Lecture 8 : BJT Switches

(Quiz)

1. Intro
2. BJT Analysis
3. BJT Design

- Exam #1 this Thu (Oct 17)
  - → Closed notes, closed book
  - → HW1, 2, 3 material
  - → See course website for sample exam + solns
- This week's lab: wrap up Lab 3 testing/demo

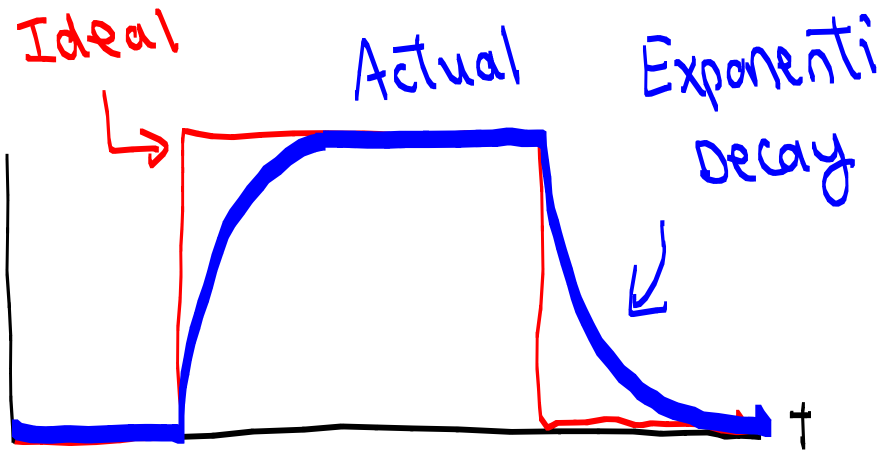
Textbook reading:

6-13 : Recognizing saturation

6-14 : Transistor switch

0. Review

① Bandwidth (small signal)

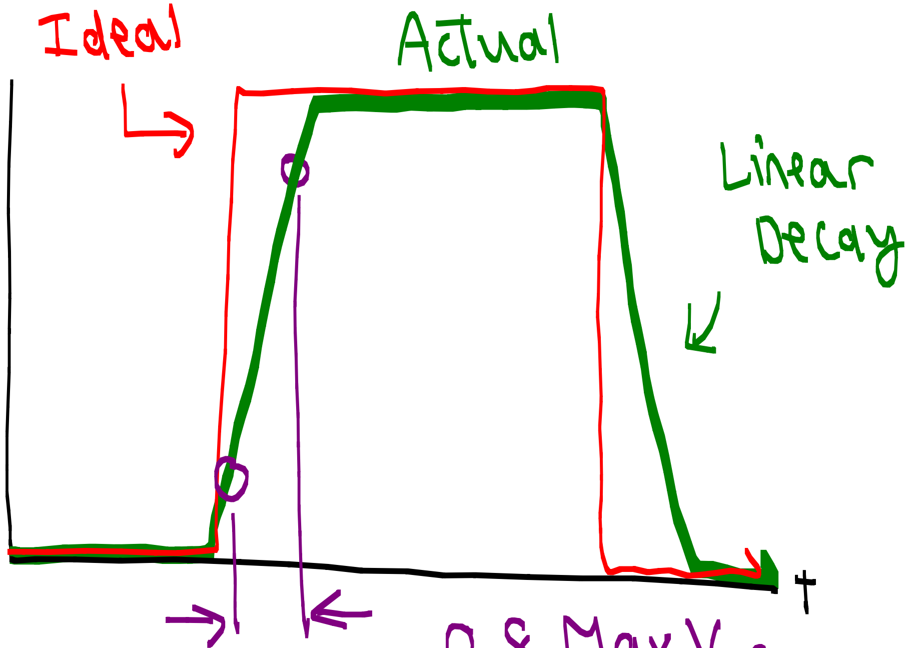


Rise Time: $\boxed{T_R = 0.35/BW}$

$$\text{Bandwidth} = \frac{GBW}{\text{Gain}}$$

GBW ← Gain-Bandwidth Product

② Slew Rate (Large Signal)



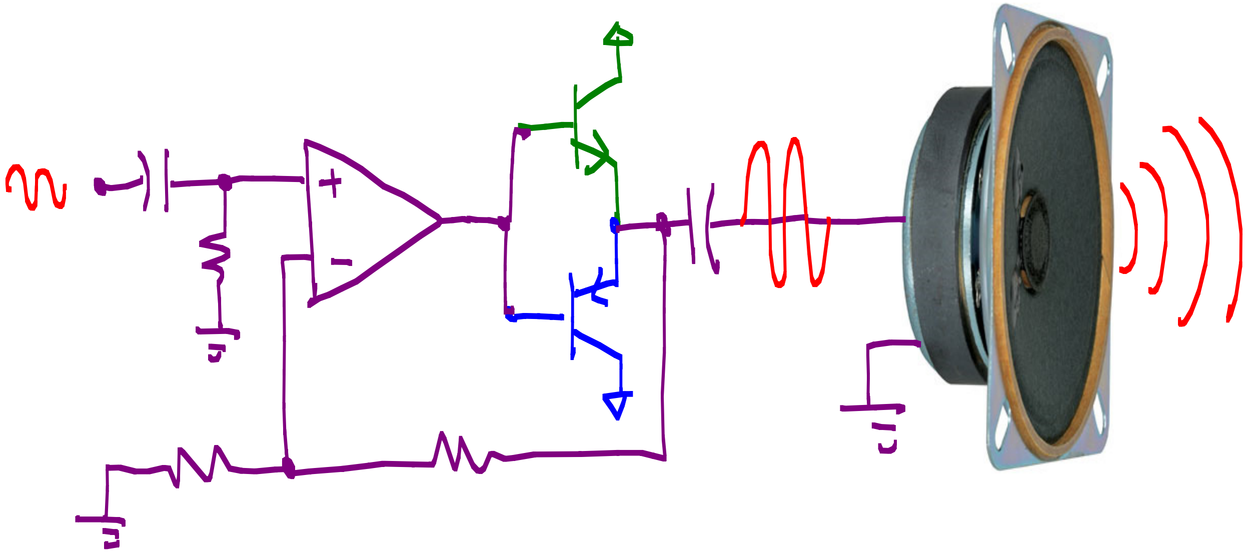
$$T_{SR} = \frac{0.8\,\text{Max}\,V_{pp}}{SR}$$

Large signal bandwidth (sine wave only) → $\boxed{f_{max} = \frac{S_R}{2\pi V_p}}$ ← Only for sine wave!

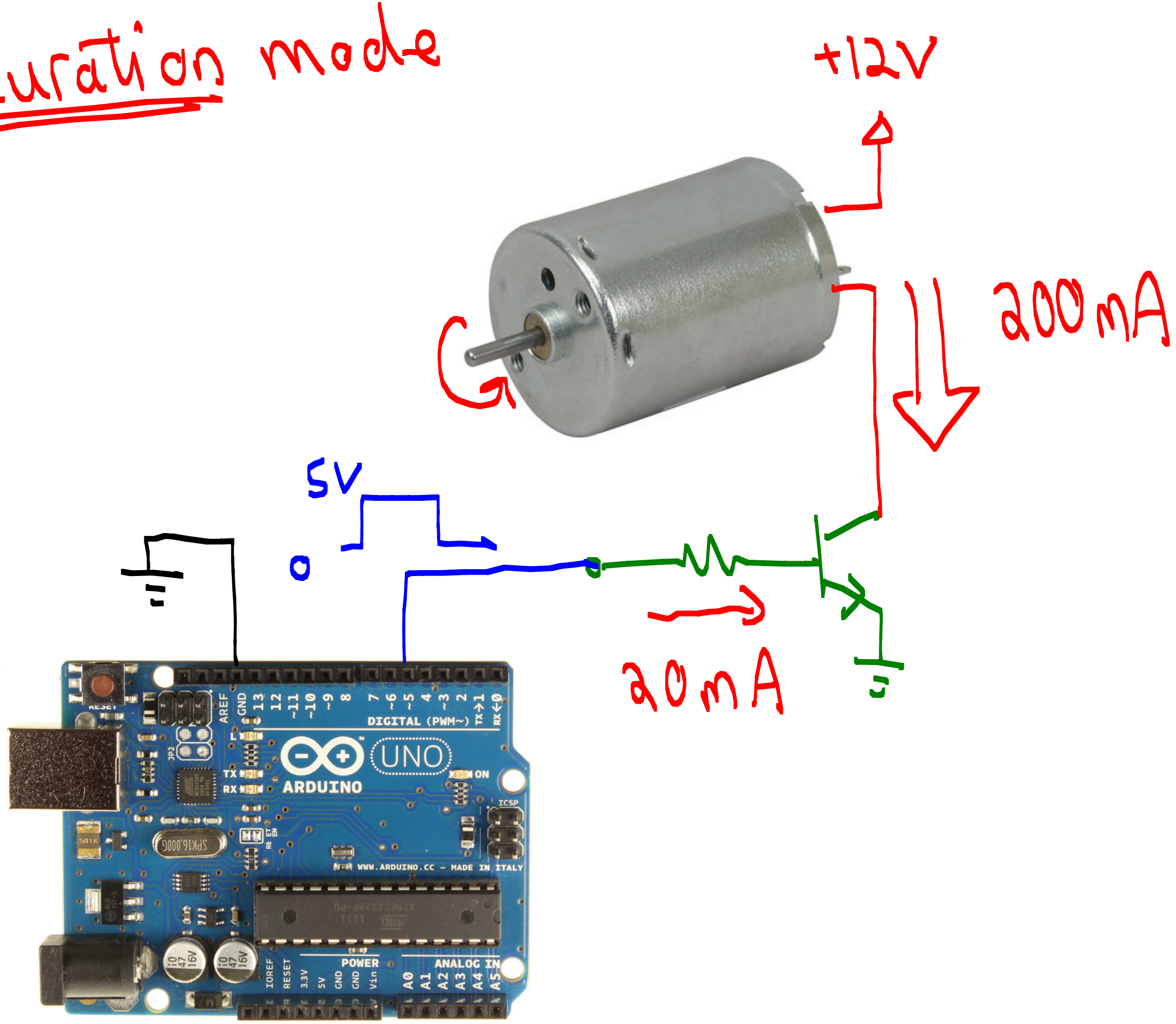
1. Intro

- So far, we have used the $\underbrace{\text{BJT}}_{\text{used in active mode!}}$ as an amplifier.

↑ Variable V_{OUT}



- Many devices (e.g. motors) require the $\underbrace{\text{BJT}}_{\text{used in saturation mode}}$ as a switch ← open or closed



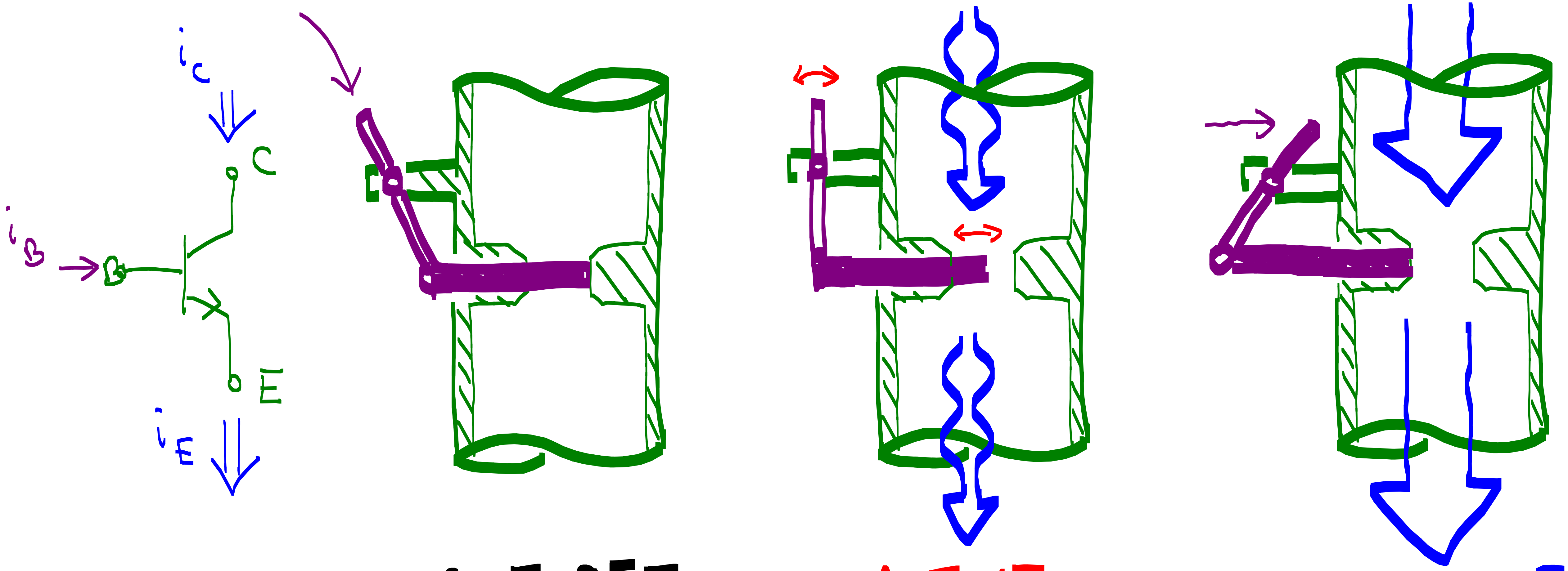
Transistor is like a valve for a large water pipe.

★ Base is like a control knob

Fully Closed

Partially open

Fully open



CUT-OFF
(No flow)

ACTIVE
(Variable Flow)

SATURATED
(Max Flow)

2. BJT Switch Analysis

- **Review** (npn switch)
  - BJT switch is either:

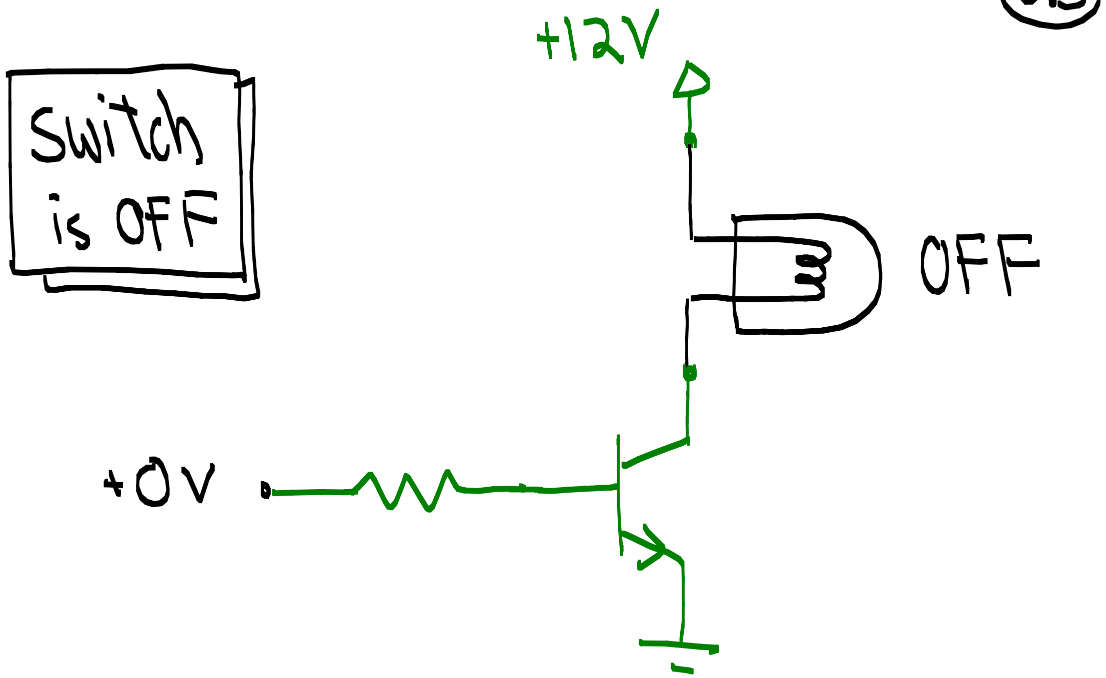
① OFF (cut-off)

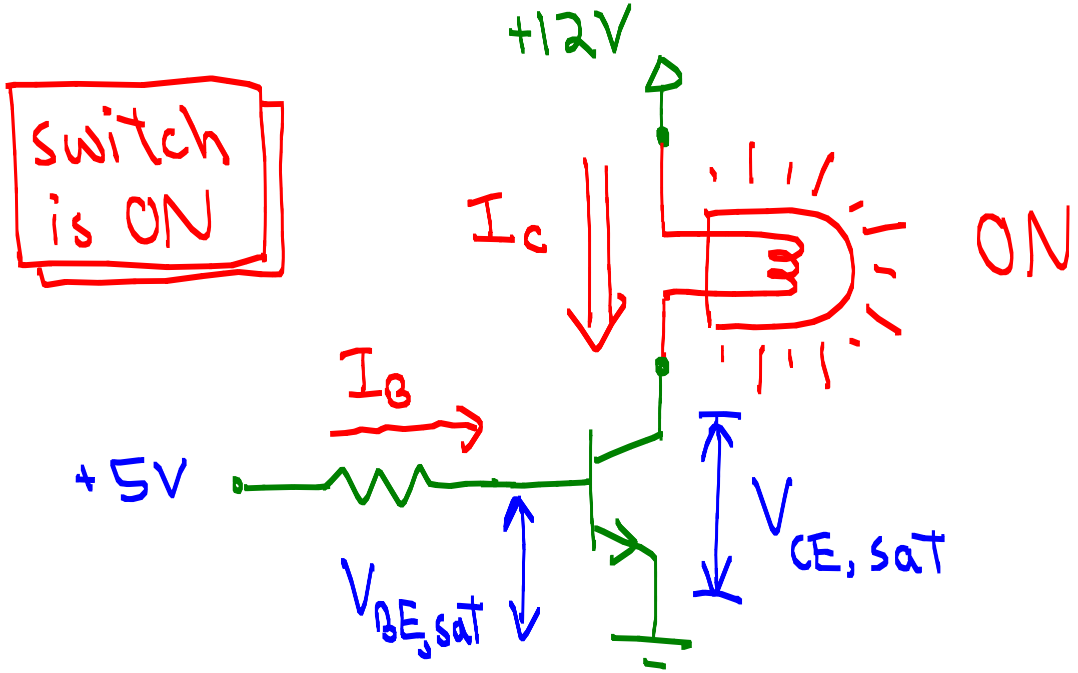
→ $I_B = 0$ and $I_c = 0$

② ON (saturation mode)

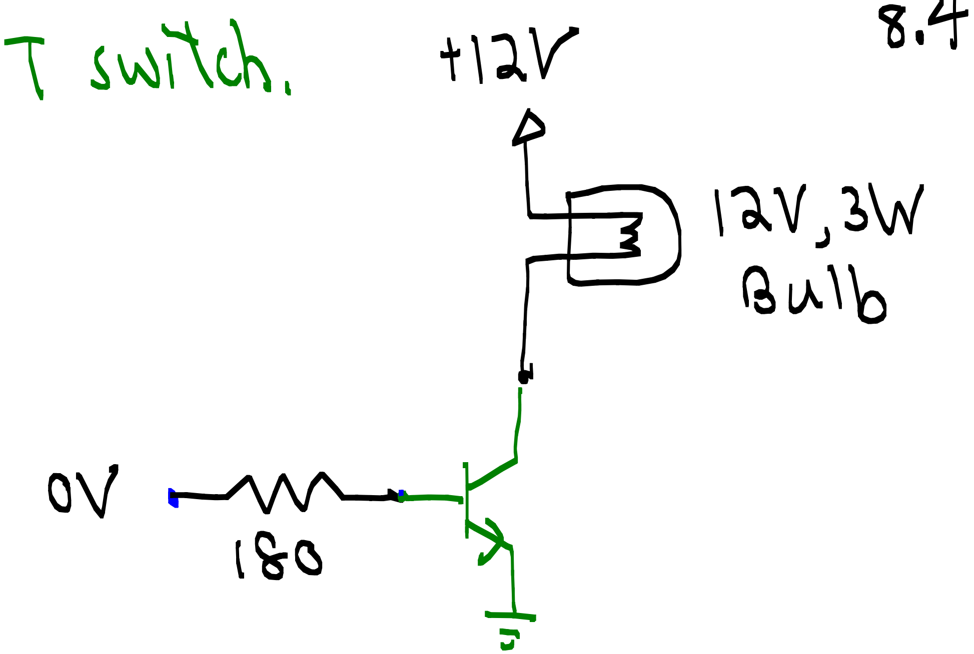
→ $V_{BE} = V_{BE,sat}$

→ $V_{CE} = V_{CE,sat}$ and $I_c \ll \beta I_B$





Example Incandescent Light bulb driven by BJT switch.



- When $V_{IN} = 0V$:

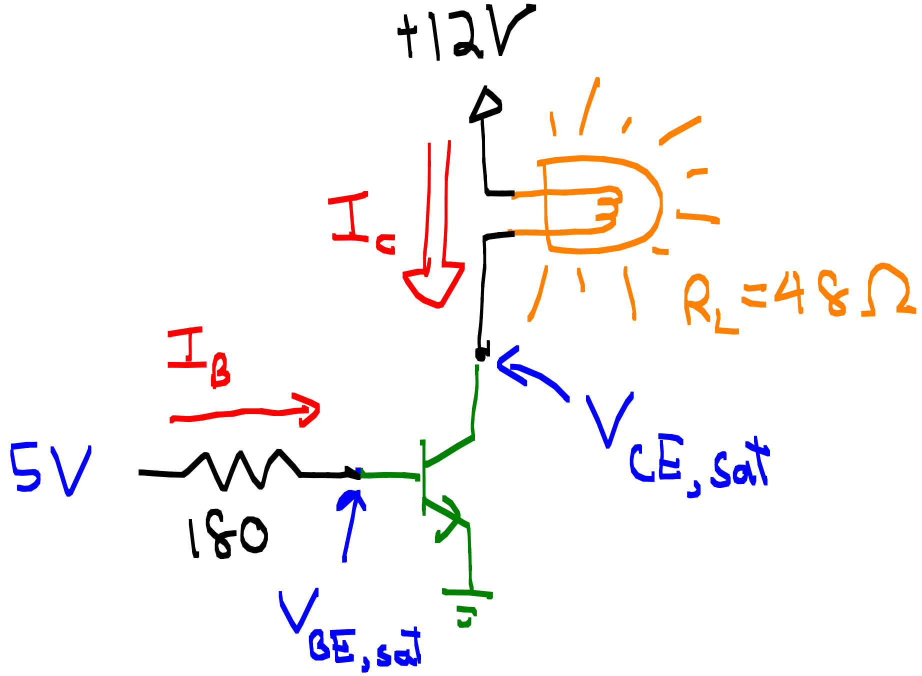
  $I_B = 0 \Rightarrow$ BJT is OFF

- When $V_{IN} = 5V$: For "quick" analysis

$$I_B = \frac{5 - V_{BE,sat}}{180\Omega} = \frac{5 - 0.7V}{180\Omega} = \underline{\underline{23.9mA}}$$

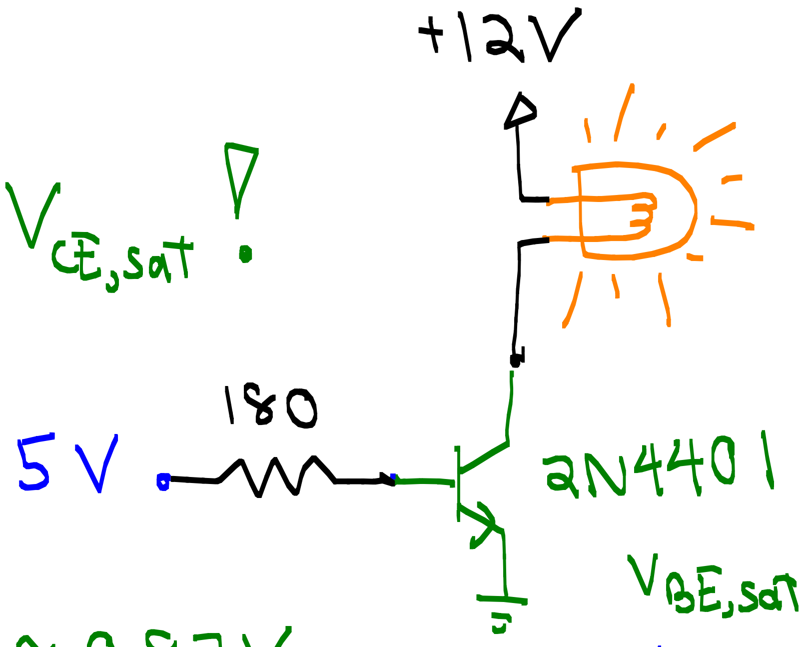
$$I_C = \frac{12 - V_{CE,sat}}{48\Omega} = \frac{12 - 0}{48\Omega} = \underline{\underline{250mA}}$$

[Bulb is basically a resistor,
so $P = \frac{V^2}{R} \rightarrow R = \frac{144}{3} = 48\Omega$]



- Typical analysis:

→ use transistor data sheet to find $V_{BE,sat}$, $V_{CE,sat}$!



$V_{BE,sat} = ?$

$V_{CE,sat} = ?$

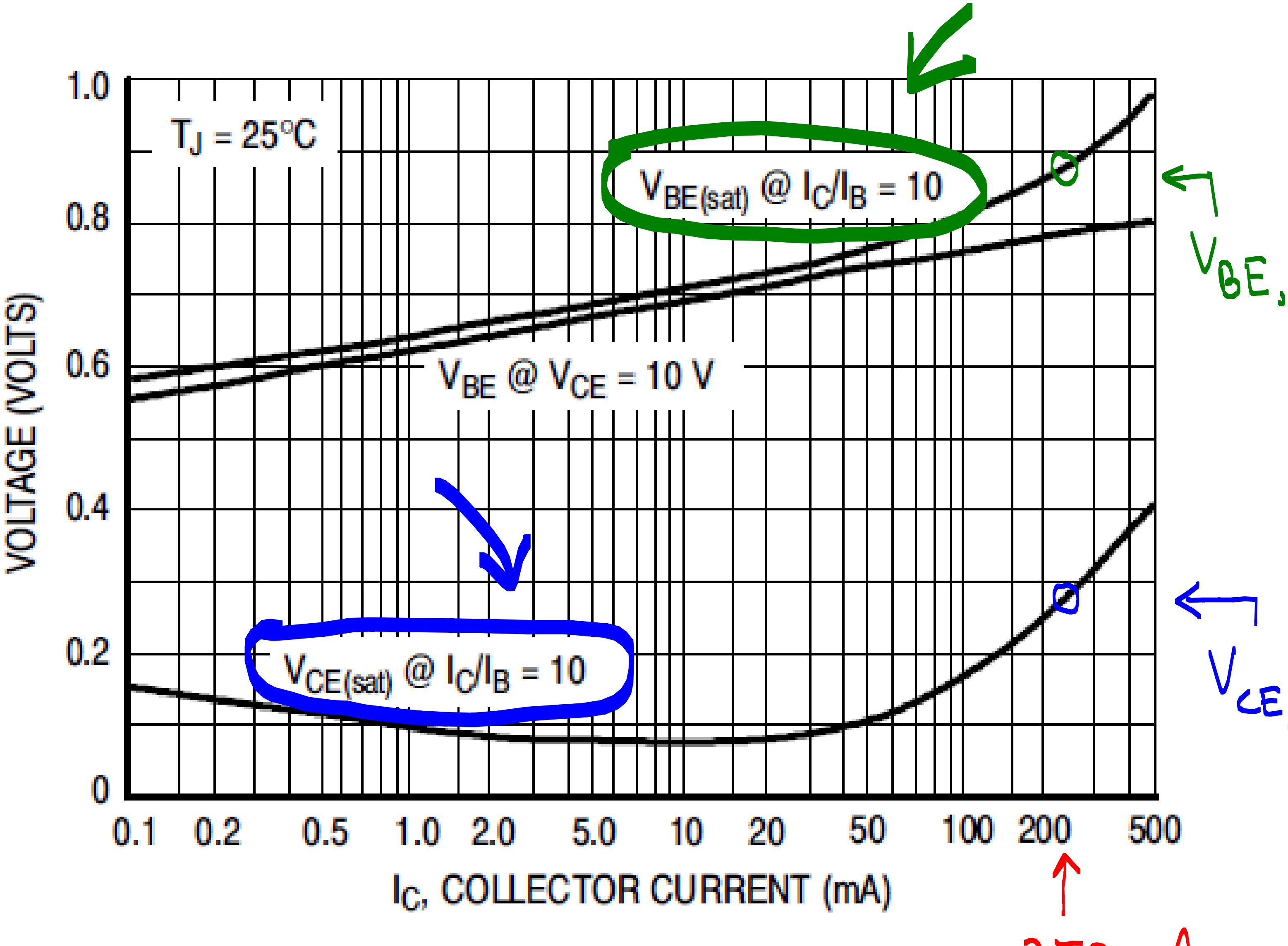


Figure 17. "On" Voltages

$V_{BE,sat} \approx 0.87V$

$V_{CE,sat} \approx 0.27V$

- Light bulb rating: 12V, 3W

→ $I = \frac{3W}{12V} = .25A$

$= \underline{\underline{250mA}}$

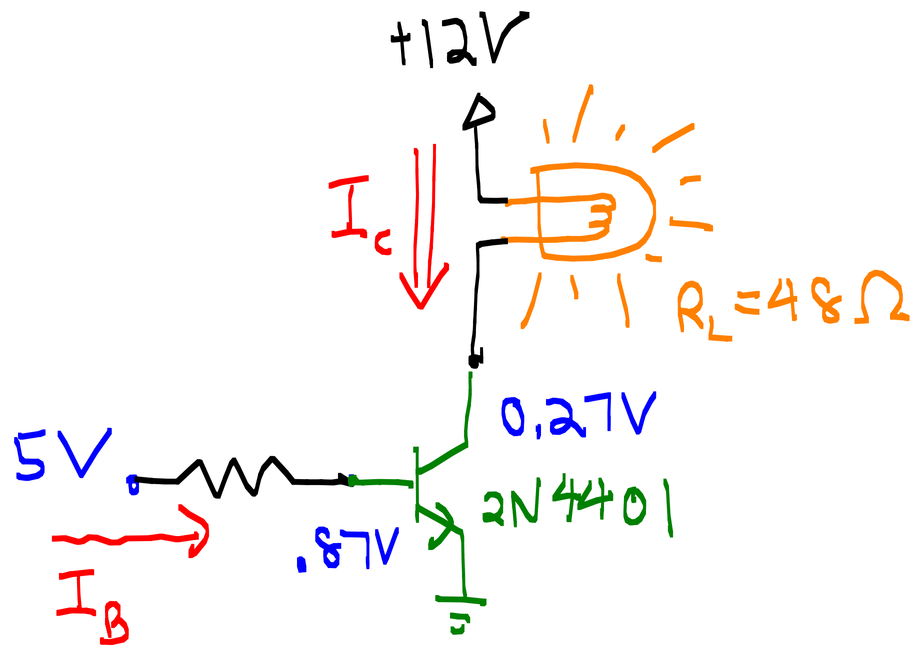
use "quick" analysis OR load rating to determine $V_{BE,sat}$ and $V_{CE,sat}$

From 2N4401 data sheet: $V_{BE,sat} \approx 0.87V$

$V_{CE,sat} \approx 0.27V$ $\Big\}$ Typical values

$$I_B = \frac{5-0.87V}{180} = .0229\,A = \underline{\underline{22.9\,mA}}$$

$$I_C = \frac{12-0.27V}{48\Omega} = .244A = \underline{\underline{244\,mA}}$$



★ For reliable operation, a BJT switch should be driven into <u>hard saturation</u>

$$\Rightarrow \boxed{\frac{I_C}{I_B} \sim 10}$$

★ For Darlington BJT:

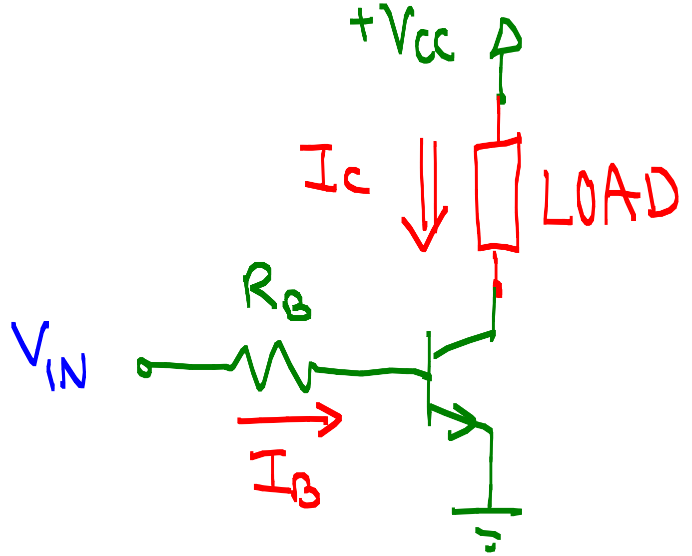
$$\Rightarrow \boxed{\frac{I_C}{I_B} \sim 250}$$

Proper Saturation?

$$\frac{I_C}{I_B} = \frac{244}{22.9} = 10.7 \checkmark$$

3. BJT switch design

Step 1 Know your load: $\underbrace{\text{current}}_{\star}$, voltage, etc



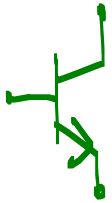
Step 2 Wisely choose the transistor

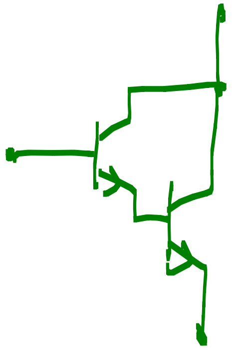
↳ check max I_c, max V_{CE}, P

Step 3 Properly <u>saturate</u> the transistor

Ⓐ $V_{CE} = V_{CE,sat}$

Ⓑ $\underbrace{I_B \approx \frac{I_c}{10}}_{\text{single BJT}}$ or $\underbrace{I_B \approx \frac{I_c}{250}}_{\text{Darlington}}$

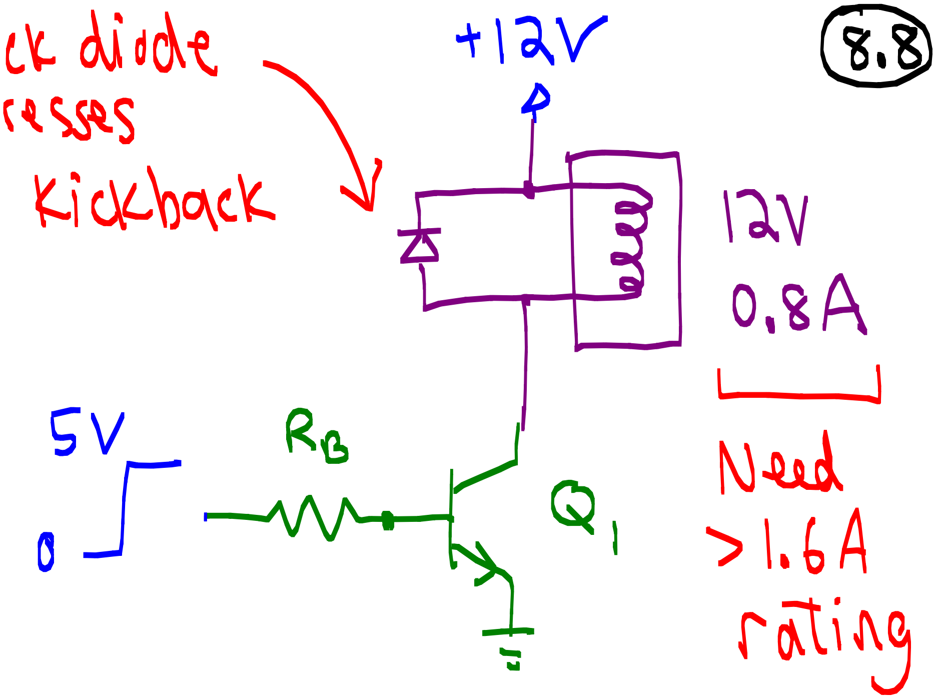




- **Design example:** Driver for 12V solenoid

STEP 1 Load properties

- Solenoid is essentially a wire coil with resistance $R_L = \frac{12V}{.8A} = 15\Omega$
- usually OK for current to be ~75% of rated value



Flyback diode suppresses inductive kickback

Need >1.6A rating

STEP 2 Choose the transistor:

	Max I_c	Max V_{CE}	(no HS) Max P	(w/HS) Max P
2N4401	600 mA ✗	40V	.625W ✓	1.5W
TIP31A	3A ✓	40V ✓	2W ✓	40W

$$P = \frac{0.8A}{10}(0.85V) + (0.8A)(0.17V)$$

$= .204W$

×2

$> .41\ W$ rating

From data sheet plots

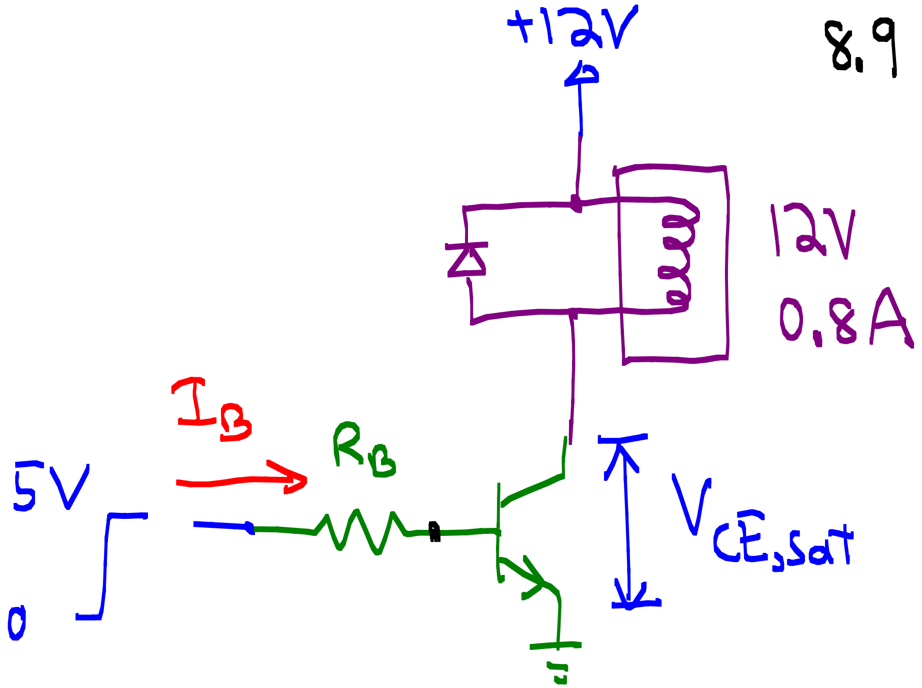
☆ Choose TIP31A (no HS)

STEP 3 Properly saturate the BJT

① Make sure load is happy

For solenoid: $I_c = \frac{12 - V_{CE,sat}}{15\Omega}$

Typical $I_c = \frac{12 - 0.17V}{15\Omega} = 0.79A$ ✓



② Base current drive

$I_B \sim \frac{I_c}{10}$

★ I_B must be large enough to drive the BJT switch into hard saturation

$\Rightarrow I_B = \frac{5 - 0.85}{R_B} \approx \frac{0.8A}{10}$

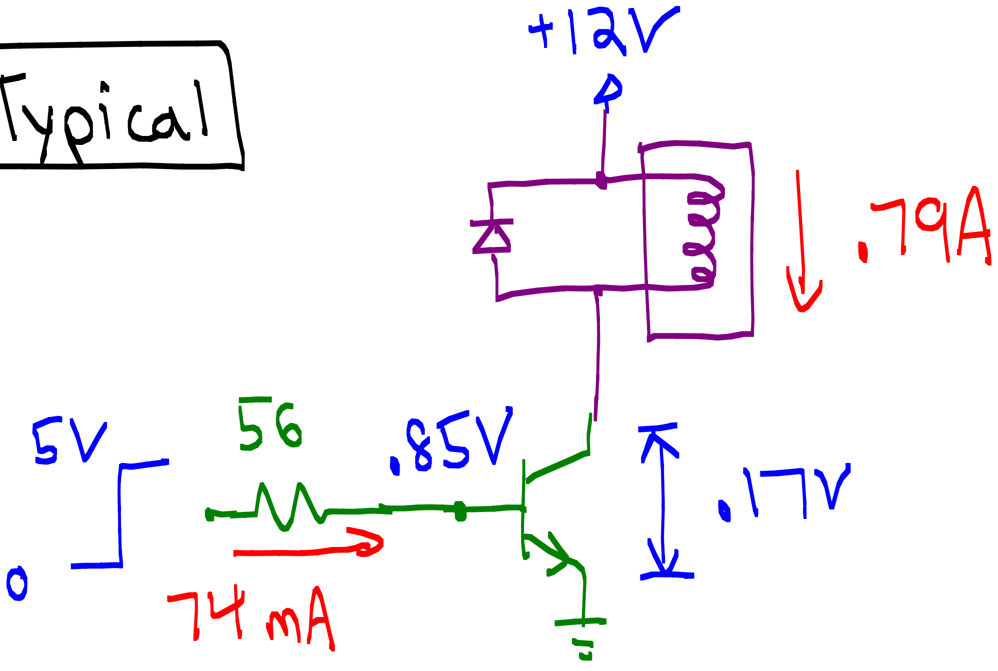
$\Rightarrow R_B \approx 51.9\ \Omega$

$\boxed{\text{Choose } R_B = 56\ \Omega}$

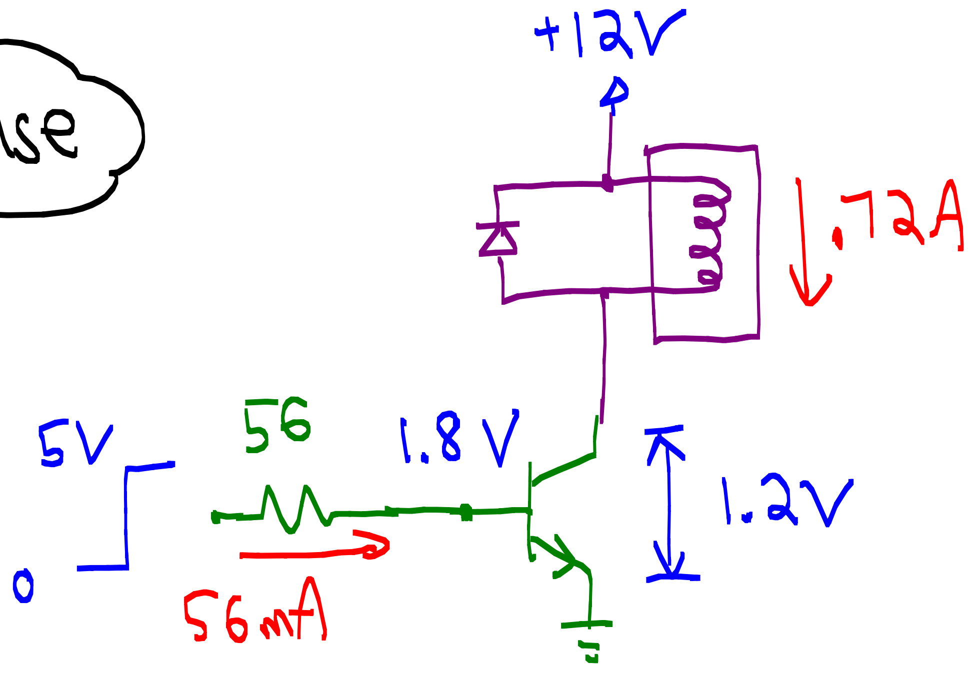
The $I_B \sim \frac{1}{10} I_c$ criterion is pretty flexible (e.g. 62 Ω is fine)

- The degree of transistor saturation depends on transistor condition!

Typical



Worst Case



$I_c = \frac{12-.17}{15\Omega} = .79A$

$I_B = \frac{5-.85}{56\Omega} = .074A$

$\Rightarrow \frac{I_c}{I_B} = 10.7$

For single BJT

$\frac{I_c}{I_B}$ between 10 to 20 is fine!

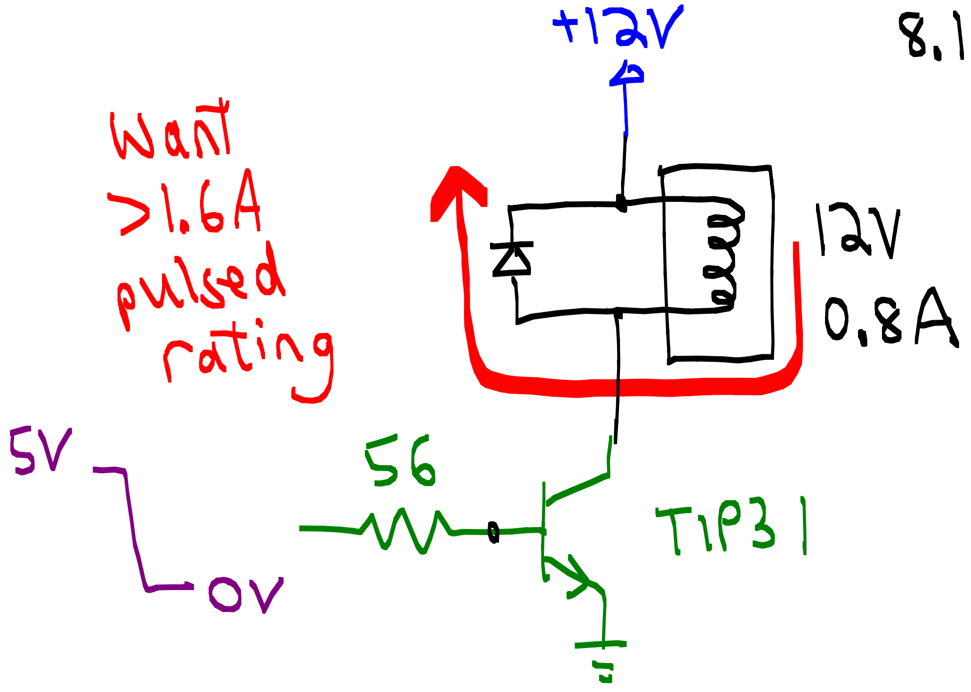
$I_c = \frac{12-1.2}{15\Omega} = .72A$

$I_B = \frac{5-1.8}{56\Omega} = .057A$ ← Smaller I_B!

$\Rightarrow \frac{I_c}{I_B} = 12.6$

- what about the flyback diode?

→ Must be able to withstand the load current (0.8A) for ~1ms



Want >1.6A pulsed rating

NOTE: The diode current is a short pulse (not continuous).

→ Choose a diode with large enough (> 2x) current rating

	1N4148	1N4002
① "Repetitive Reverse voltage breakdown" V_{RRM}	✓ 75V	100V ✓
② "Non-repetitive peak forward surge current" I_{FSM}	✗ 1A (1 s) ✓ 2A (1μs)	30A (8.3 ms) ✓

very short ↗

Safer choice!