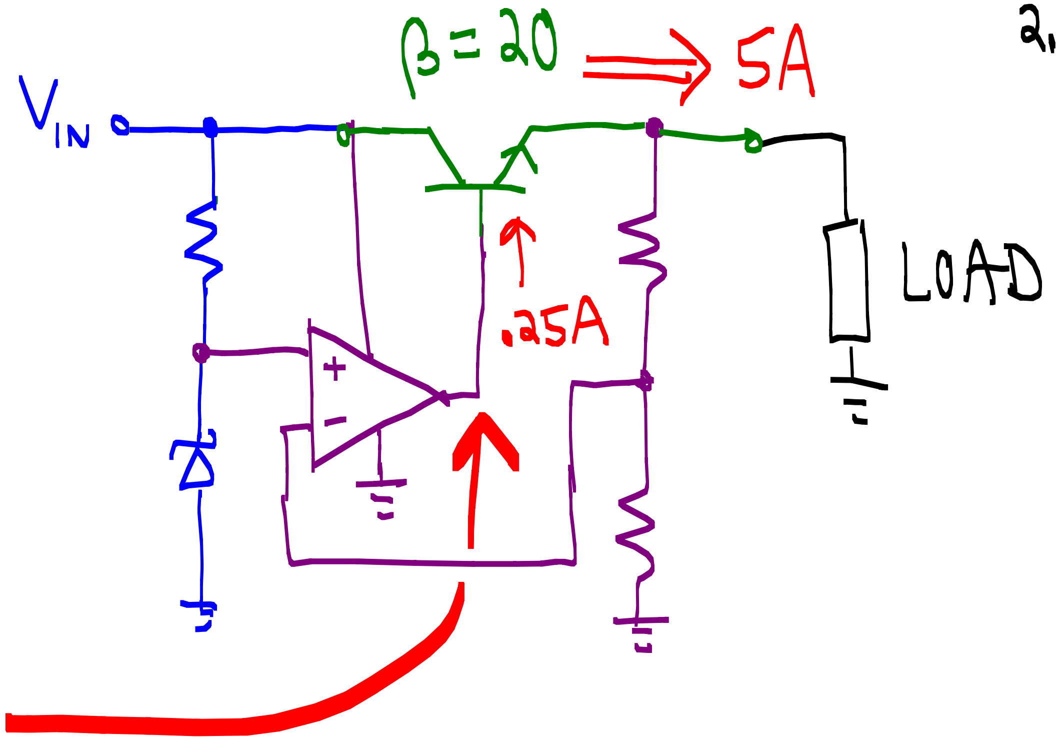
This also means $V_M = V_{OUT}\frac{R_1}{R_1+R_2} = V_Z$ ✓

$$\Rightarrow V_{OUT} = \frac{AV_Z - V_{BE}}{1 + A\frac{R_1}{R_1+R_2}} \underset{\uparrow}{\approx} \frac{\cancel{A}V_Z}{\cancel{A}\frac{R_1}{R_1+R_2}} = \overbrace{V_Z\left(1+\frac{R_2}{R_1}\right)} \checkmark$$

When A is HUGE

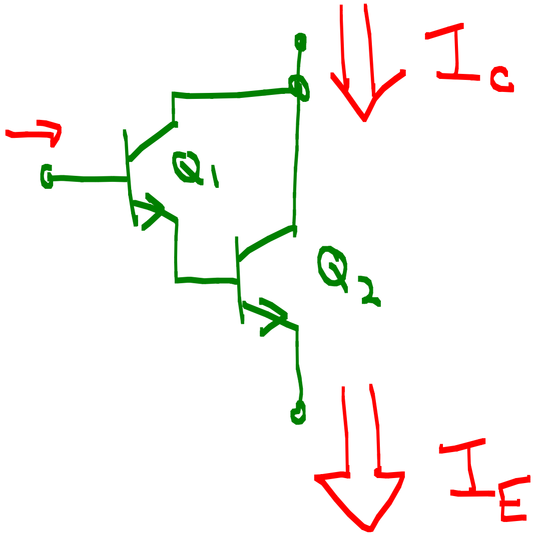
- Negative feedback greatly improves V_{OUT} regulation. ☺
- Need to be careful with large I_{OUT}
  - ↳ Pass transistor has large I_B
  - ⇒ Most op amps are limited to ~25mA output current! ☹

Ex:



A: use a Darlington connection!

$$I_B = \frac{I_E}{(\beta_1\beta_2+1)}$$

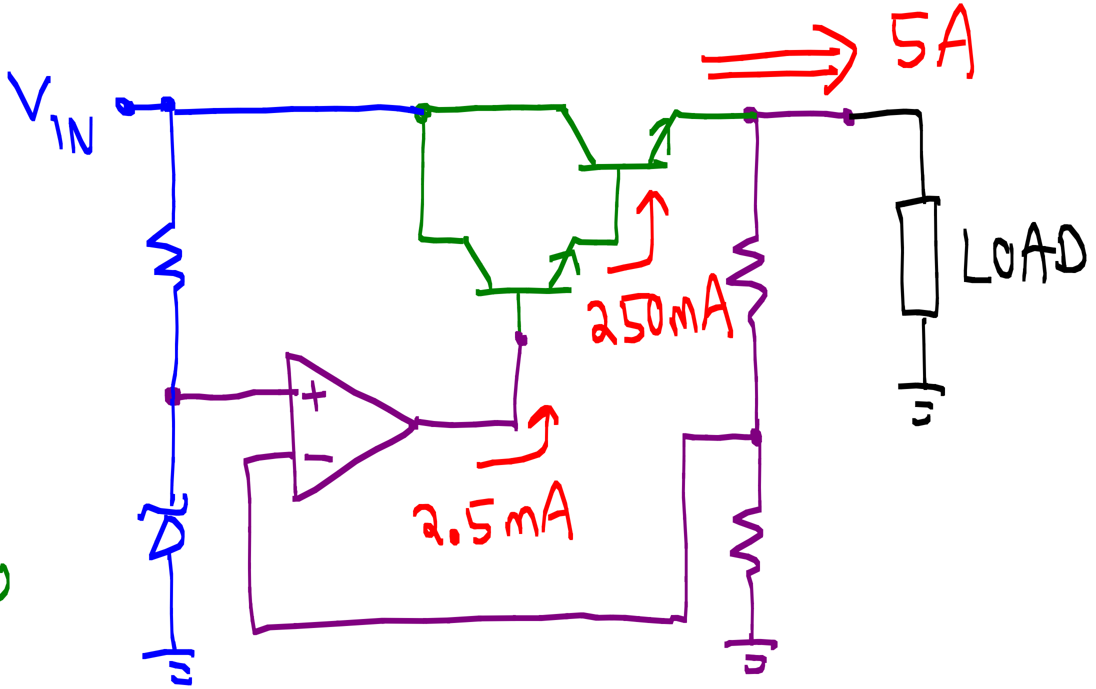


$\beta_1 \sim 100$

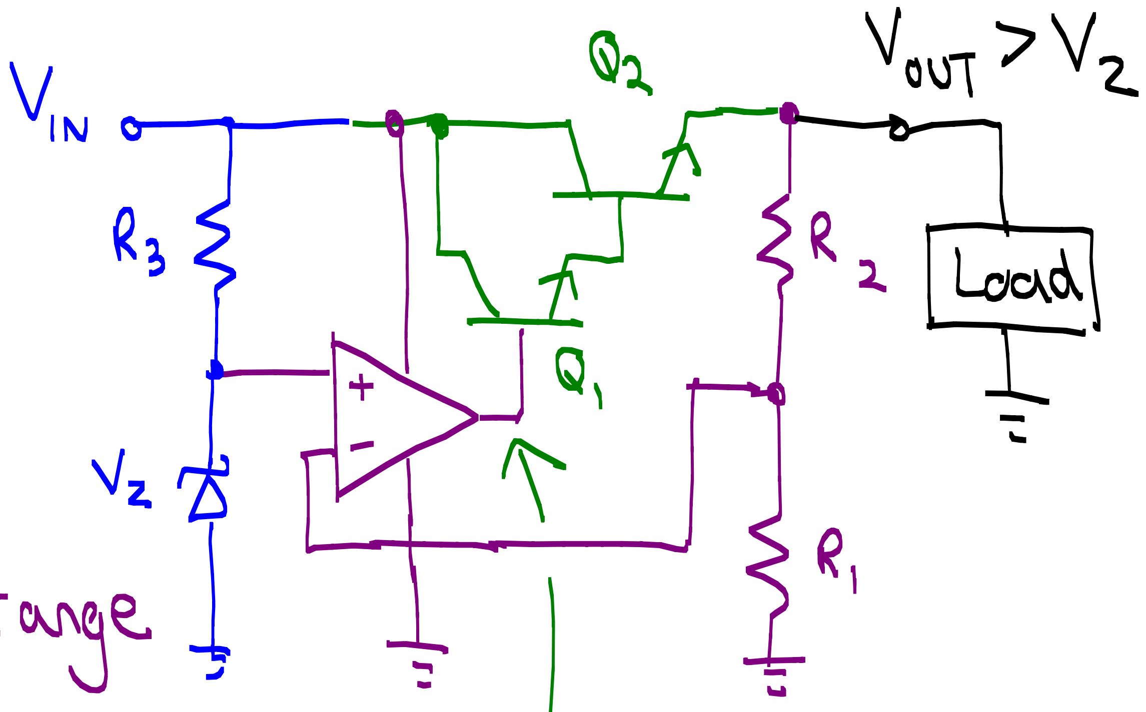
$\beta_2 \sim 25$

$\beta_1\beta_2 \sim 2500$ ☺

Ex:



3. Design Guidelines for Linear Regulator



- Minimum I_Z is 10 mA
  - → Ensure zener is happy
- Max Q_1 base current < 5 mA
  - → Does not significantly reduce max op amp output voltage
- R_1 and R_2 are typically kΩ or 10kΩ range
  - ✱ Draw ≤ 1mA from V_{OUT}
- Make sure minimum $V_{IN} > V_{OUT} + 3V$
  - → Ensures op amp output can reach $\approx \overbrace{V_{OUT} + 1.4V}$
- Don't fry your components.
  - → Choose power ratings > 2x actual power dissipation

Example: $V_{IN} = 19\text{-}22V$, $V_{OUT} = 15V$, $R_L > 20\Omega$

① Choose $V_z = 6.2V \leftarrow$ Zeners in ~6V range have small temp drift

$$10\,mA < \frac{19-6.2}{R_3} \Rightarrow R_3 < 1.28k \xrightarrow{\times 0.95} 1.22K \Rightarrow \text{choose } \boxed{R_3 = 1.2K}$$

② $I_{L,max} = \frac{15V}{20\Omega} = \underline{\underline{0.75A}}$

Need to choose Q_2 and Q_1! Q_2:

		Max P	
	Max I_c	($T_A=25°C$)	($T_c=25°C$)
2N3904	200mA ✗	.625W	
2N4401	600mA ✗	.625W	1.5W
TIP31	3A ✓	2W ✗	40W ✓
2N3055	15A		115W

"Quick" analysis: $\beta = 100$

"Typical" : $\beta \sim 70$ @ .75A

↳ $\text{Max } P = I_B V_{BE} + I_C V_{CE}$

$$= \left(\frac{.75A}{71}\right)\underset{\substack{\uparrow \\ \text{Typ } V_{BE}}}{(.8V)} + \frac{70}{71}(.75A)(22-15) = 5.18W \xrightarrow{\times 2} \underline{10.4W}$$

Determine heat sink later → TIP31 ✓

Q_1: $I_{E1} = \frac{I_{E2}}{\beta + 1} = \frac{.75A}{71} = 10.6\,mA \leftarrow \underline{\underline{2N3904}}$ seems OK

$\beta_{Typ} \sim 225 \rightarrow$ $P = \frac{10.6mA}{226}\underbrace{(0.72)}_{\text{Typ } V_{BE}} + \frac{225}{226}(10.6mA)(22 - 15.7V)$

$= 66.5\,mW$ ✓

(don't need heat sink)

$I_{B1} = \frac{10.6mA}{226} = .047\,mA$ ✓

③ $V_{OUT} = 15 = 6.2\left(1 + \frac{R_2}{R_1}\right) \rightarrow \frac{R_2}{R_1} = 1.42$

$I_{divider} = \frac{15}{R_1 + R_2} < 1mA \rightarrow R_1 + R_2 > \underline{\underline{15K}}$

R_1	$1.42 R_1$	Closest R_2	Actual R_2/R_1
9.1K	12.9K	13K	1.43
10K	14.2K	15K	1.5
11K	15.6K	16K	1.45
12K	17.0K	18K	1.5

④ Minimum $V_{IN} = 19V > (15+3)$ ✓

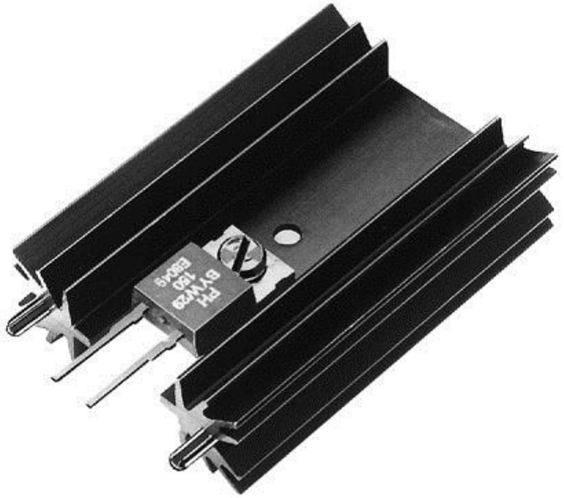
⑤ Power ratings

1/4W is fine

V_2: Max $I_2 = \frac{22 - 6.8}{1.2K} = 12.7mA \rightarrow P = (12.7mA)(6.2V) = 78.7\,mW \leftarrow$

R_3: Max $P = \frac{(22-6.8)^2}{1.2K} = 192.5\,mW \rightarrow$ Use ½W rating!

Q_2: Tip31 needs a heat sink! Let's assume: $\begin{cases} T_A = 25°C \\ \text{Max } T_J = 85°C \end{cases}$



$$T_J = T_A + P \times (\theta_{JC} + \theta_{CS} + \theta_{SA}) < 85°C$$

$$25°C + 5.18W \times (3.125°C/W + .5°C/W + \theta_{SA}) < 85°C$$

Actual power ↗ Data sheet ↗ Assume this ↗

$$\Rightarrow \boxed{\theta_{SA} < 7.96\,°C/W}$$

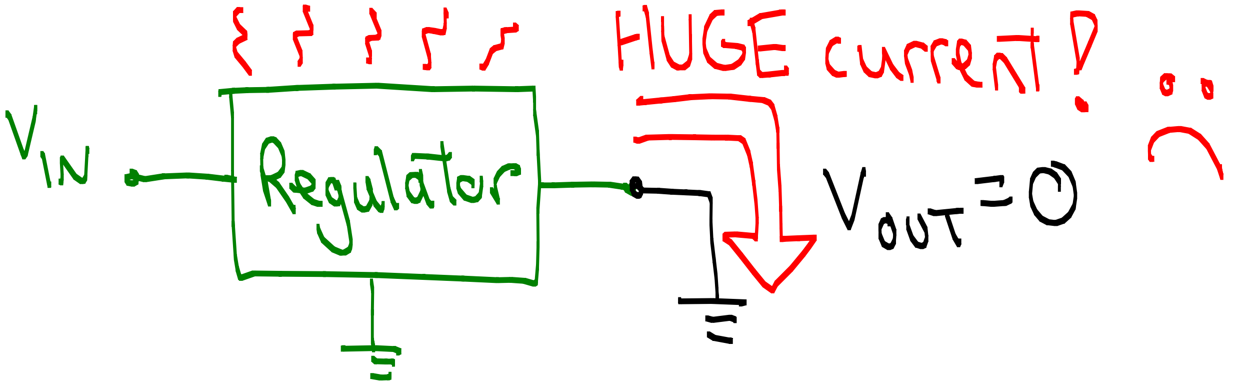
R_1 and R_2: $I = \frac{15V}{9.1K + 13K} = .68\,mA \rightarrow (.68\,mA)^2(9.1K) = 4.2\,mW$

$\hookrightarrow (.68\,mA)^2(13K) = 6.0\,mW$

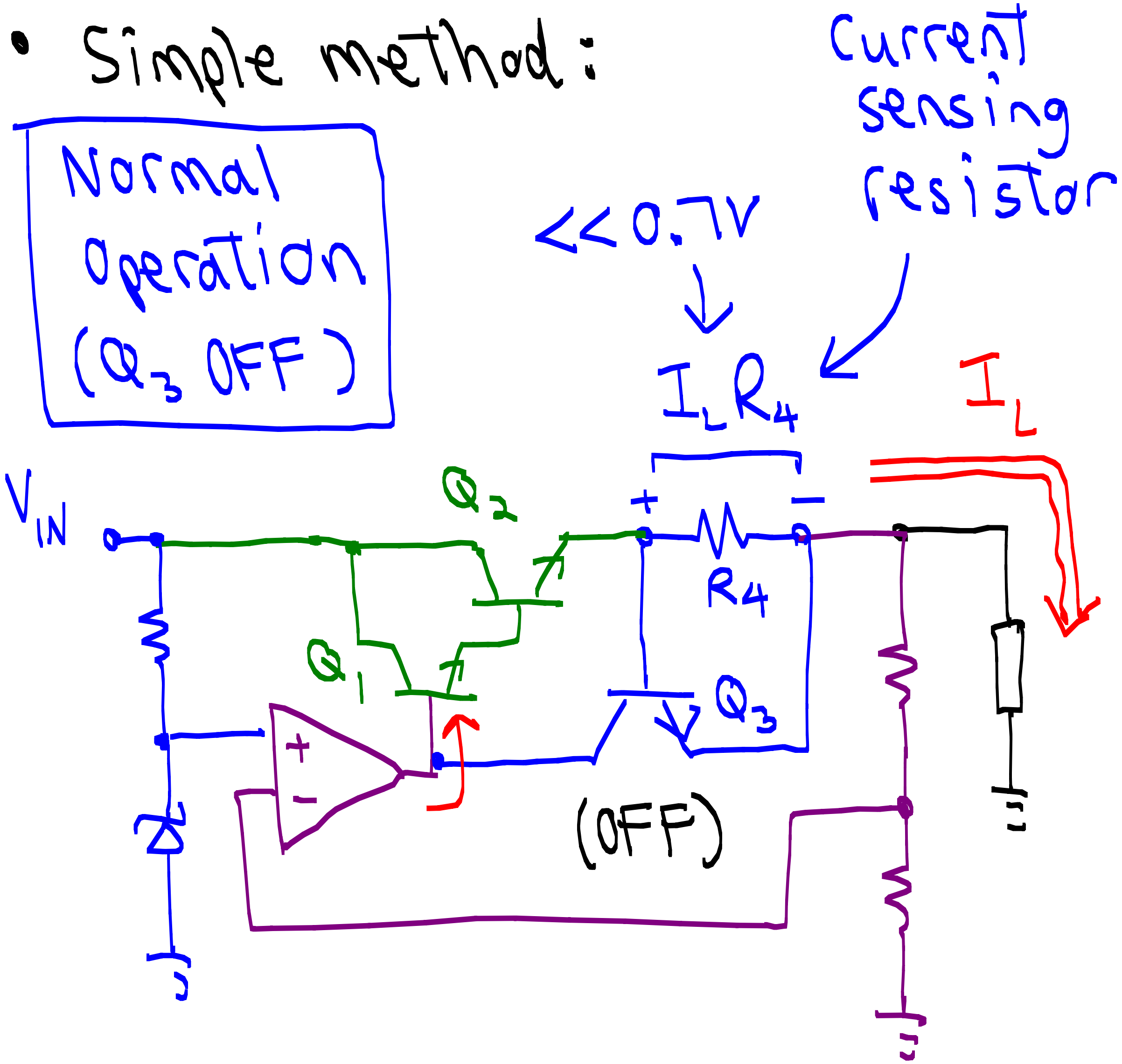
¼ W resistors are fine

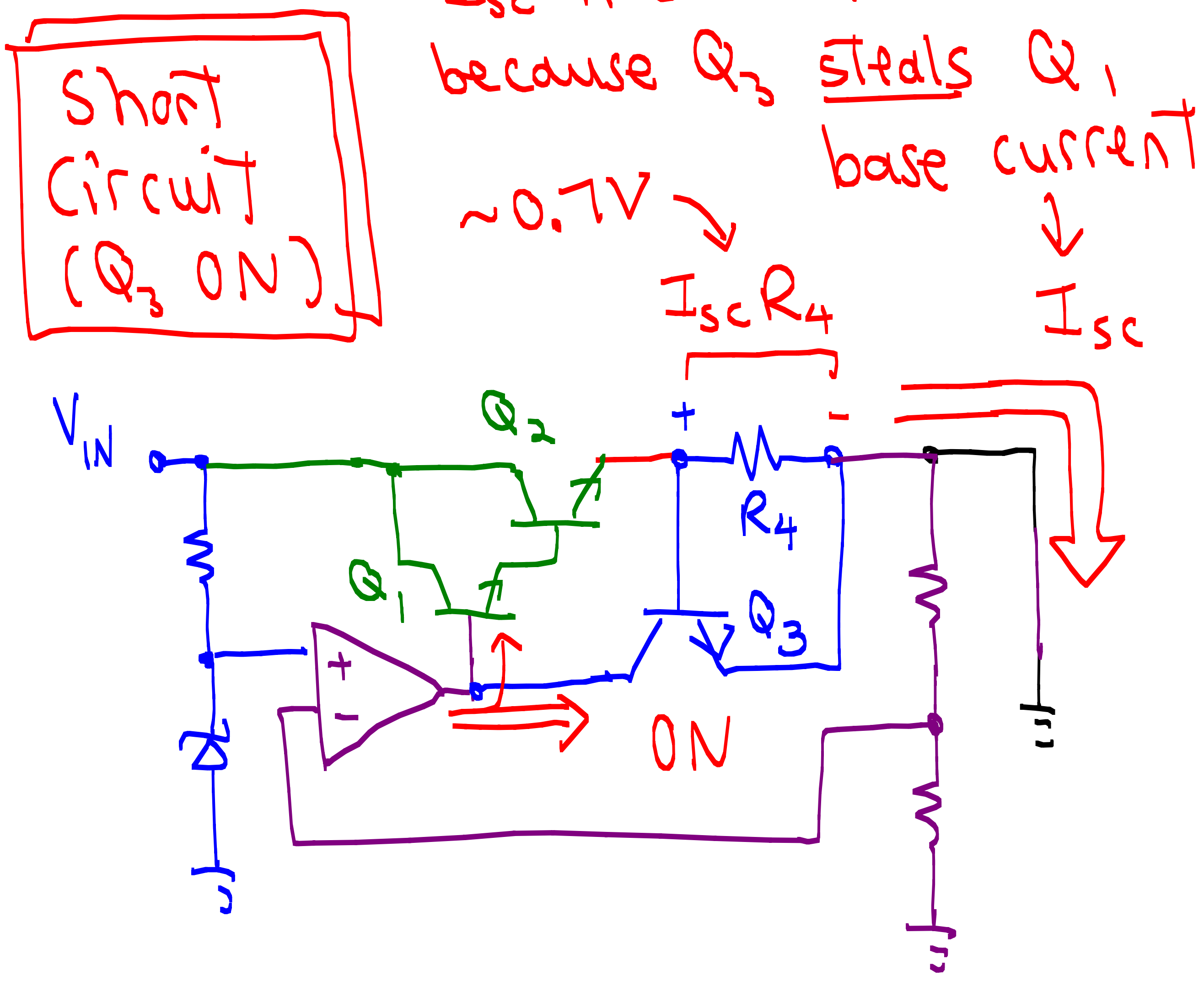
3. Current Limiting

- Any regulator needs protection from short circuited output



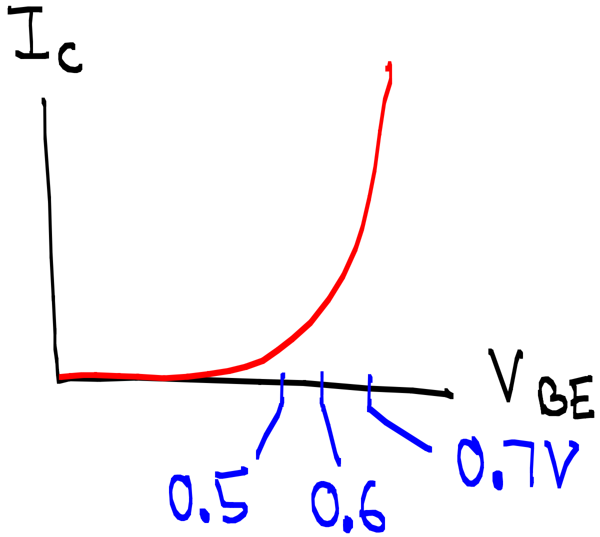
- Simple method:

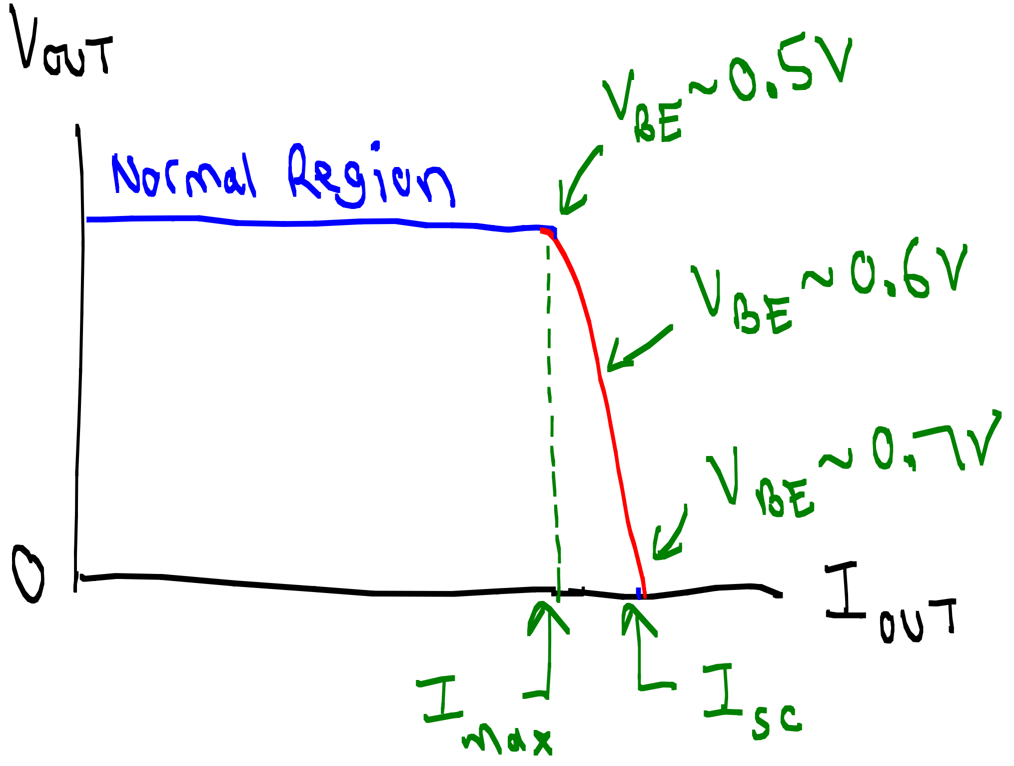


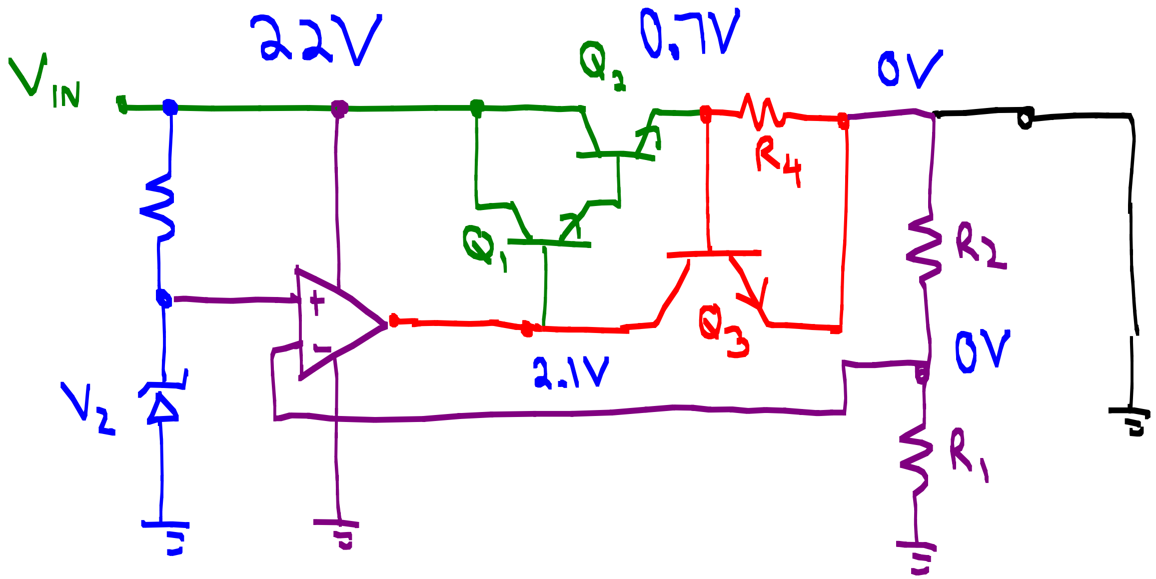


I_{sc} has limited value because Q_3 steals Q_1 base current

NOTE #1: Q_3 does not abruptly turn ON.







NOTE #2: When $I_{out} = I_{sc}$, power dissipation in Q_2 can still be pretty large.

Ex: $R_4 = 0.8\Omega$, $V_{IN} = 22V$

$$\Rightarrow \quad I_{sc} \sim \frac{0.7V}{0.8\Omega} = 0.83A$$

$$P_2 = \frac{.83A}{71}(.8V) + \frac{70}{71}(.83A)(22-0.7) = \underline{\underline{17.4W}}!$$

Appendix #1

TIP31

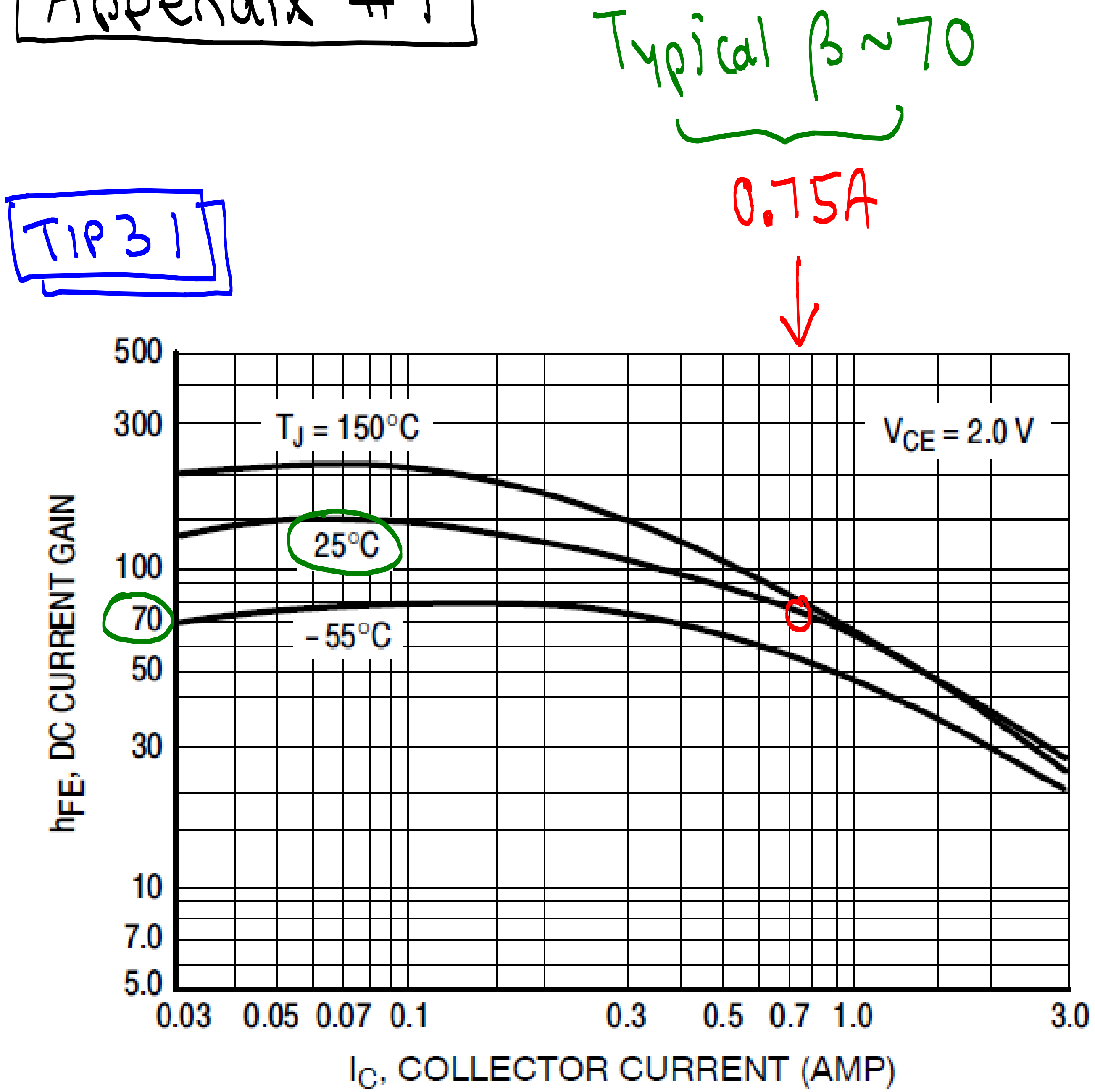


Figure 9. DC Current Gain

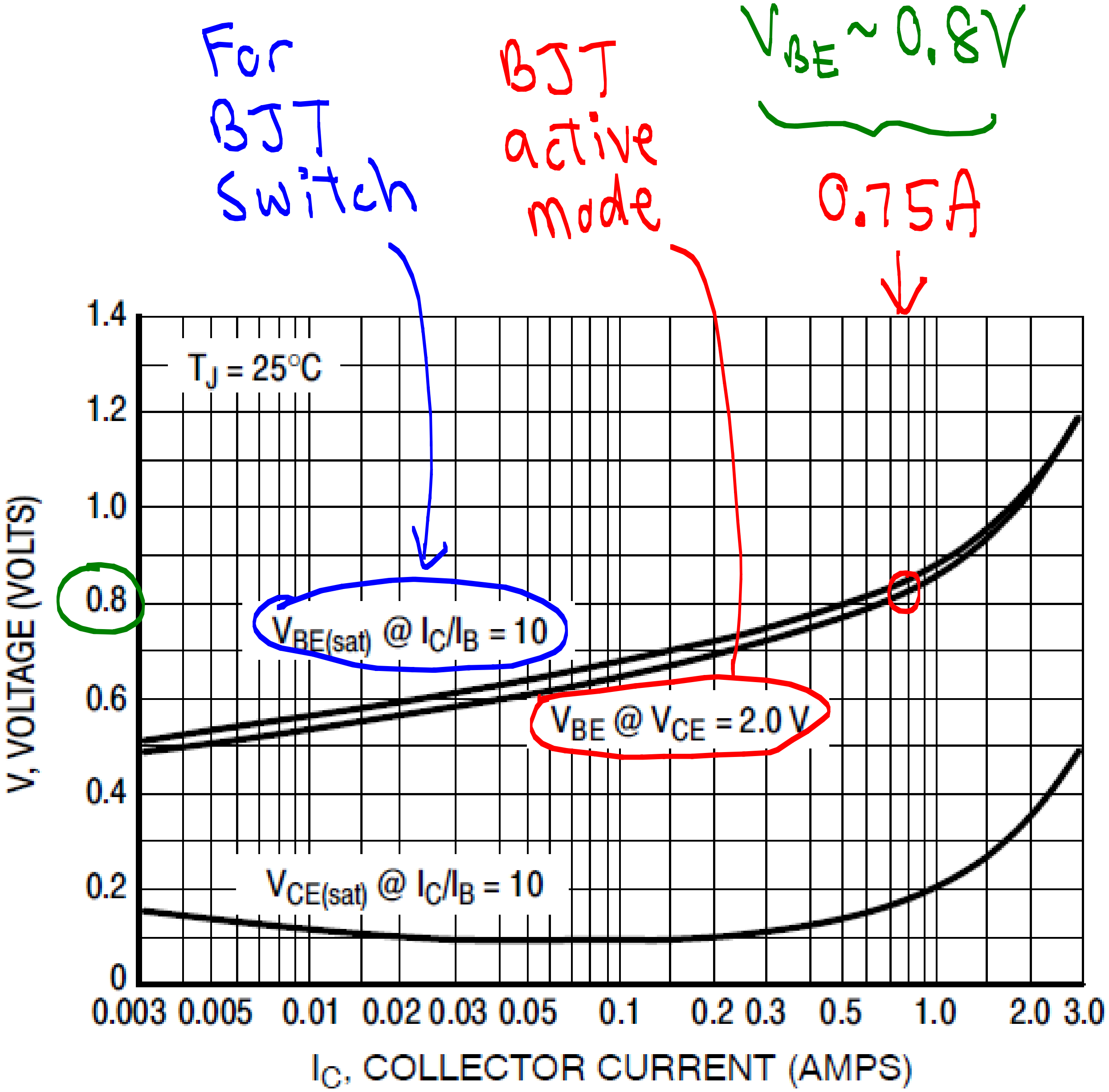


Figure 11. "On" Voltages

A.2

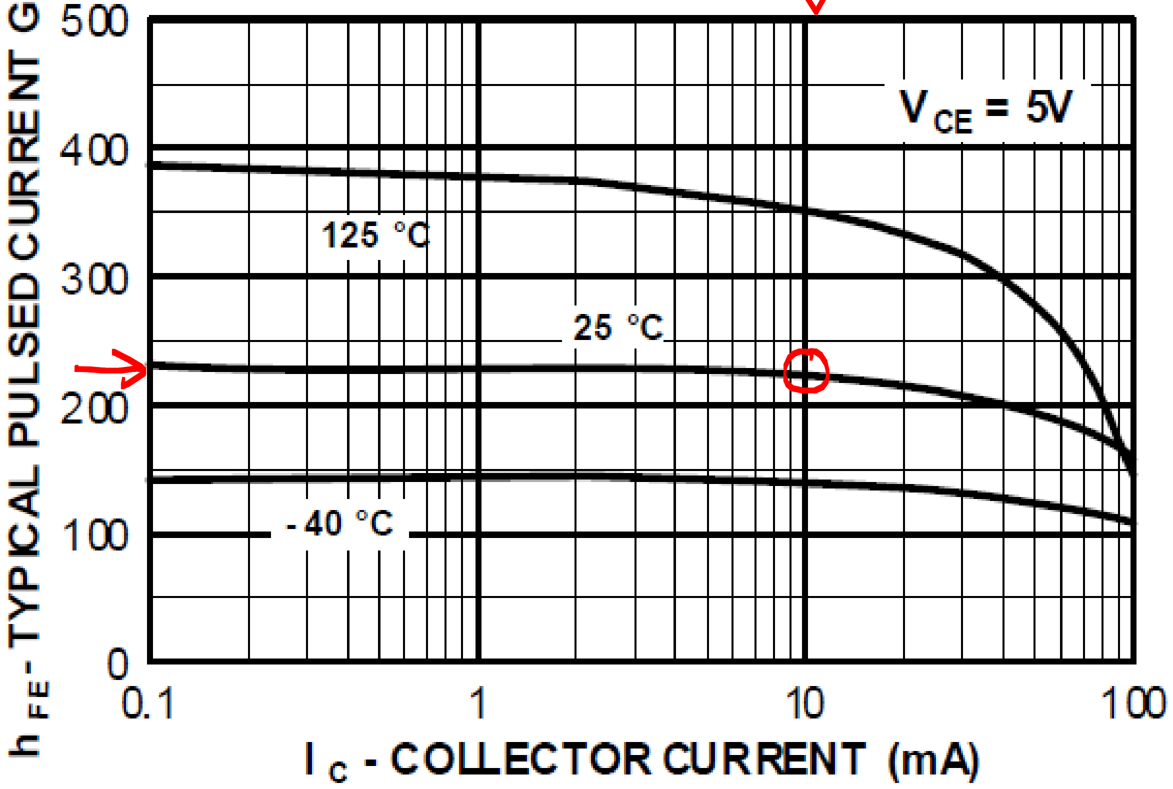
2N3904

$\beta \sim 225$

10 mA

~ 0.72V

Typical Pulsed Current Gain vs Collector Current



Base-Emitter ON Voltage vs Collector Current