Lecture 4: Push-Pull Output Stage

(Quiz)

0. Review

1. Push-Pull Stage
2. Push-Pull Design

- Quiz today
- PreLab 2 due at lab session
- HW2 due Fri (Sep 27)
- Lab1 report due next Wed (Oct 01)
  → see course website for template

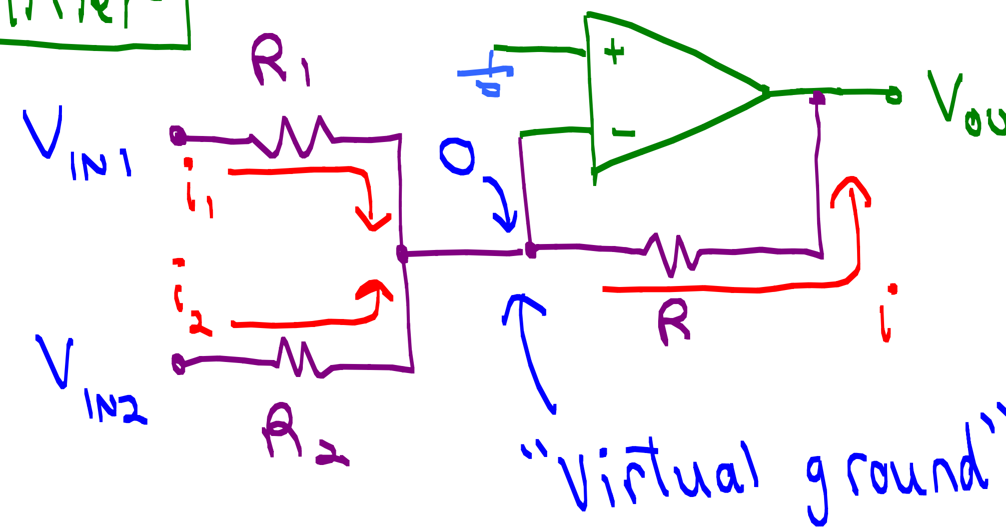
Textbook reading: 16-2 The 741 Op Amp
16-3 The Inverting Amplifier
16-5 Two Op Amp applications
18-7 Current Boosters

0. Review

Op Amp Golden Rules:

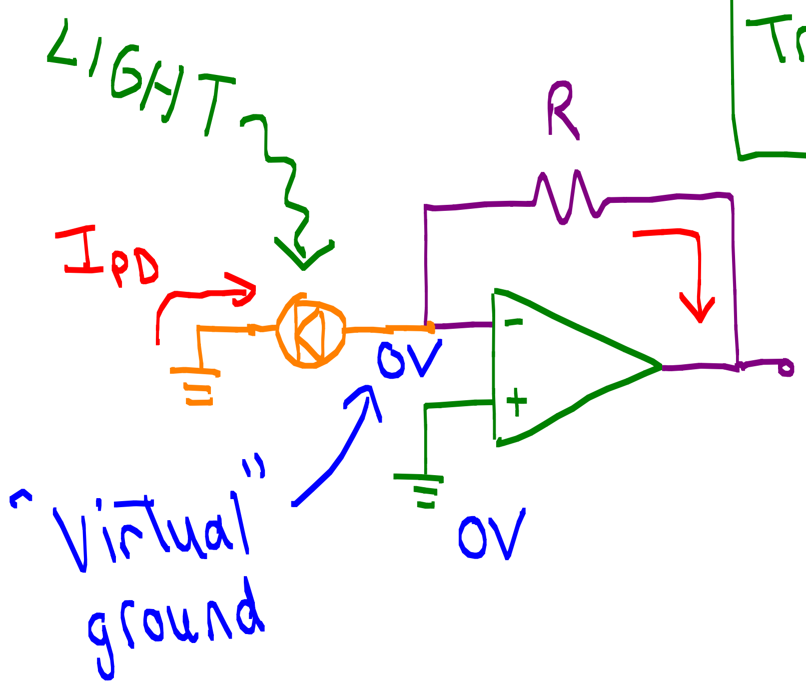
1. $V_{IN+} = V_{IN-}$ ← "virtual short"
2. zero input current

Summing Amplifier



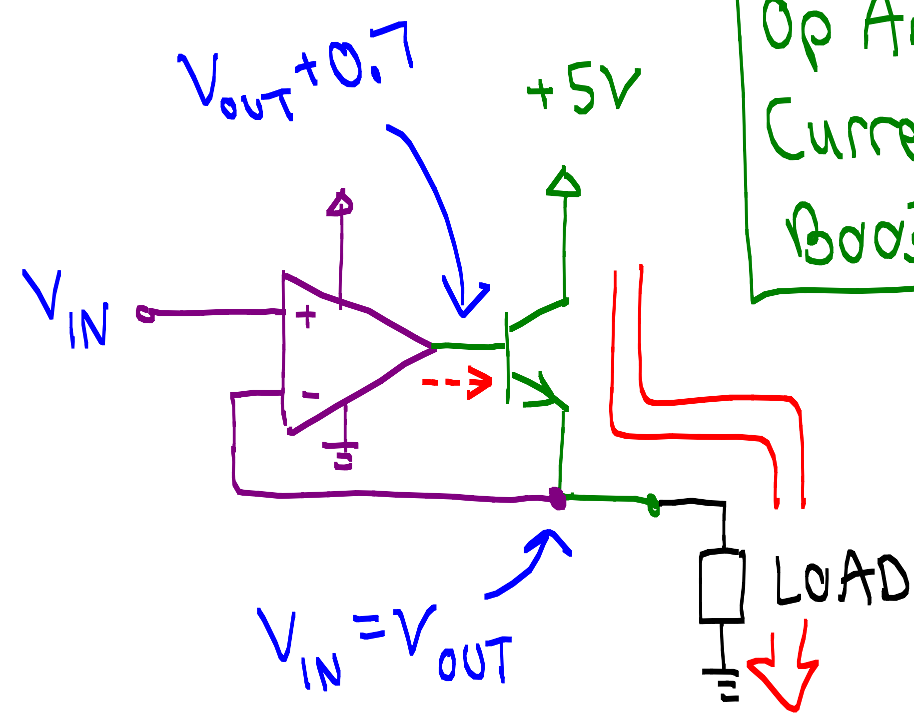
$$V_{OUT} = -\left(\frac{R}{R_1}V_1 + \frac{R}{R_2}V_2\right)$$

Transimpedance Amplifier



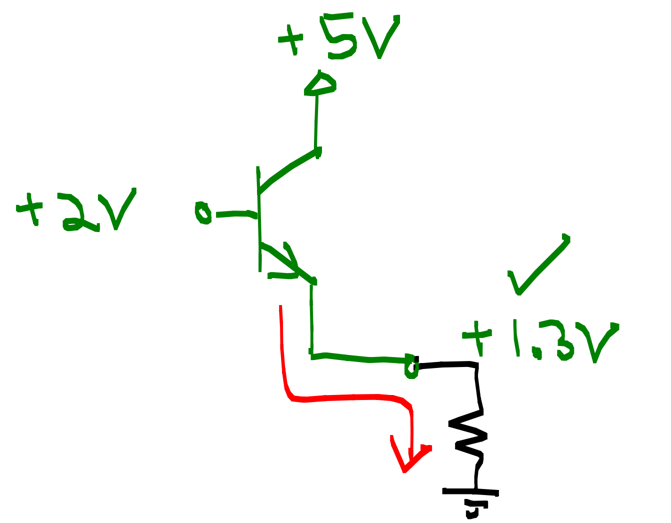
$V_{OUT} = -I_{PD}R$ → (−) voltage

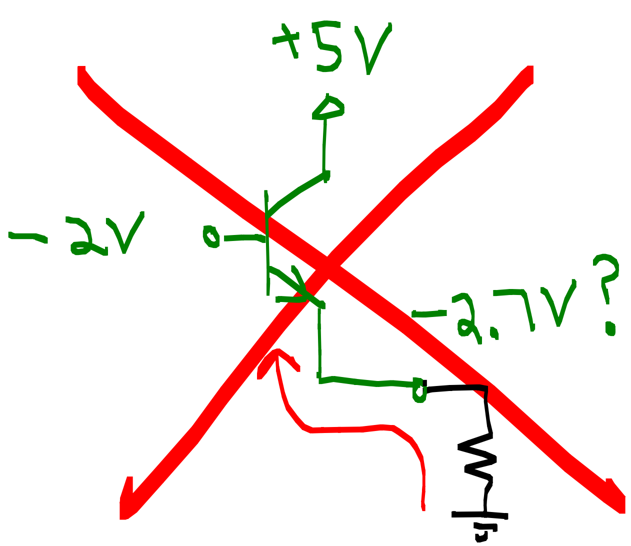
Op Amp Current Booster



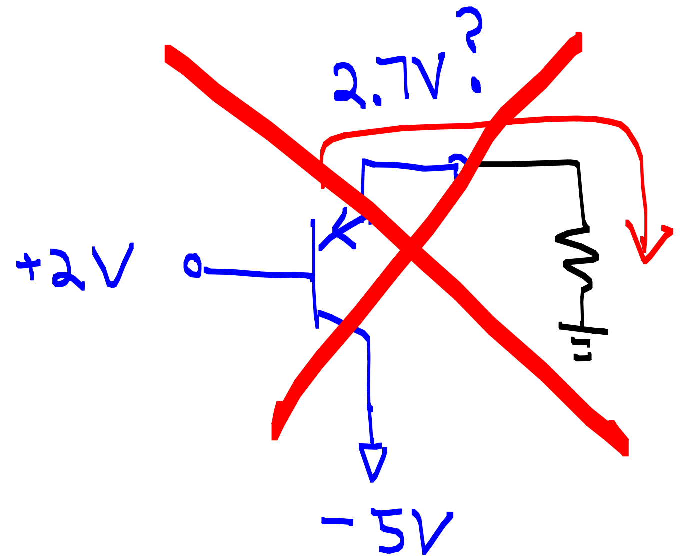
1. Push-Pull Stages

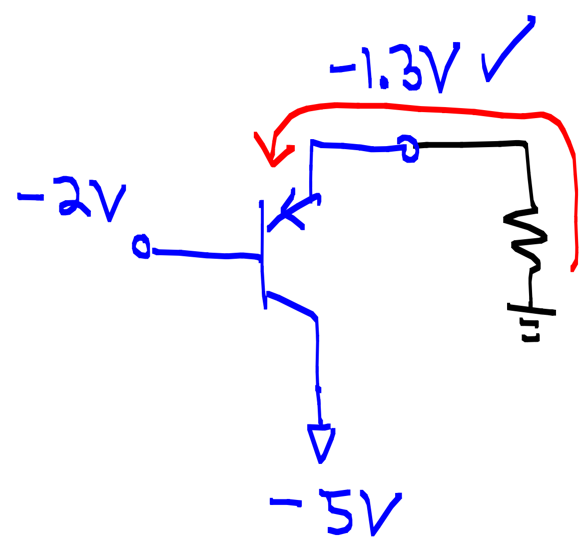
- An npn follower can only "push" current



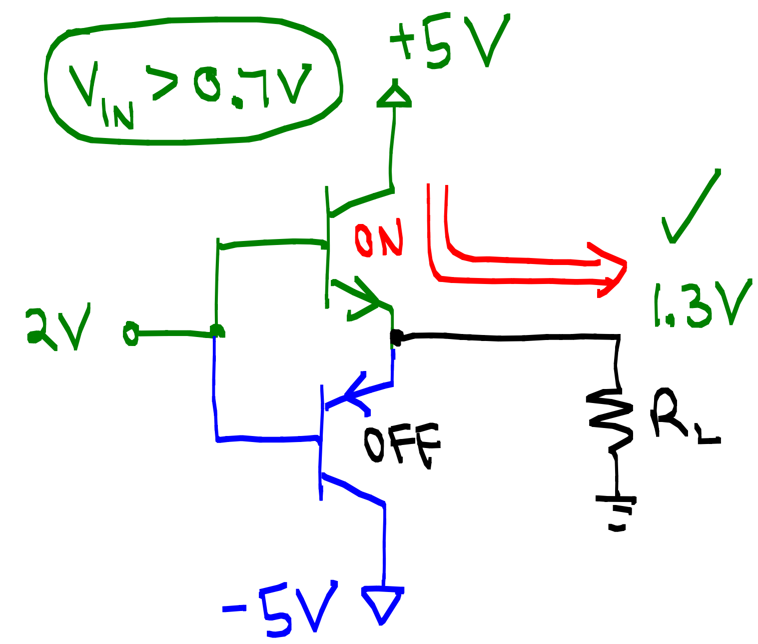


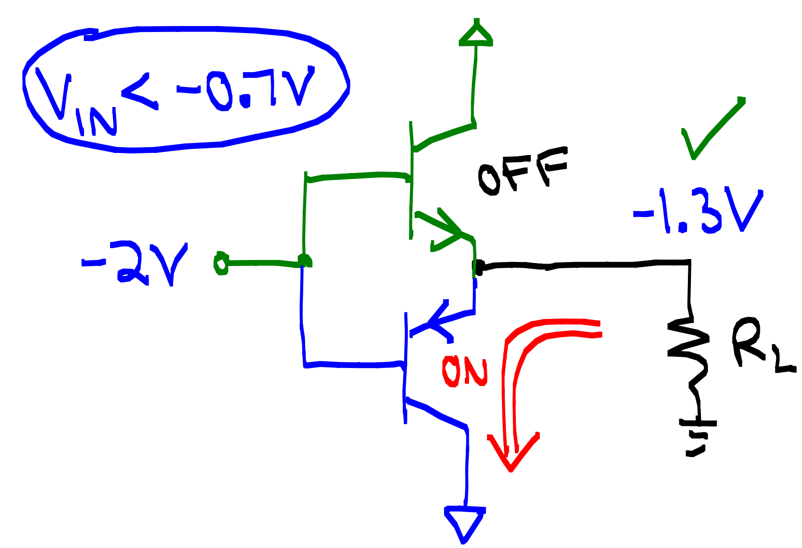
- A pnp follower can only "pull" current



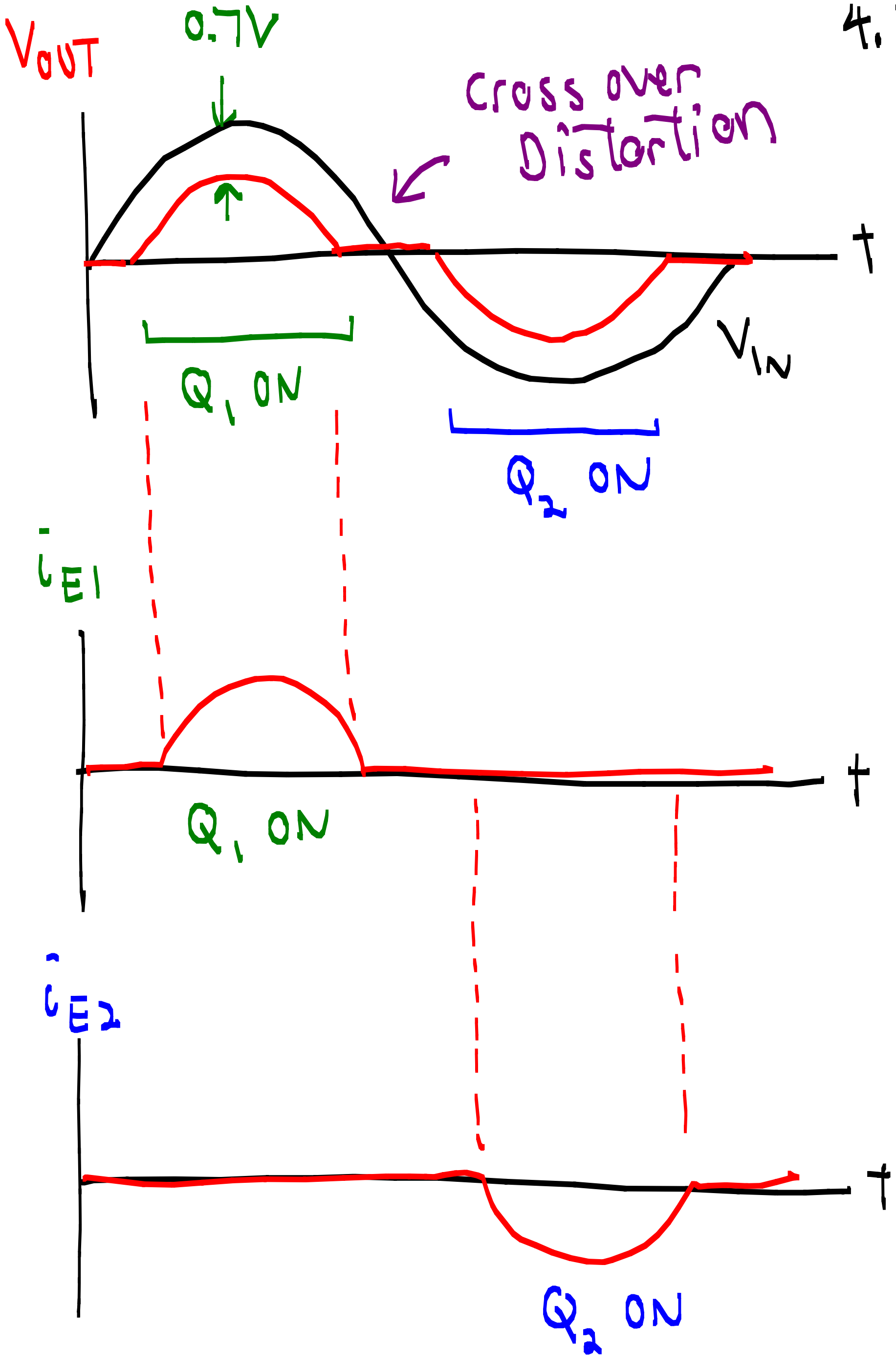


- Combine npn + pnp to "push-pull" current!





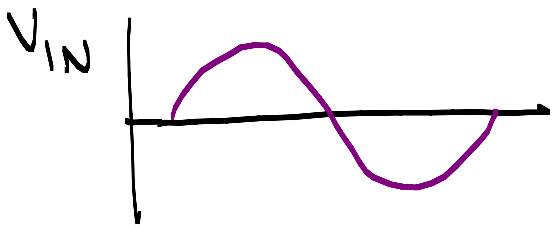
★ Called a Class B "push-pull" or "totem-pole" stage

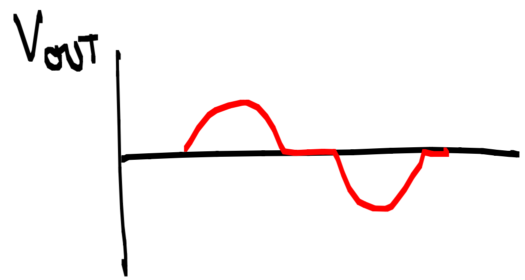


Is there a catch? Unfortunately, YES. :(

⇒ Crossover Distortion!

- $V_{OUT} = 0$ when $-0.7V < V_{IN} < +0.7V$ (Both Q_1 and Q_2 are OFF)] output has "Dead zone"





⇒ Obviously,  is not a desirable output waveform.

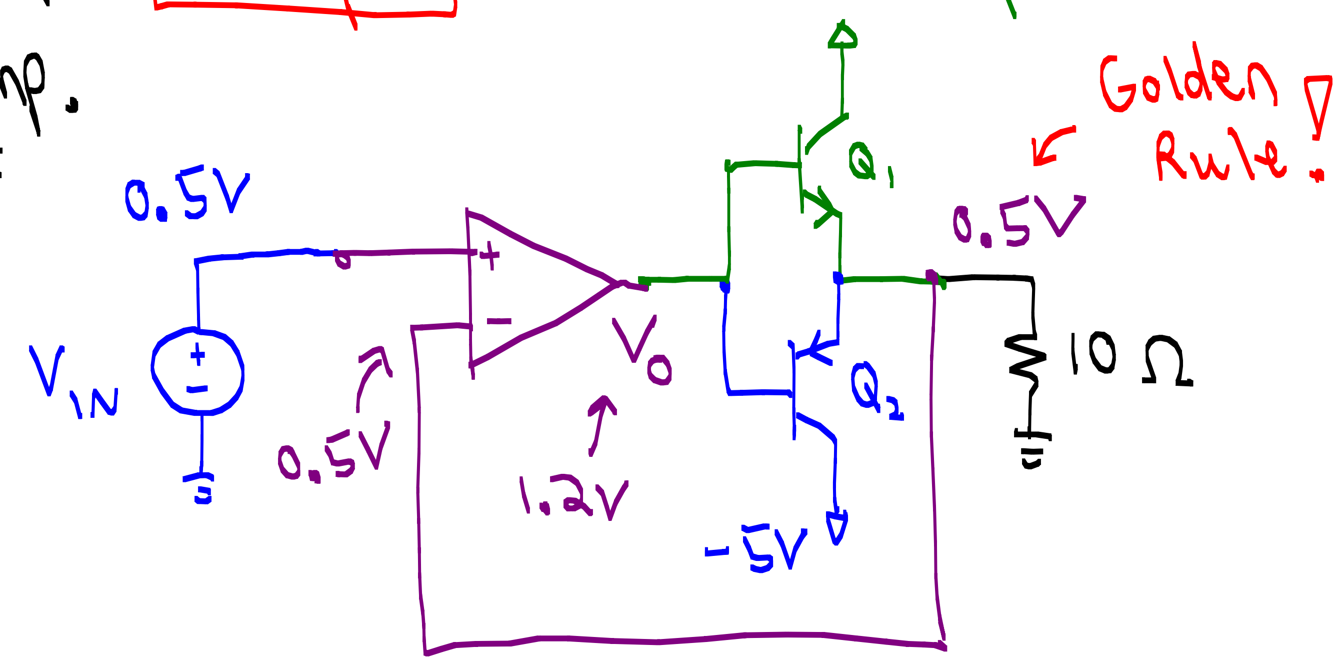
One way to reduce crossover distortion is to use the push-pull <u>with an op amp</u>.

→ op amp makes sure that $V_{LOAD} = V_{IN}$

when $V_{IN} > 0$: $V_o = V_{LOAD} + 0.7$

when $V_{IN} < 0$: $V_o = V_{LOAD} - 0.7$

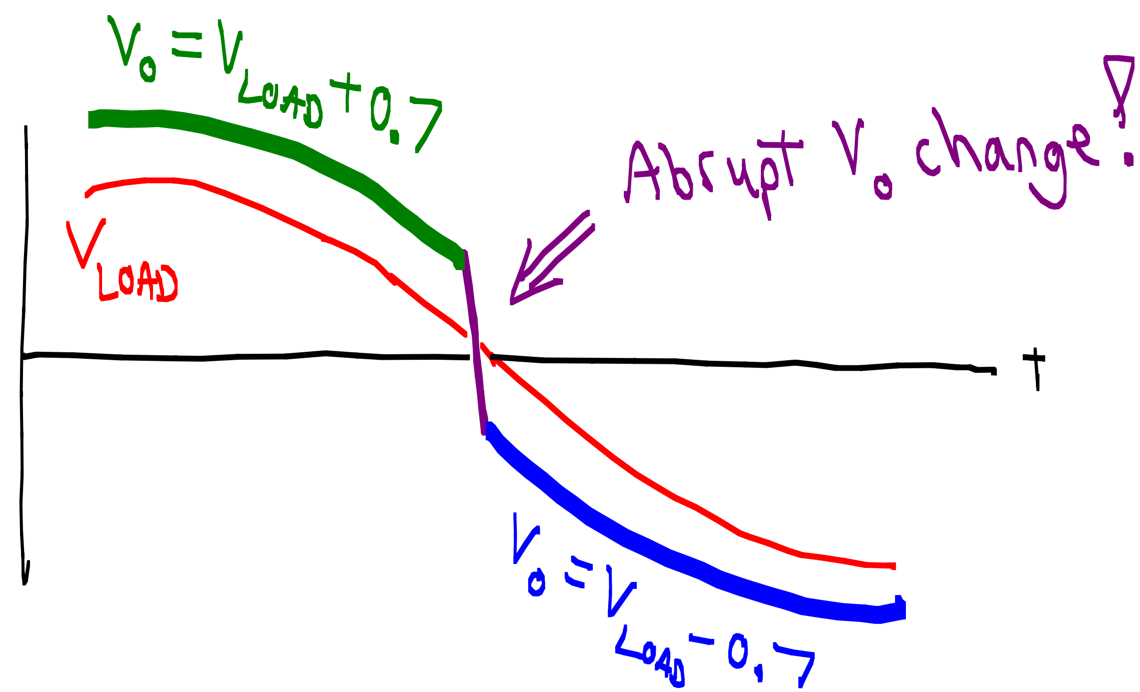
Example



☆ NOTE: Even with an op amp, crossover distortion gets worse at high freq

why?: op amp output has large $\frac{dV}{dt}$ in crossover region

↑ limited by op amp's slew rate (V/μs)



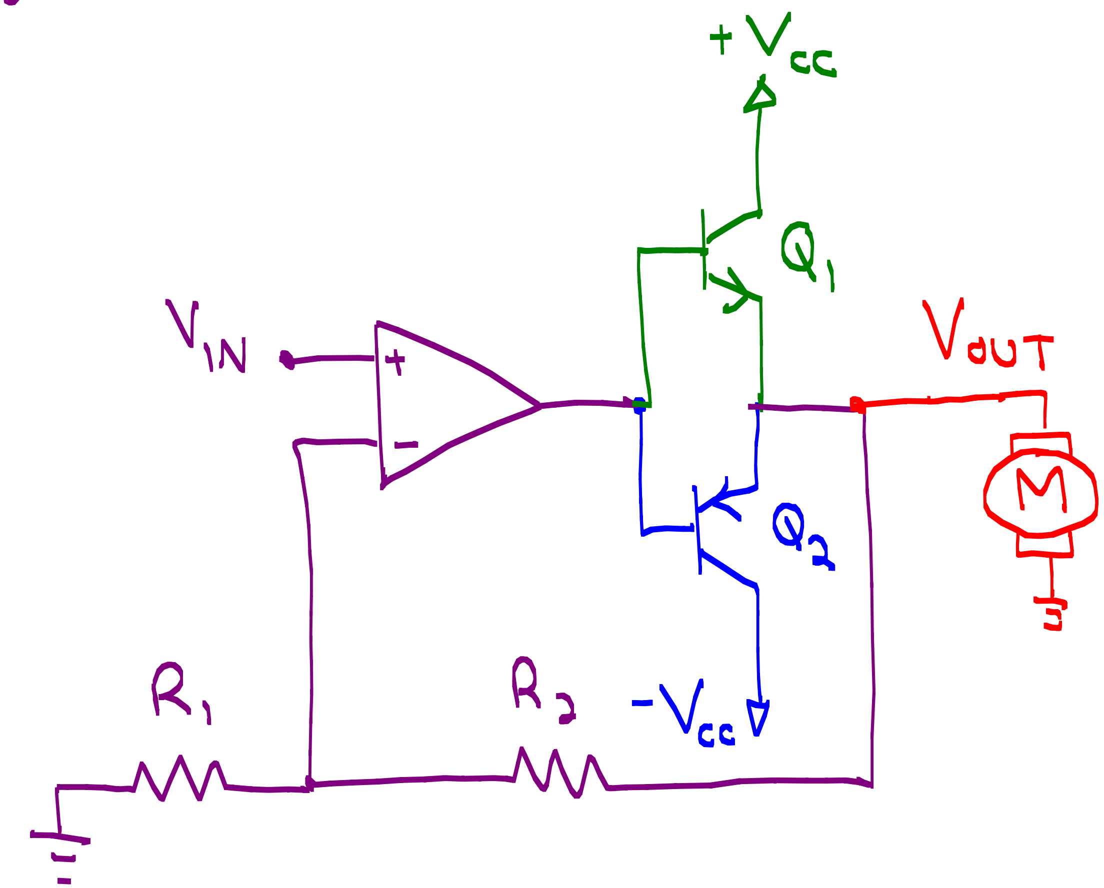
2. Push-Pull Design

Example: Motor driver

- ±9V max
- 2W max
- Gain = 20 ± 5%

V_{cc} = 9, 12, 15, or 18V

↑ We'll use "worst case" parameters for this example.



① Start with max desired output

$\text{Max } V_{OUT} = \boxed{\pm 9V}$

$\text{Max } I_{OUT} = ?\quad P = IV$

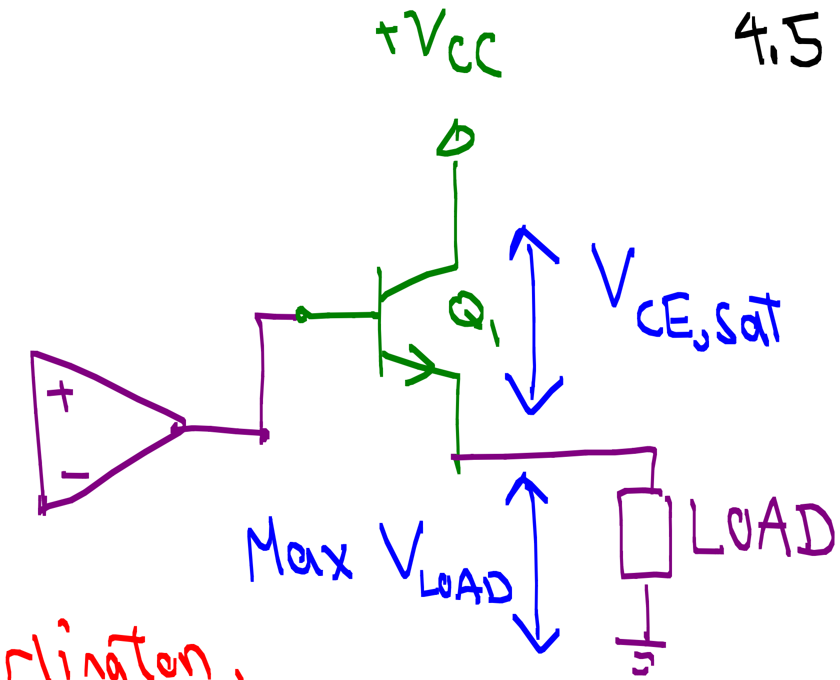
$\rightarrow I = \frac{2W}{\pm 9V} = \boxed{\pm 0.222A}$

② Choose V_{cc}

Make sure Q_1 never saturates!

"Head room" is a good idea ↓

★ We want $\underbrace{\min V_{CE}}_{V_{cc} - \max V_L} > V_{CE,sat} + 2V$



$$\Rightarrow \boxed{V_{cc} > \max V_L + V_{CE,sat} + 2V}$$

If Q_1 Darlington, this would be 0.7V

- First do "quick" analysis to estimate V_{cc}:

$V_{cc} > 9 + 0 + 2$

$V_{cc} > 11V \Rightarrow$ Try $\boxed{V_{cc} = 12V}$

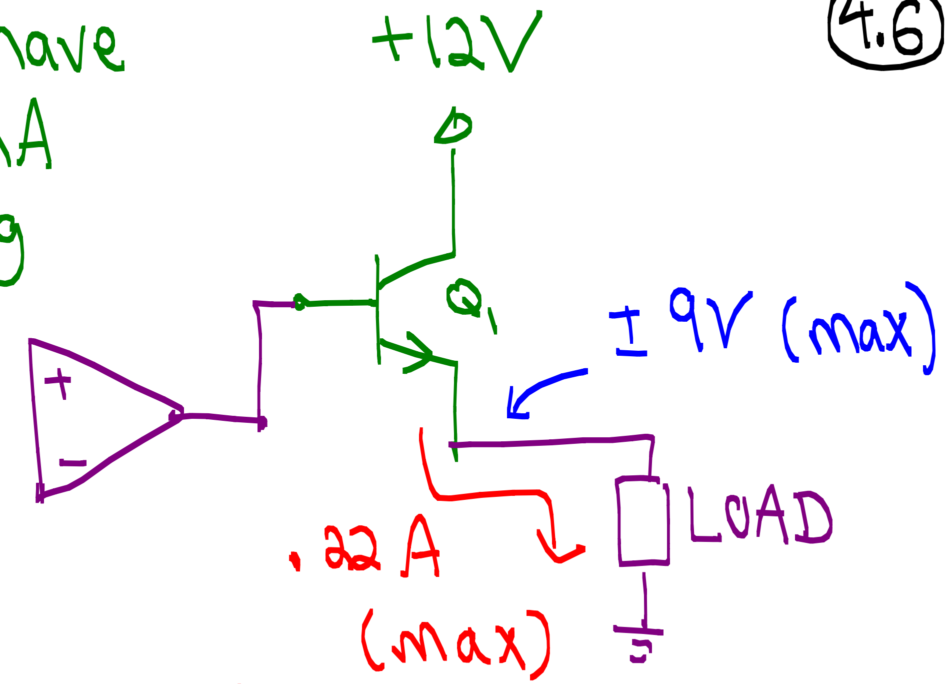
May need to revise later.

③ Choose Transistor

Demanded by circuit:

Max $I_c \approx 222\ mA$ —(×2)→ Ideally have > 340 mA rating

Max $V_{CE} = 12 - (-9) = 21V$ ↑ when Q_1 off, Q_2 on —→ > 42V rating



Estimate max $P = \frac{.22}{101}(0.7) + 0.99(.22)(12-9) = .655W$ —(×2)→ 1.31 W rating or higher

Q_1	Max I_c	Max V_{CE}	P_{Rating} (no HS)	P_{rating} (w/HS)
2N3904	200 mA ✗		.625W	
2N4401	600 mA ✓	40V ← (close enough)	.625 W ✗	1.5W ✓

Choose heat sink later

④ Max op amp output OK?

4.7

See appendix:

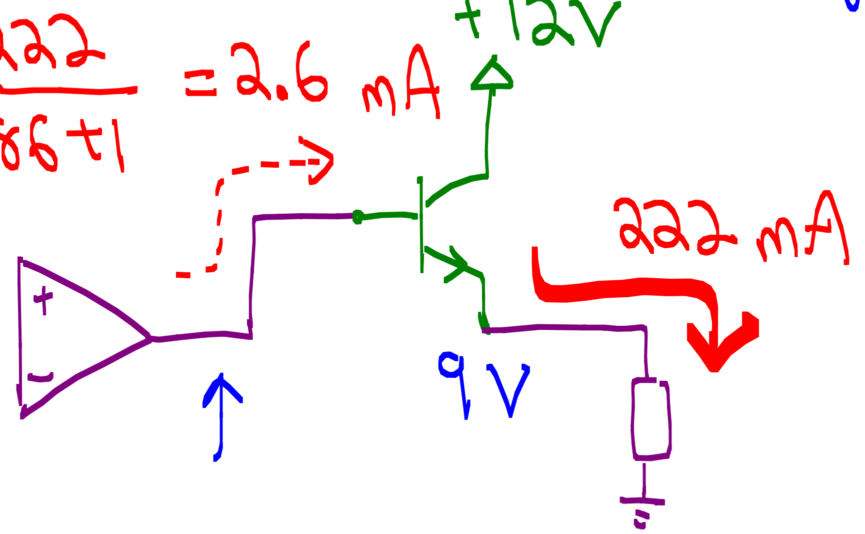
Min $\beta \sim 86$

$(I_c = 222\ mA)$

$V_{BE} \approx 1V$

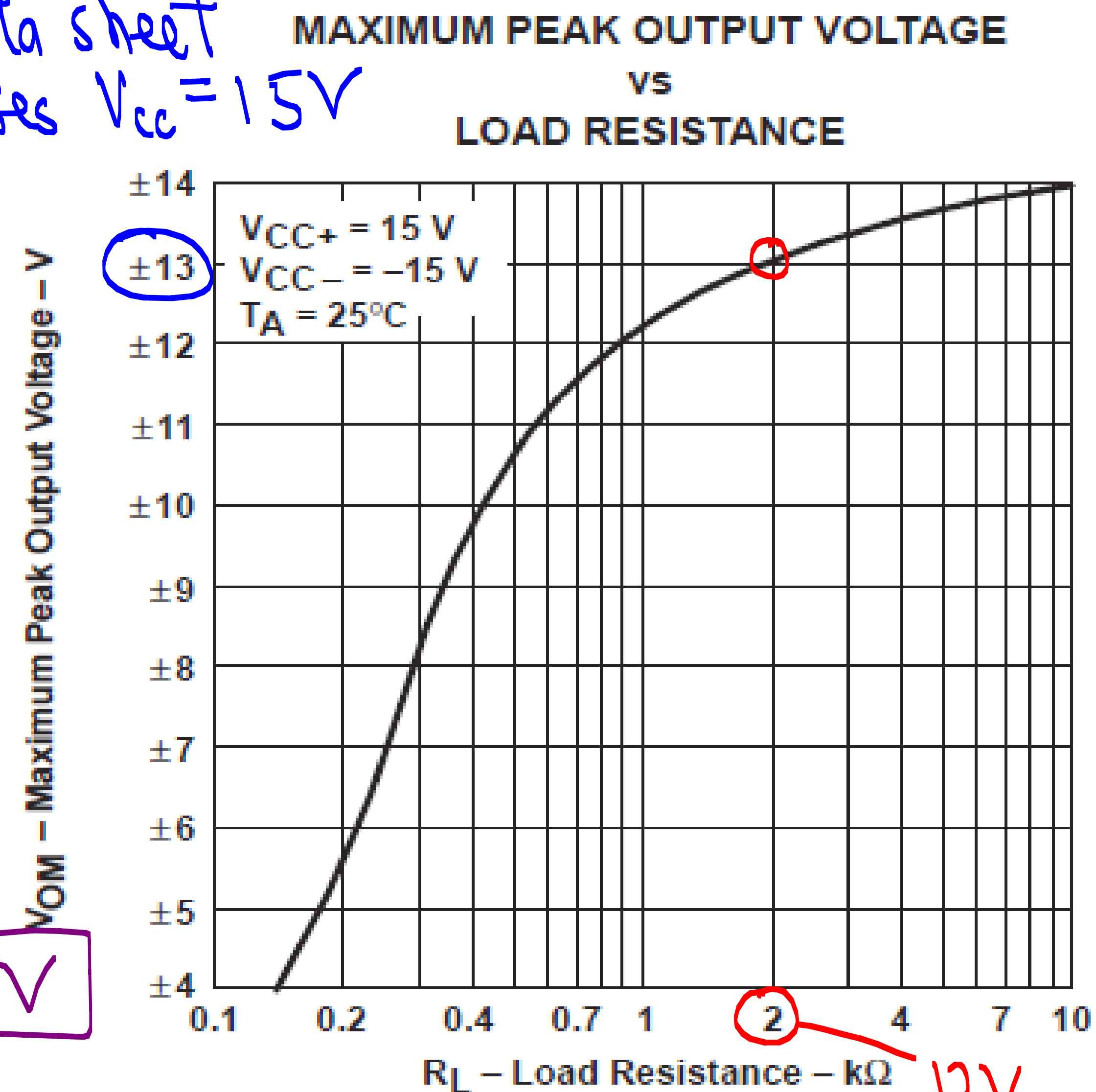
$(I_c = 222\ mA)$

$\frac{222}{86+1} = 2.6\ mA$



Max $V_o = 9 + V_{BE} = \underline{\underline{10V}}$

Data sheet uses $V_{cc} = 15V$



$\frac{13V}{2K} = \underline{\underline{6.5mA}}$

Op amp headroom $= V_{cc} - \max V_o = 12 - 10 = \boxed{2V}$

Q: Can op amp output 2.6mA with 2V headroom?

Same headroom with $V_{cc} = 15V$ is $\max V_o = 15 - 2 = \underline{\underline{13V}}$ @ 6.5 mA > 2.6mA

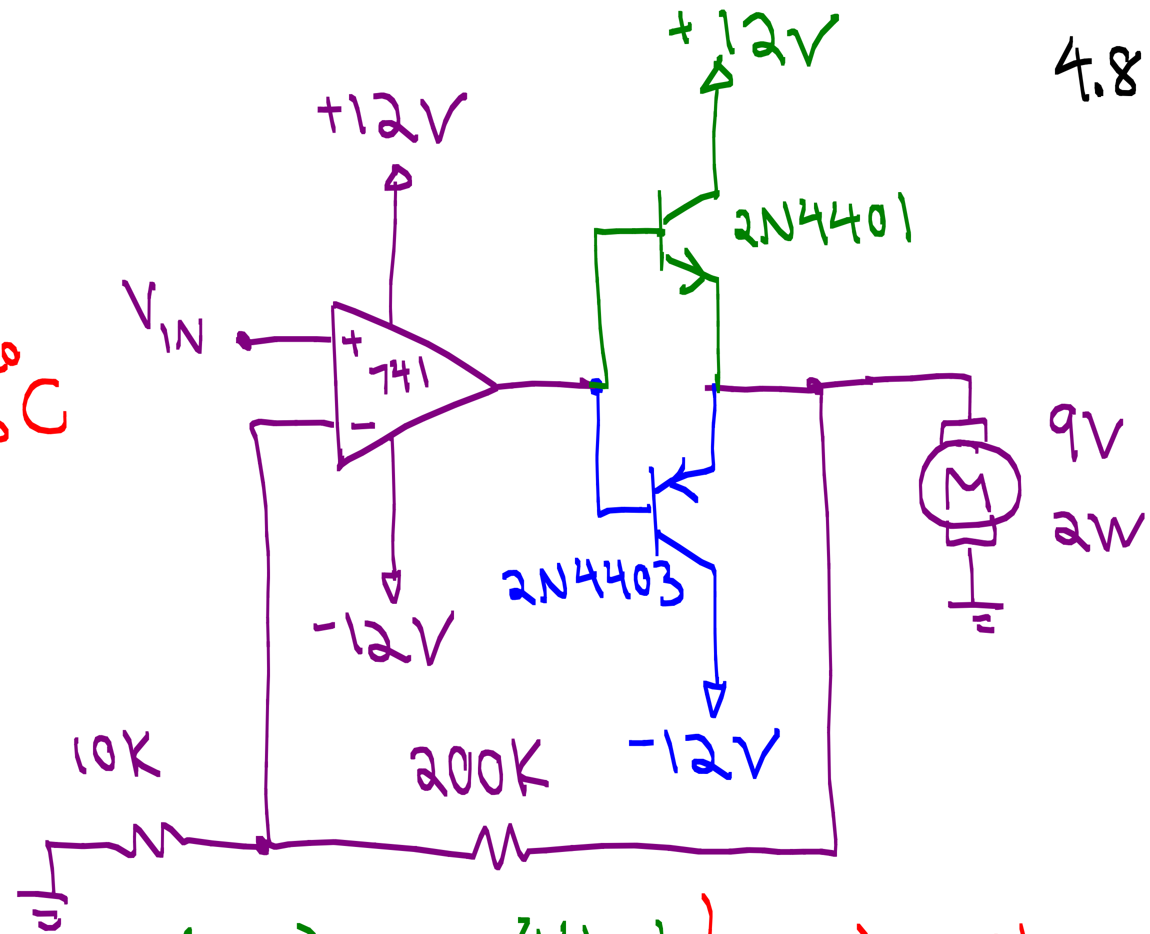
YES!

(5) Compute heat sink:

* Find Θ_{SA} needed for $T_J < 85°C$:

$$25°C + (.66W)(83.3°C/W + .5°C/W + \Theta_{SA}) < 85°C$$

$\rightarrow \Theta_{SA} < \underline{\underline{7.1\ °C/W}}$ ← Pretty low value (Probably need forced air)



(npn) 2N4401 } complementary pair
(pnp) 2N4403

• Op amp feedback resistors?

$$G = 1 + \frac{R_2}{R_1} = 1 + \frac{R_2}{10K} = 20 \Rightarrow R_2 = 190K$$

Choose $R_2 = 200K$

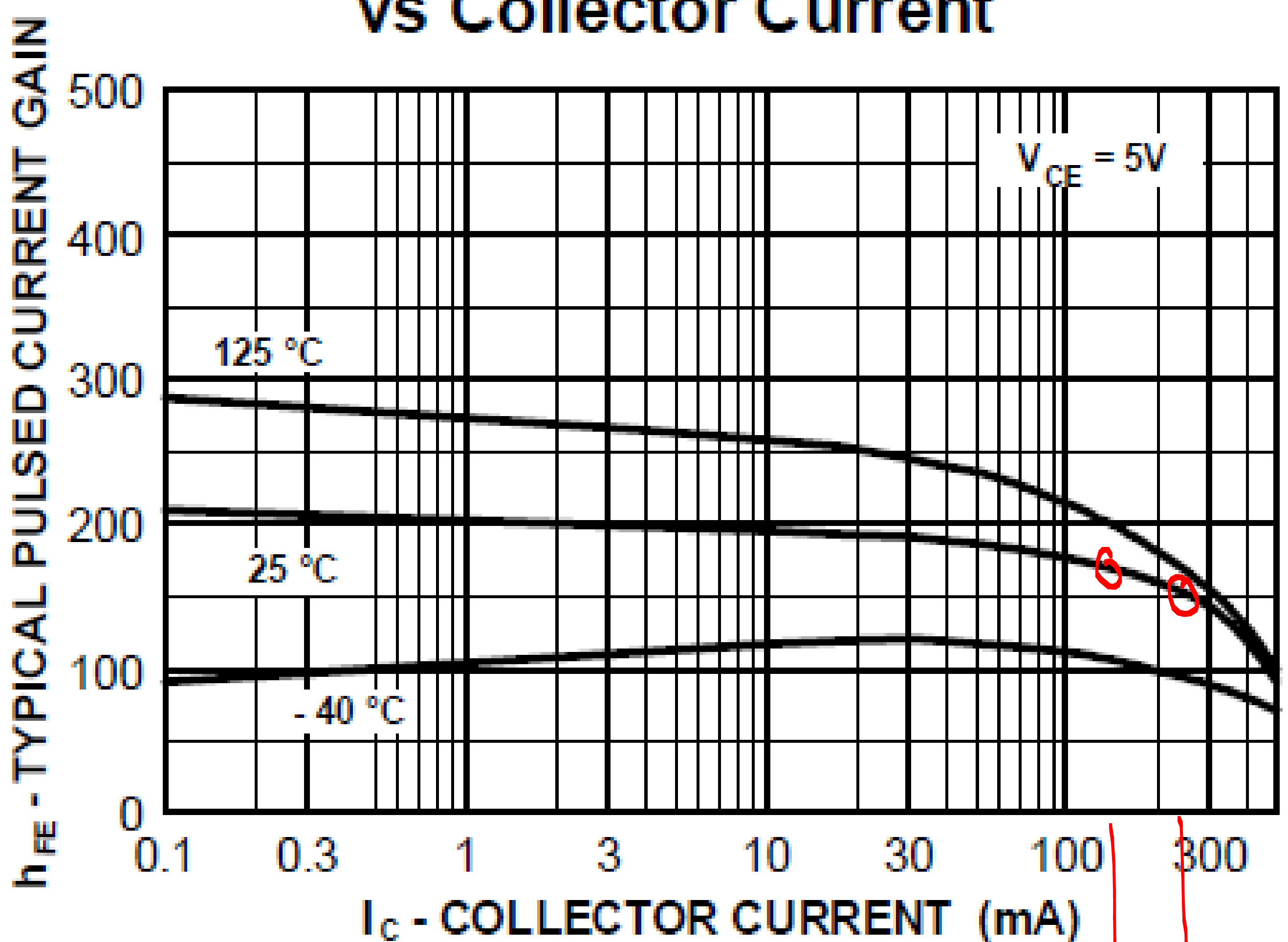
↑ Typically, $1K < R_1 < 10K$

Actual $G = 1 + \frac{200K}{10K} = 21$ ← (+5%) ✓

Appendix

2N4401 data sheet (Fairchild)

Typical Pulsed Current Gain vs Collector Current



150mA

~222mA

	150mA	222mA

$$\frac{\beta_{Typ}}{\beta_{min}} \simeq \frac{175}{100} \approx \frac{150}{?}$$

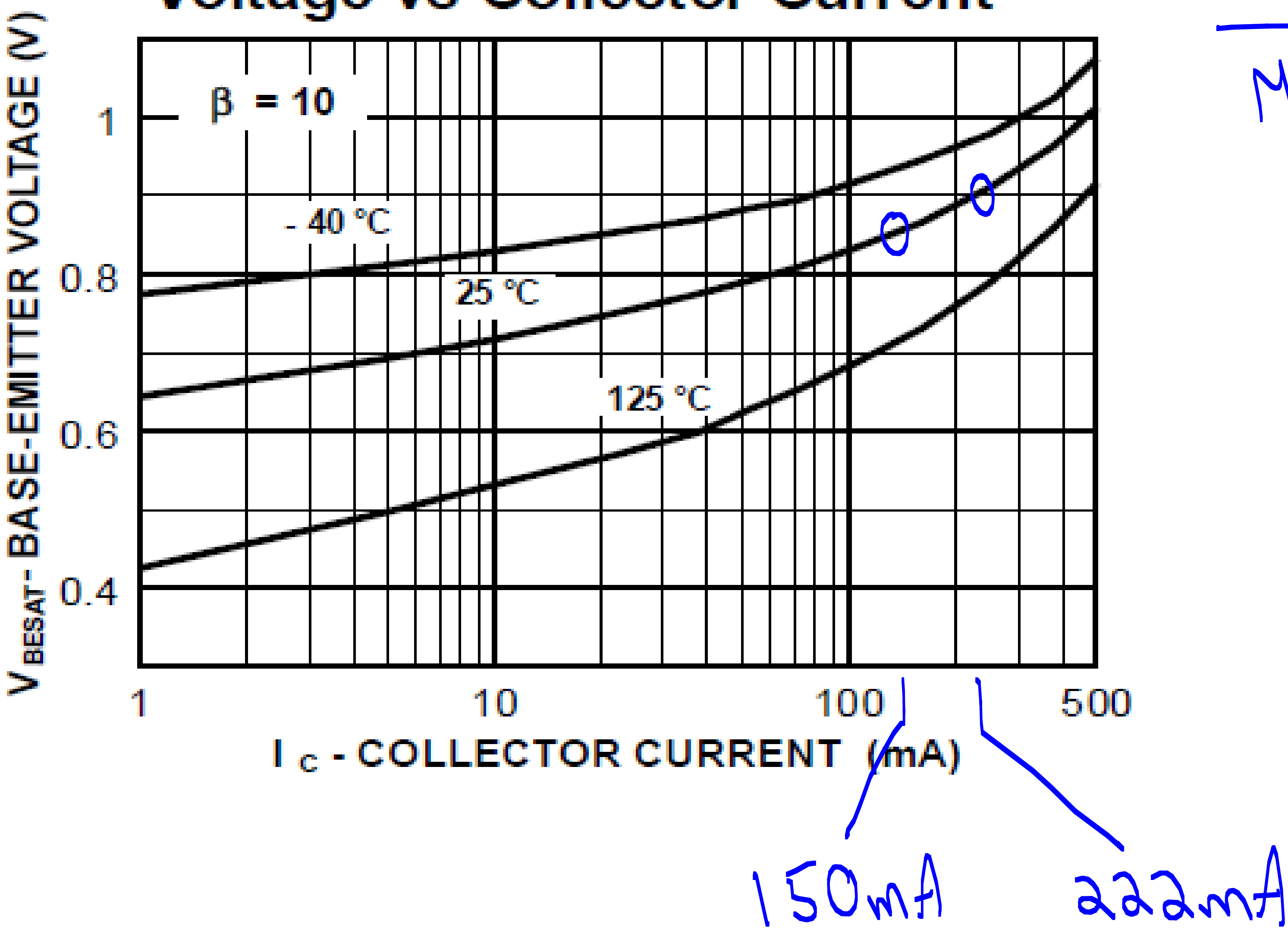
$$\Rightarrow \beta_{min} \sim 150 \times \frac{100}{175}$$

$$= \underline{\underline{86}} \text{ @ } 222mA$$

A.2

☆ V_{BE} increases with I_C

Base-Emitter Saturation Voltage vs Collector Current



$$\frac{\text{Typical } V_{BE}}{\text{Max } V_{BE}} \approx \frac{.85V}{.95V} \approx \frac{0.9V}{?}$$

$$\Rightarrow \text{max } V_{BE} \approx 0.9 \times \frac{.95}{.85}$$

$$= \underline{\underline{1V}} \text{ @ } 222mA$$