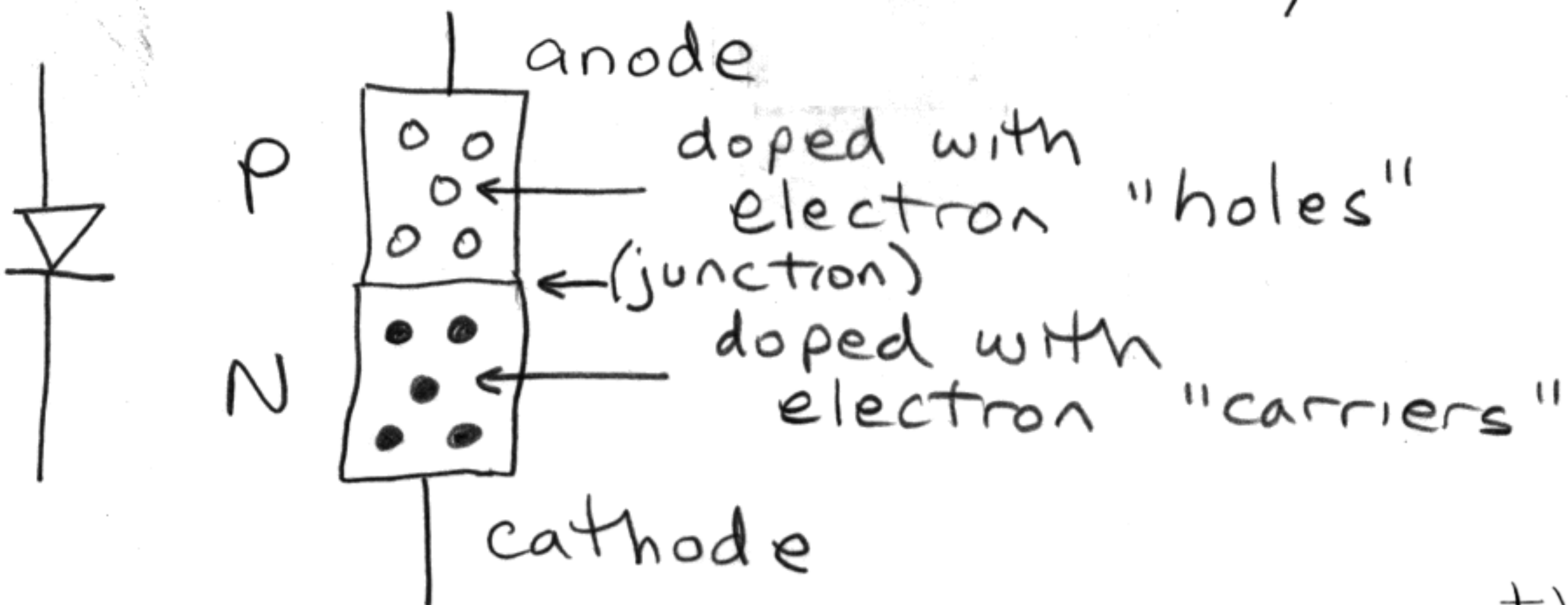
Non-Linear Circuits

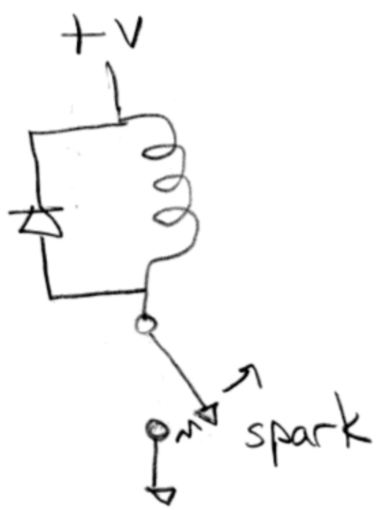
- We have been talking about linear circuits
  - DC represented by Linear equations
  - AC represented by Linear *differential* equations

- Now we introduce non-linear circuits
  - Mathematical representation more complex
  - We describe their behavior in other ways
  - Simplifying assumptions actually make it easier sometimes than linear circuits
  - New capabilities can include *gain* (amplification)

Diode

Solid state diodes have two types of material: P = positive, N = negative





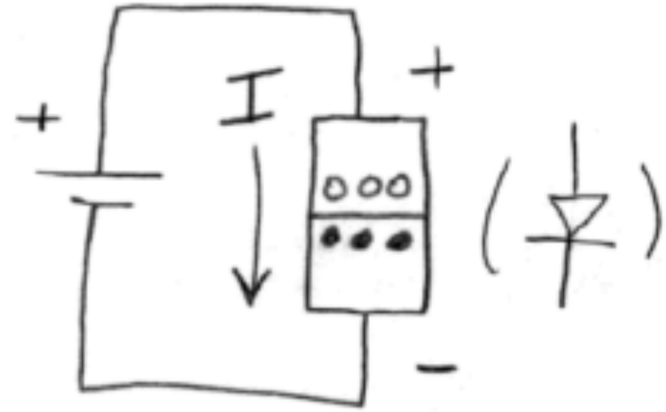
we've seen the diode once already, shorting out the surge in a coil.

Little piece of the period Table

	hole (missing electron)	semiconductor (covalent)	carrier (extra electron)	
	5 B	6 C	7 N	
	13 Al	14 Si	15 P	← most commercial solid-state devices
	31 Ga	32 Ge	33 As	← some more exotic devices
Valance group	3	4	5	

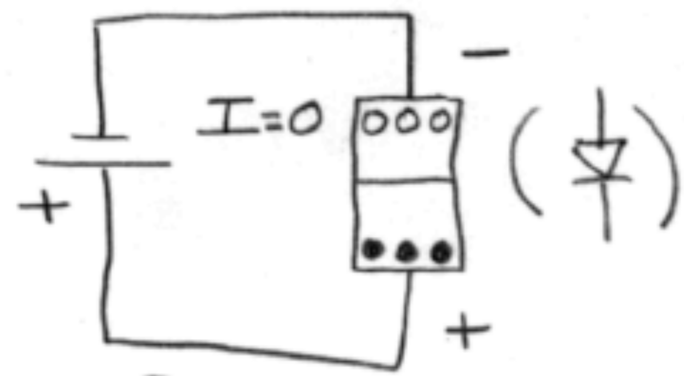
Diode acts as a one-way valve

when "forward baised" holes touch carriers at the junction and current flows.



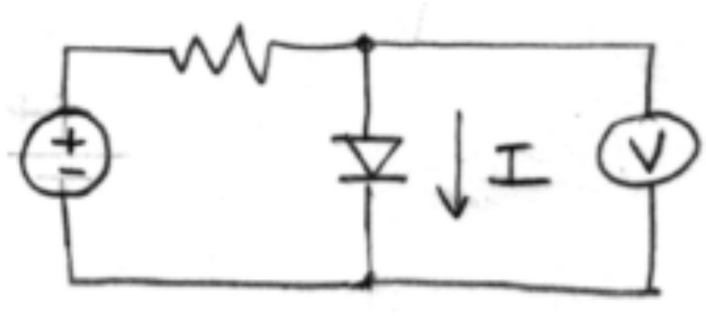
forward biased

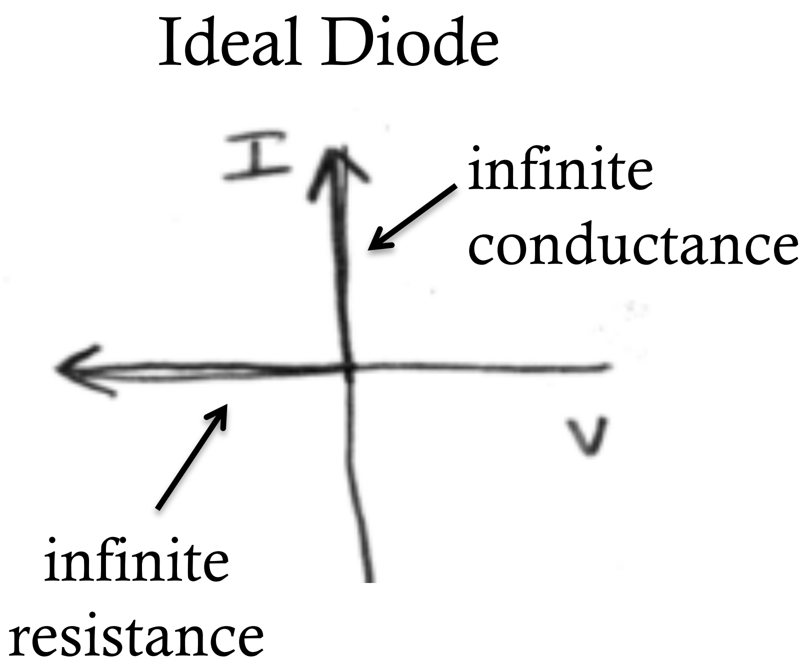
when "reverse biased" holes do not touch carriers and current does not flow.

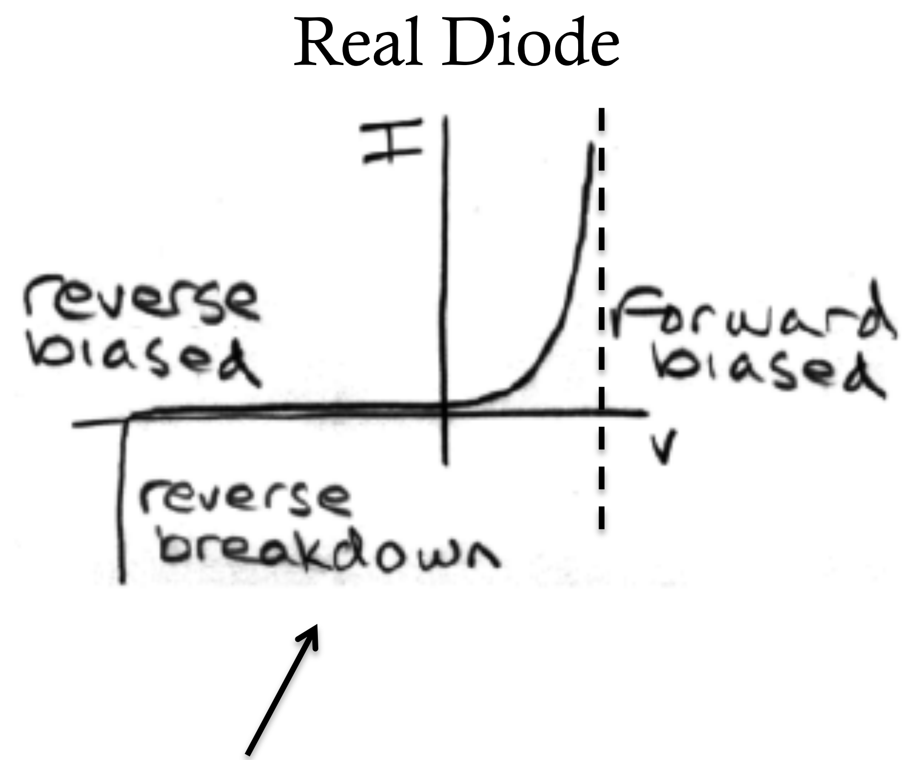


reverse biased

Graphical Representation on *V-I* Plane

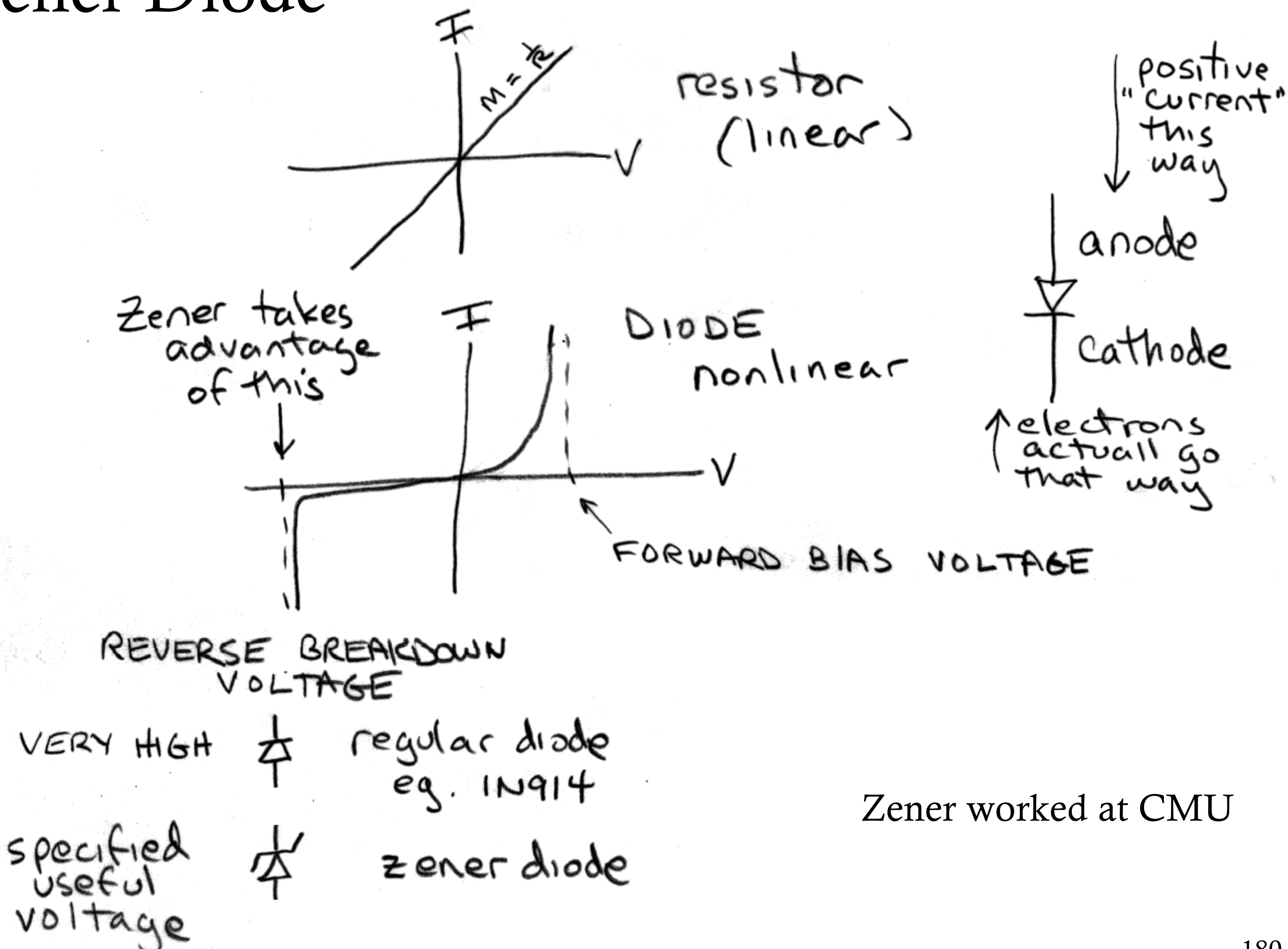






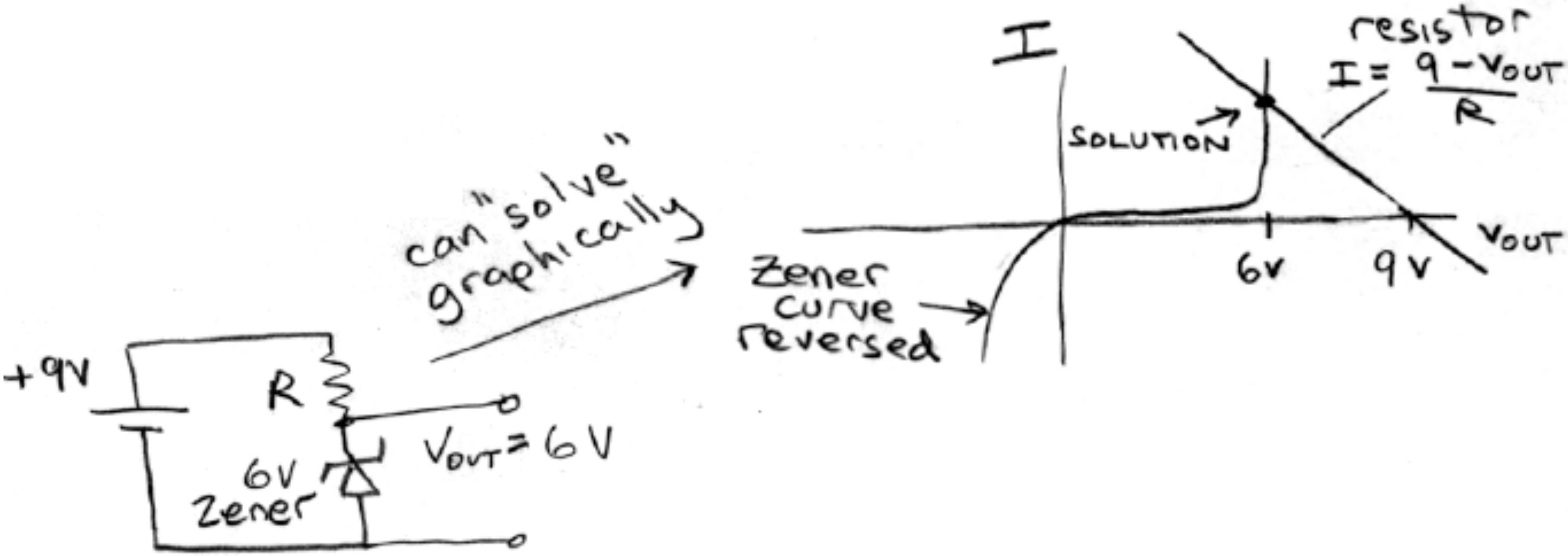
- Forward biased current is exponentially related to voltage, asymptotes to 0.5-0.7 V for silicon, ~0.2V for germanium.
- Reverse biased current is zero until “reverse breakdown” voltage.

Zener Diode



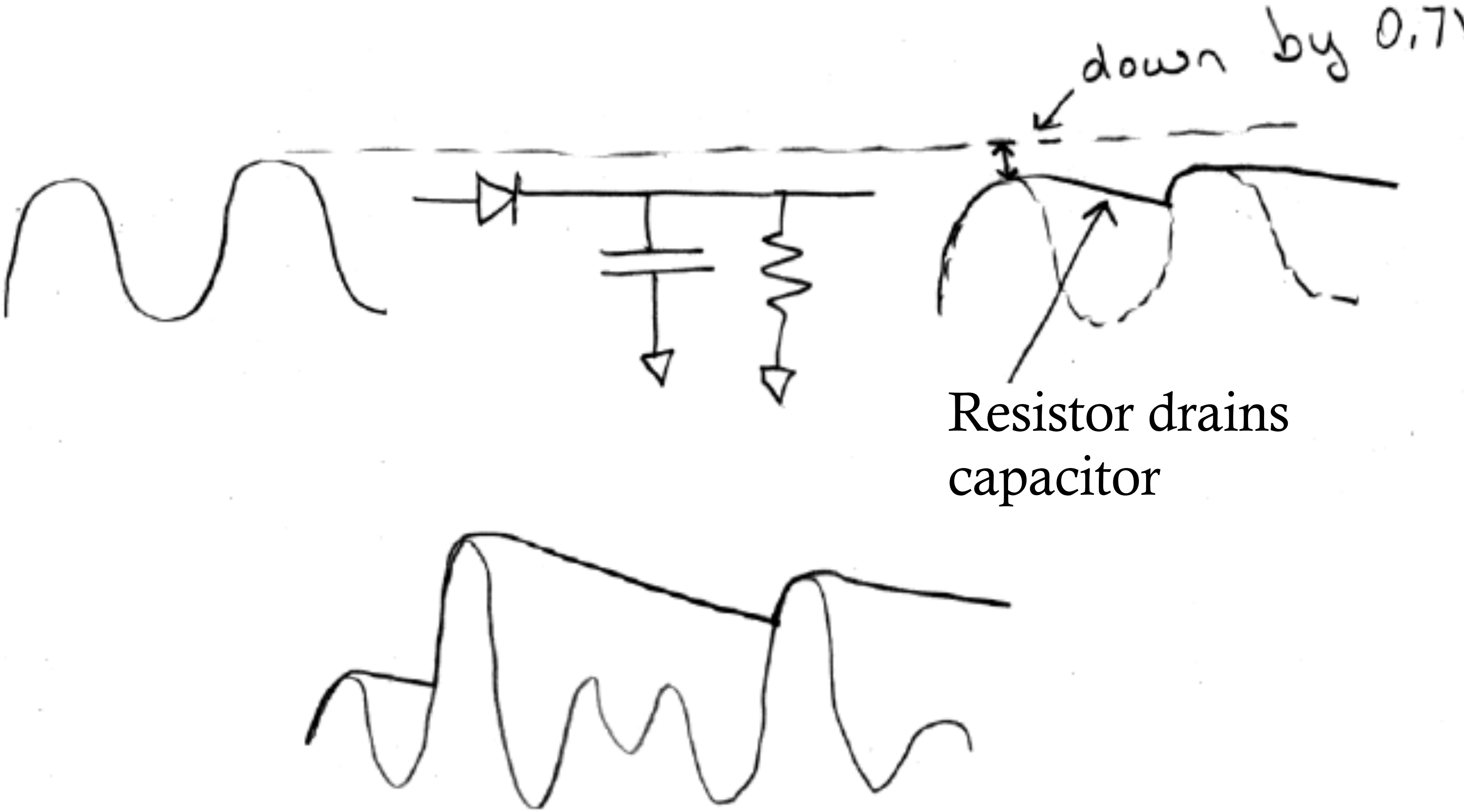
Zener worked at CMU

Can solve circuits graphically on *V-I* graph



- Zener points *into* the current and is purposefully *biased* in the reverse breakdown region.
- Like pressure regulator on a SCUBA tank.

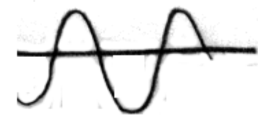
Diode as *Peak Detector*

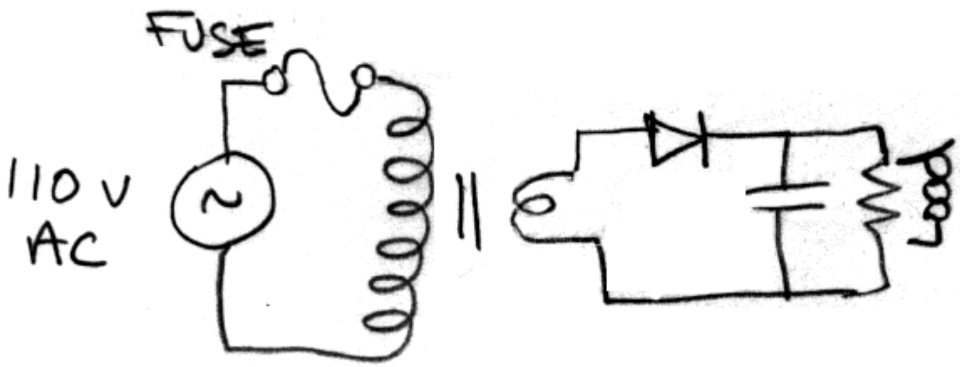


- Keeps a running maximum (down by diode drop)
- Resistor “resets” peak detector with time constant RC
  - Otherwise it gives highest voltage since beginning of time

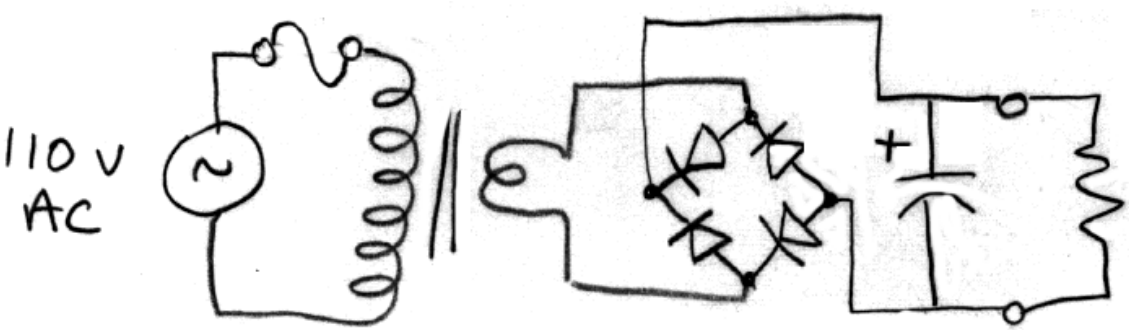
Rectification

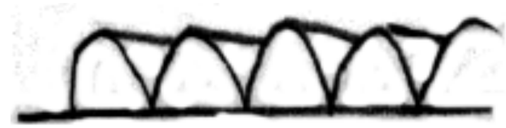
- Turns AC into DC
- Half-Wave Rectification



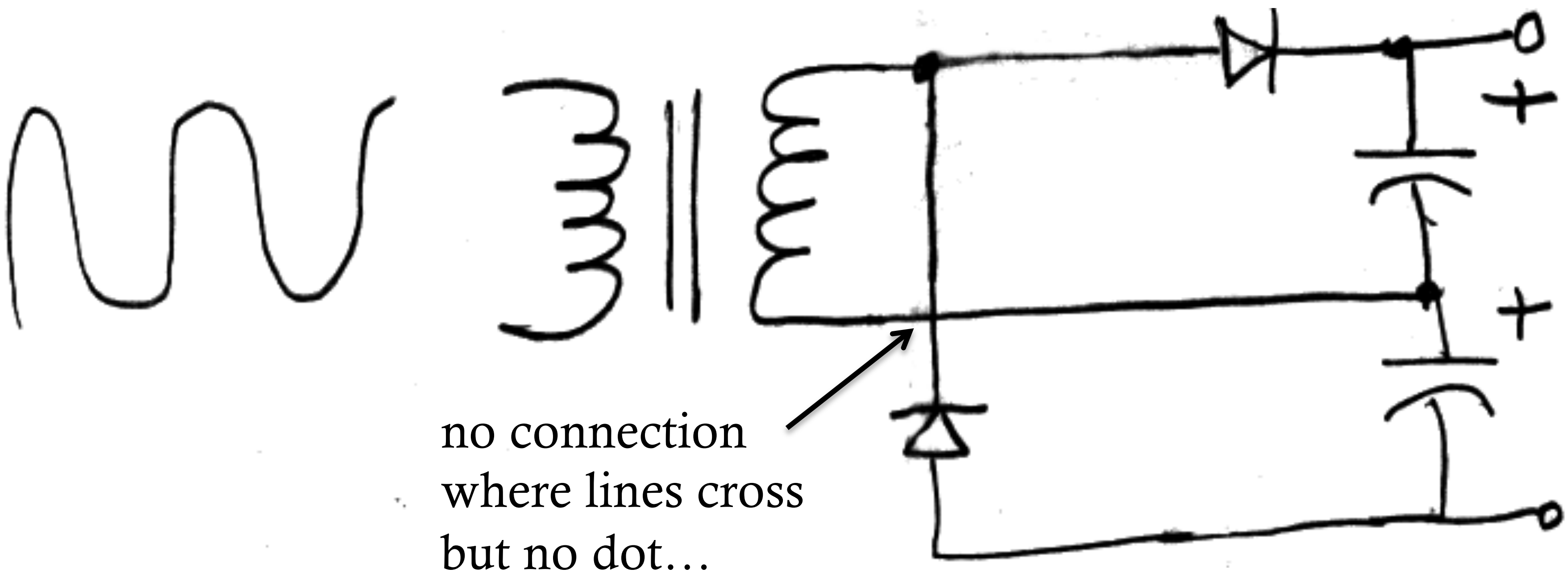


- Full-Wave Rectification

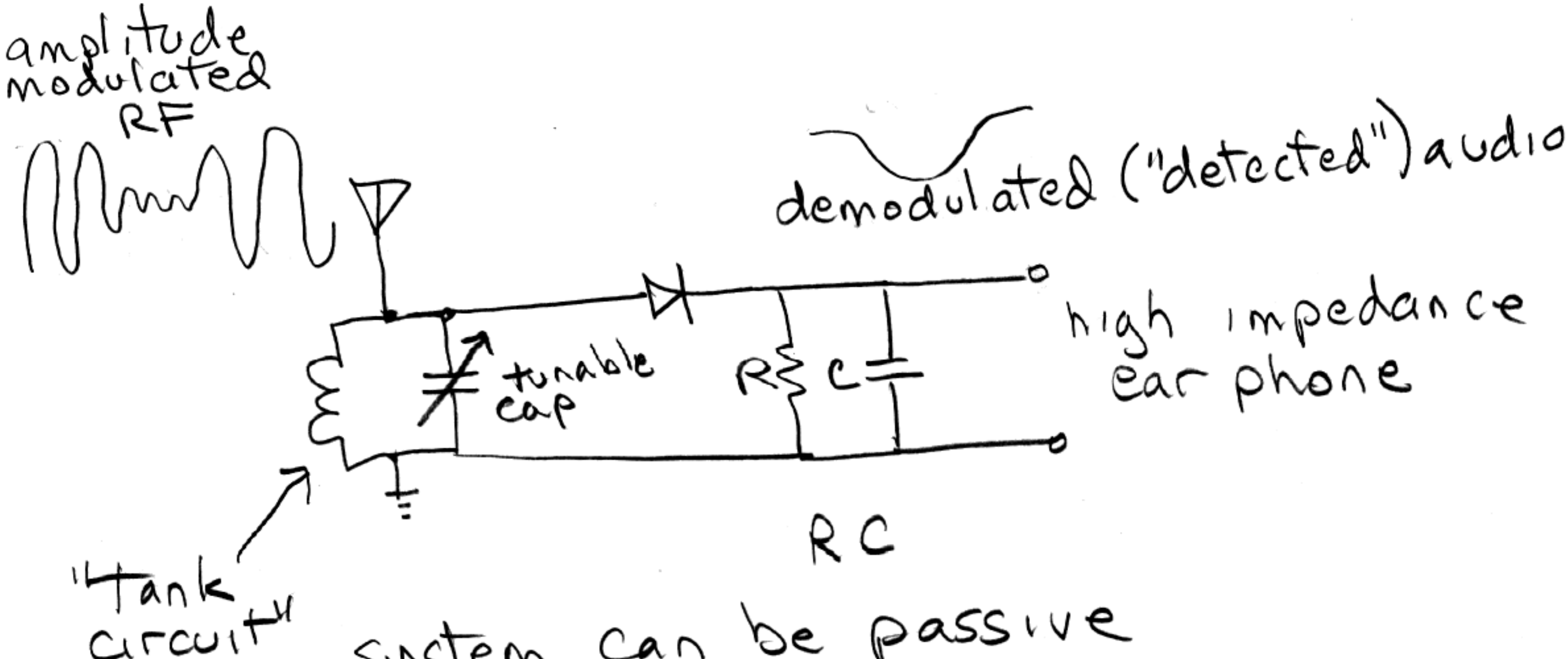




Voltage Doubler



Amplitude Modulation (AM) radio receiver



Z=∞ at resonant freq.

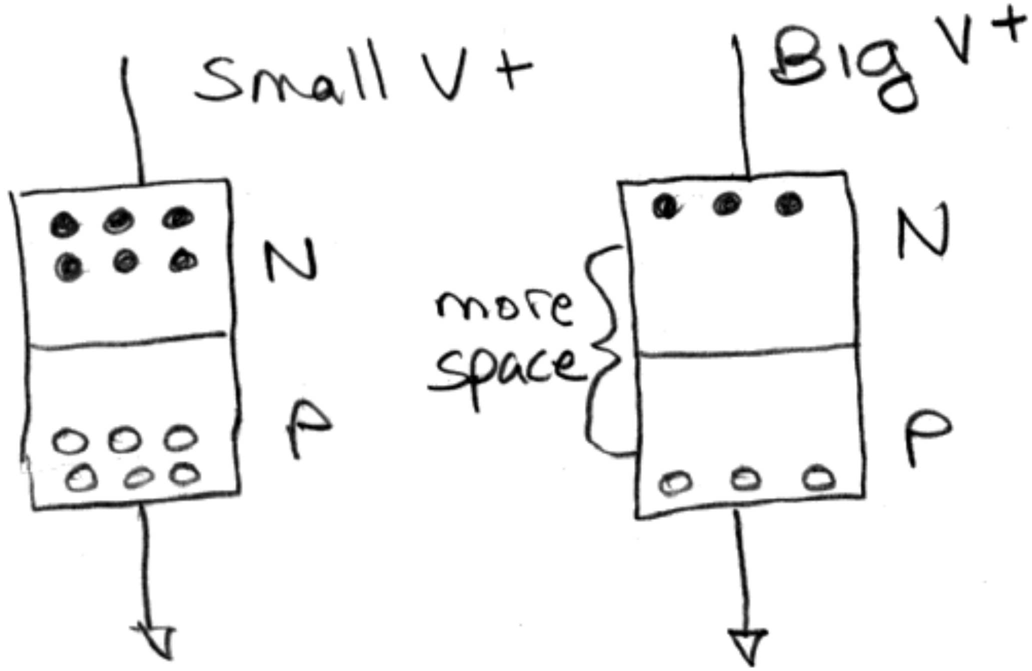
system can be passive (no battery)

some people's dental cavities pick up radio stations

Invented by Reginald Fessenden, Chair EE U. Pitt.

Varactor (variable capacitor diode)

C increases with V+

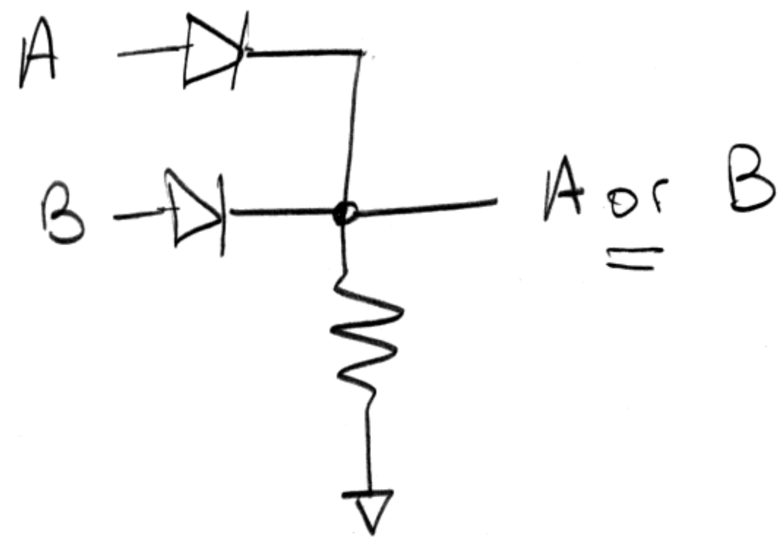


used to modulate RF (radio freq.) oscillators

Logic with Diodes

Logic is non-linear
"Boolean"

A	B	A or B
0	0	0
0	1	1
1	0	1
1	1	1



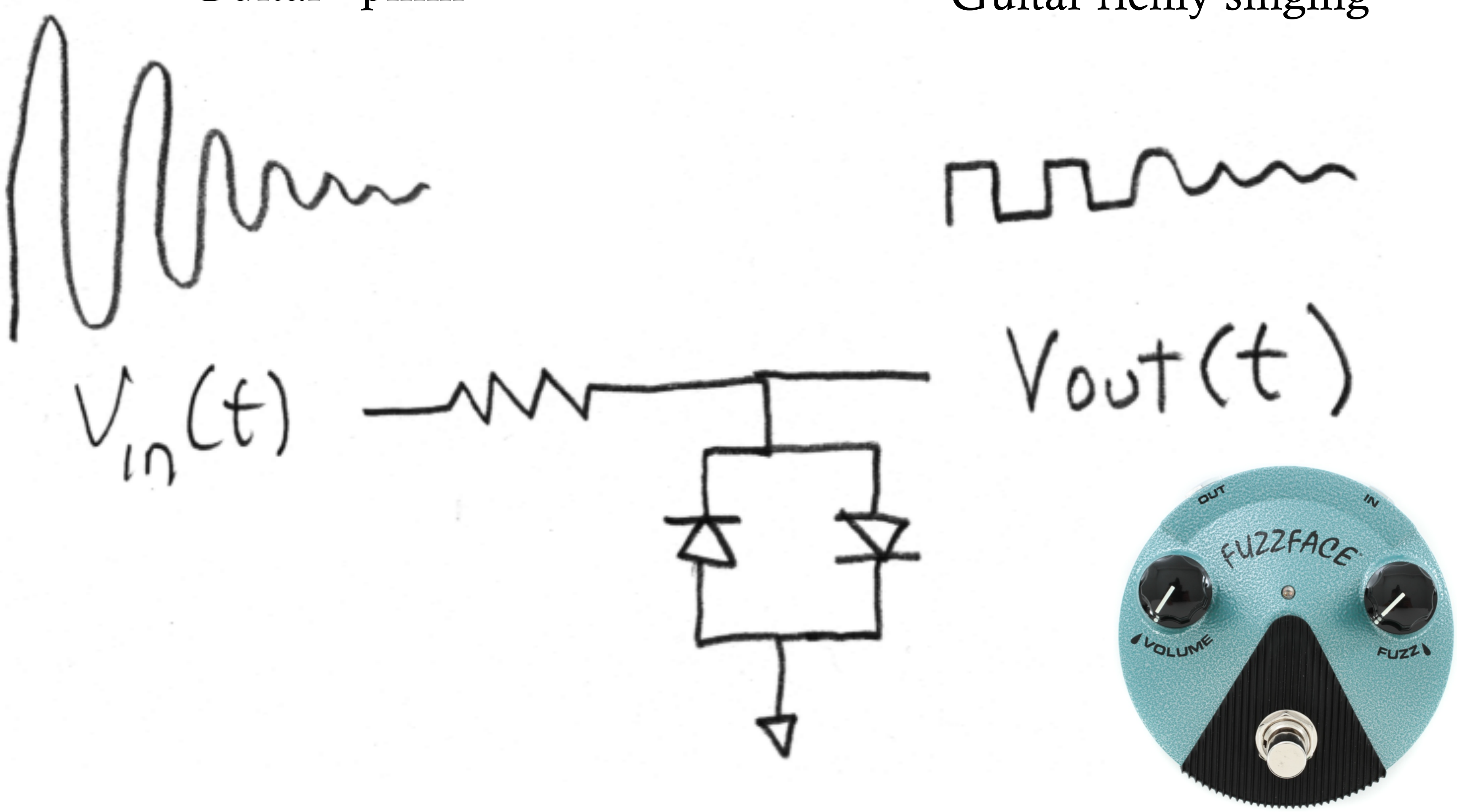
1 means 5V

0 means 0V

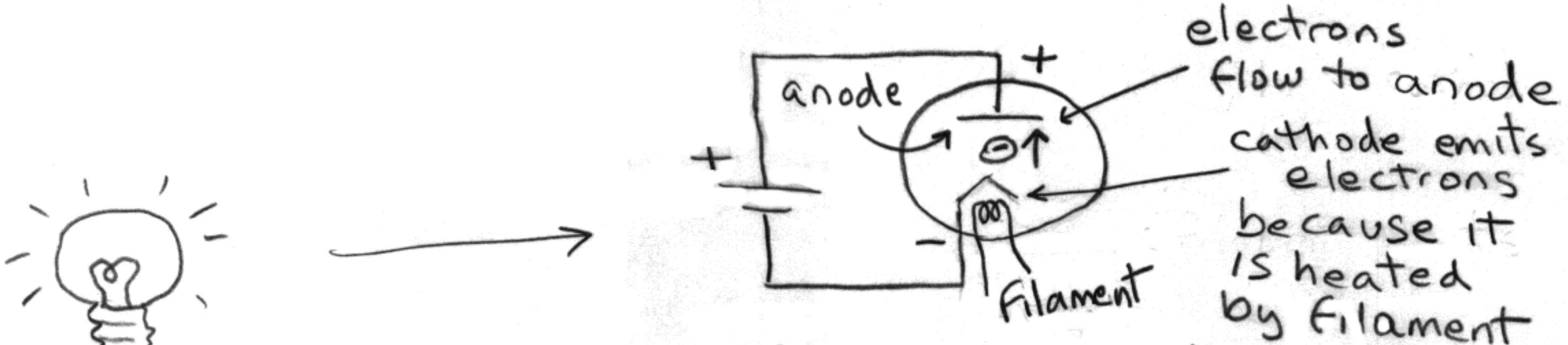
- When A is at 5V its diode is forward biased.
- If B is then at 0V, its diode is reverse biased, preventing it from bringing the output down.
- The inputs change each other's effect on the output, superposition does not apply, so the system is non-linear.

“Fuzz Box” guitar effect

- Non-linear system, clips voltage to diode forward voltage.
- Produces distortion / sustain



Before solid state there were vacuum tube diodes.

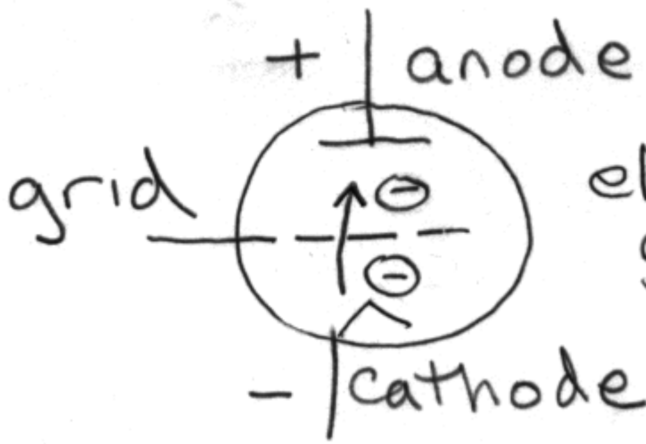


vacuum tube diode

Edison's light bulb
led to the first diode vacuum tube,
current running only from
cathode to anode

Triodes - Amplification

The addition of a "grid" allowed control of the flow of electrons from cathode to anode.

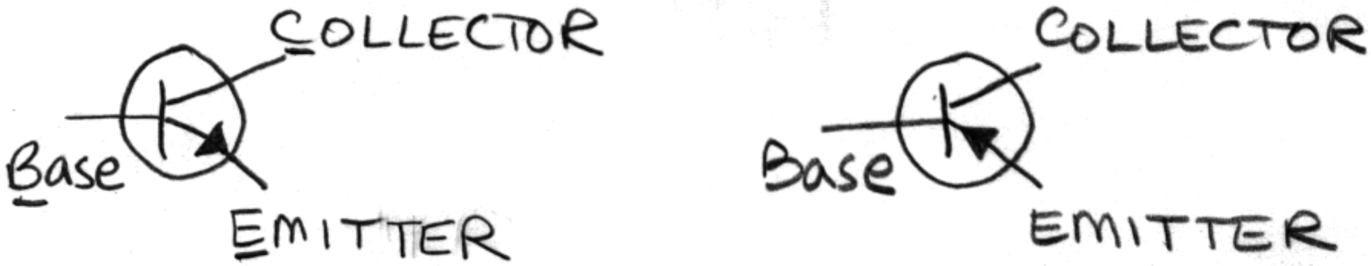


electrons flow through grid (or not) depending on grid voltage

Introduced in 1920's. British called them "valves".

Transistor add a third layer, equivalent to the grid in the vacuum tube, called the "base"

Two kind, NPN and PNP

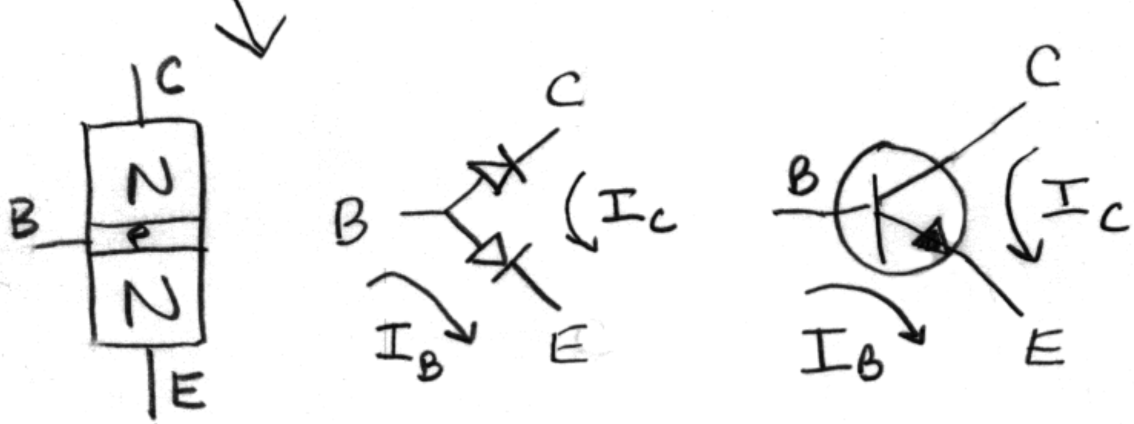


NPN PNP

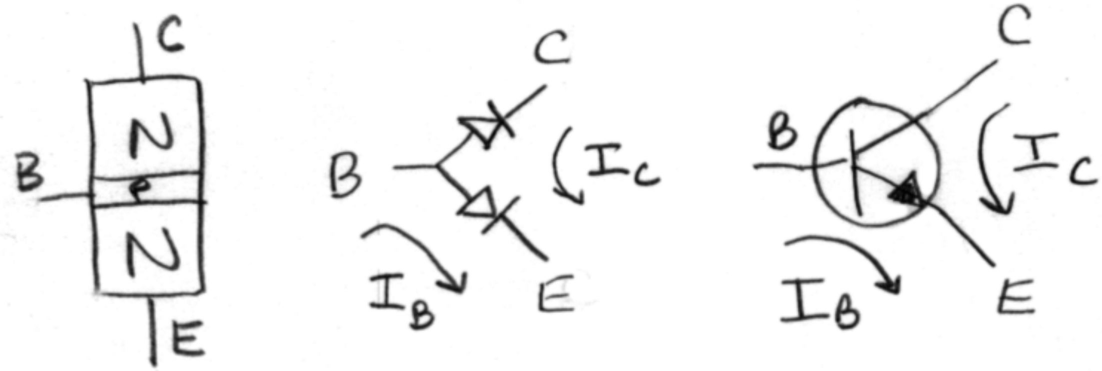
WE WILL USE ONLY NPN

2N3904

TOP VIEW



These are *Bipolar* Transistors (vs. *Field Effect* Transistors, which we'll see later).



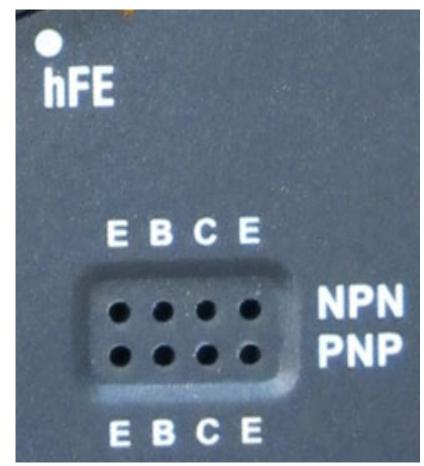
FORWARD BIASING THE "DIODE" IN THE BASE-EMITTER JUNCTION FILLS THE HOLES IN THE THIN P LAYER AND ALLOWS THE REVERSE-BIASED COLLECTOR-BASE "DIODE" TO CONDUCT

I_B = BASE CURRENT

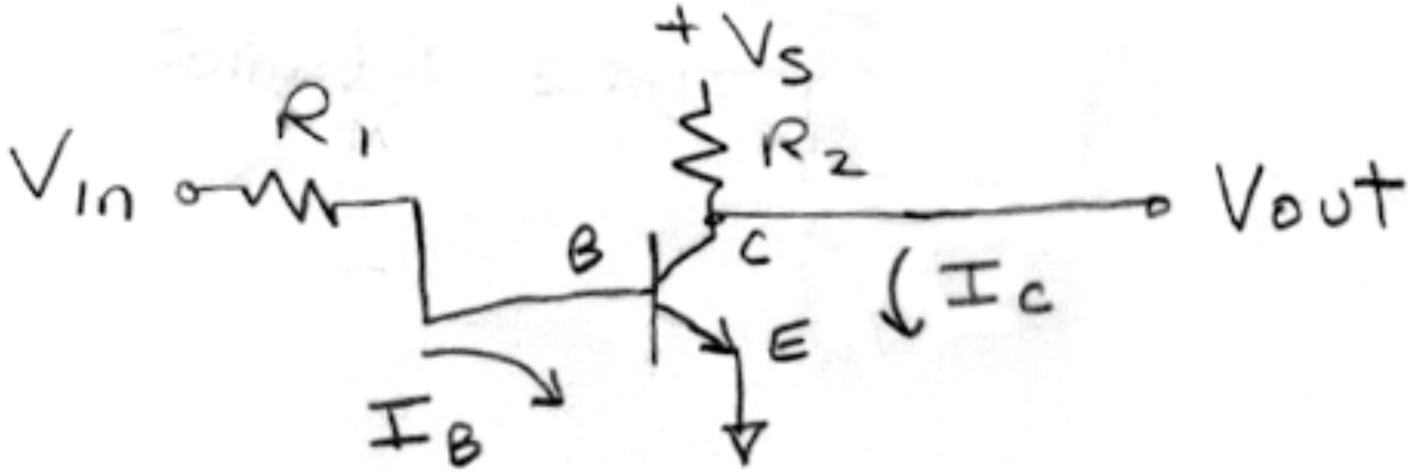
I_C = COLLECTOR CURRENT

WHEN PROPERLY BIASED

$I_C = \beta I_B$ $\quad$ β is a constant also known as h_{FE}



Transistor Circuits: *Common Emitter*

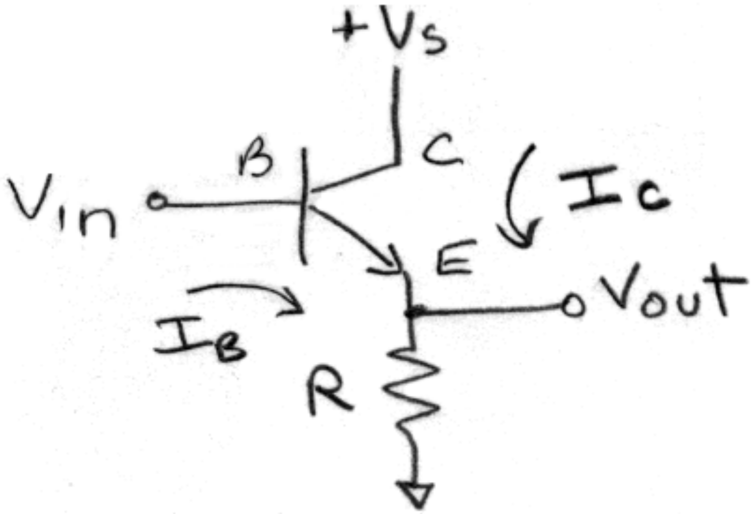


transistors often drawn without circle

Assuming 0.5 V base-emitter forward bias voltage drop

- $I_\mathrm{B} = \frac{V_\mathrm{in} - 0.5\mathrm{V}}{R_1}$
- $I_\mathrm{C} = \beta I_\mathrm{B} = \beta \frac{V_\mathrm{in} - 0.5\mathrm{V}}{R_1}$
- $V_\mathrm{out} = V_\mathrm{S} - (V_\mathrm{in} - 0.5\mathrm{V})\beta \frac{R_2}{R_1}$
- $\mathrm{Gain} = \frac{\Delta V_\mathrm{out}}{\Delta V_\mathrm{in}} = -\beta \frac{R_2}{R_1}$

Transistor Circuits: *Emitter Follower*



assume the diode drop across the B-E junction is 0.5 V

$V_{out} = V_{in} - 0.5\,V$ (with <u>current</u> <u>gain</u>)

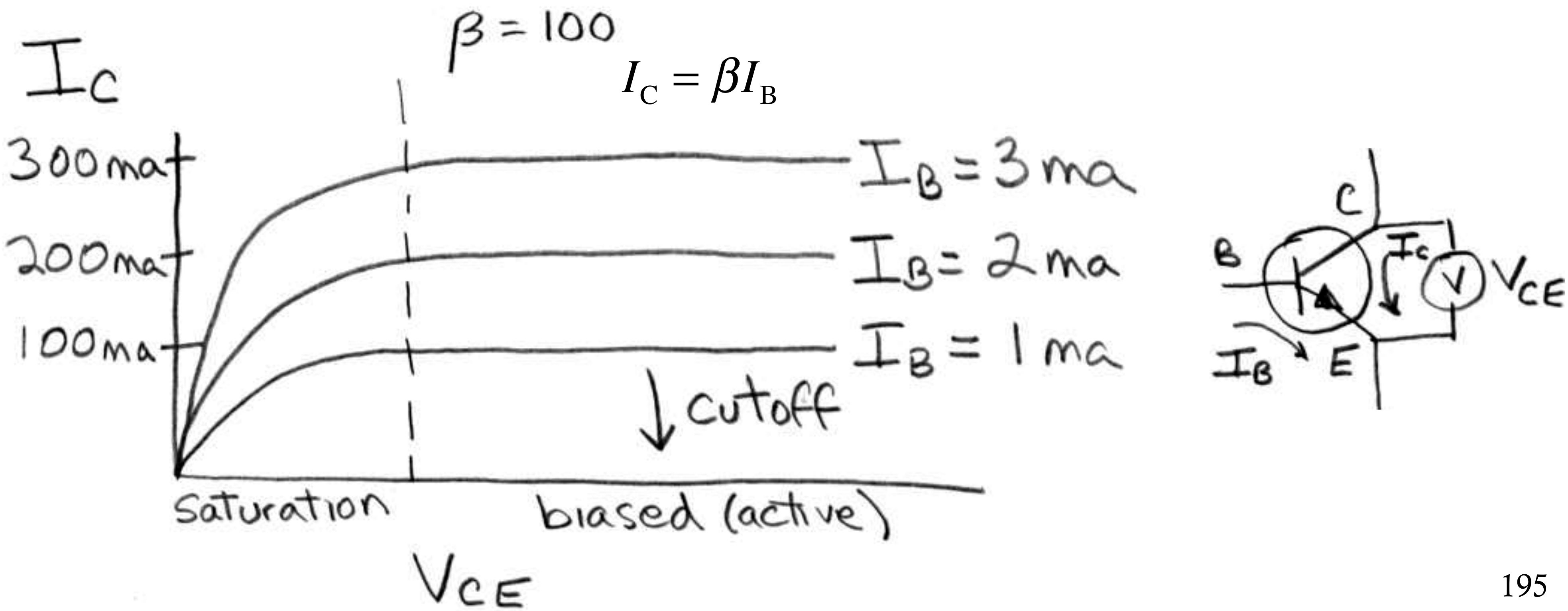
Very tight negative feedback

if V_{out} "too low" $\Longrightarrow \uparrow I_B \Rightarrow \uparrow I_c \Rightarrow \uparrow V_{out}$

if V_{out} "too high" $\Rightarrow \downarrow I_B \Rightarrow \downarrow I_c \Rightarrow \downarrow V_{out}$

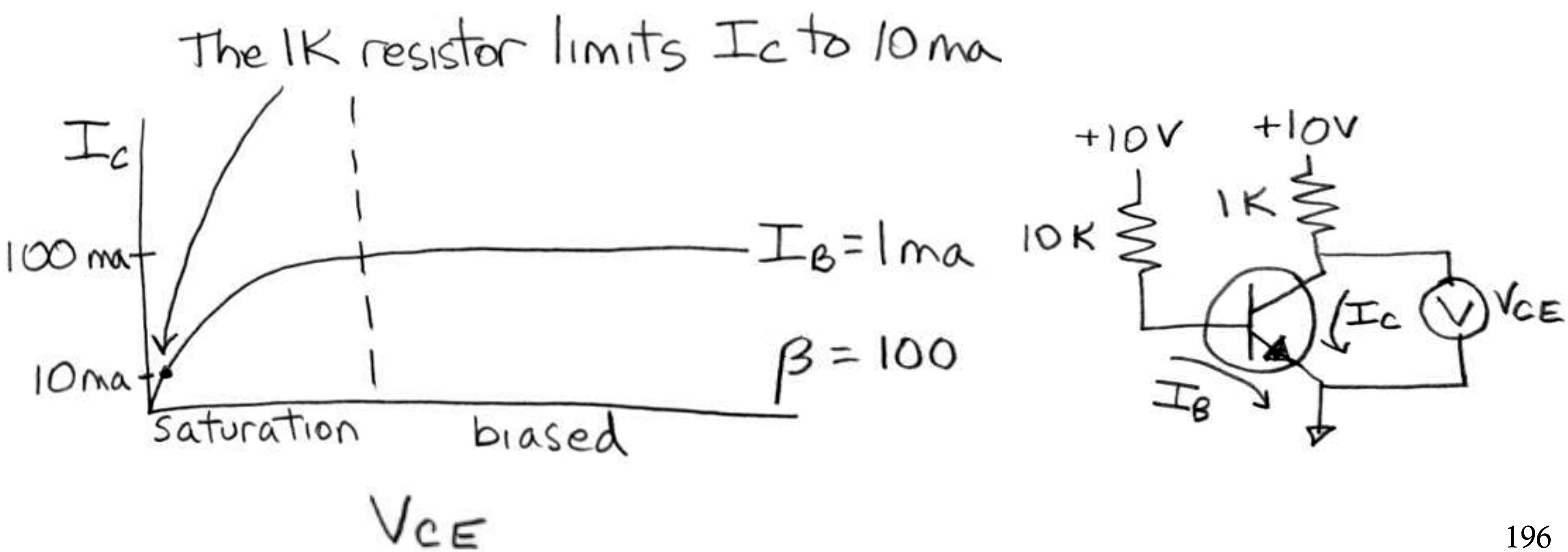
"just right" is $V_{out} = V_{in} - 0.5\,V$

- Transistors operate in 1 of 3 regions:
  - *Biased* (*active*) : $I_C = \beta I_B$ independent of V_{CE} , where β is constant for a given transistor (50<β<250 for our 2N3904).
  - *Cutoff* : transistor is effectively turned off when I_B is too small.
  - *Saturation* : transistor is "wide open" with the current limited elsewhere in the circuit.

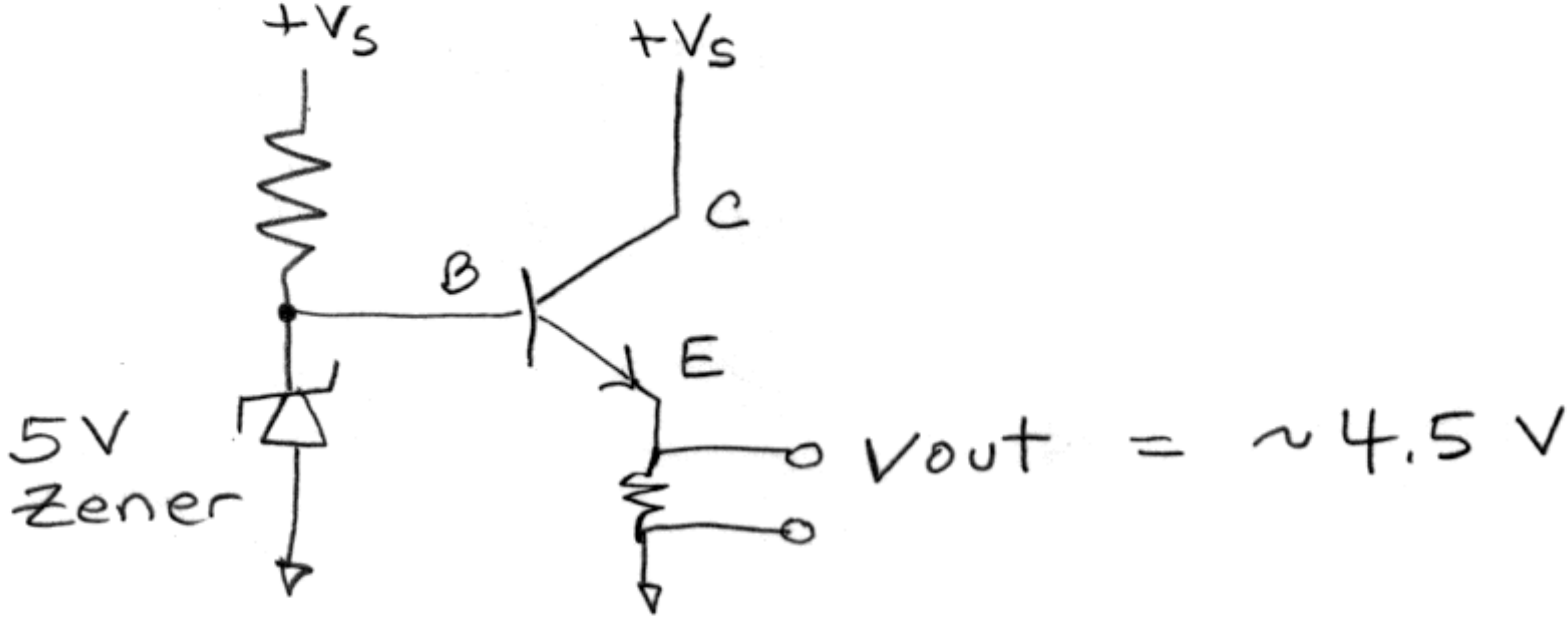


Transistor in the *saturated* region

- I_B = 1 mA so I_C should be 100 mA, making V_{CE} = –90 V!
- Transistor is not a source of energy and can't do that.
- So transistor is wide open, with current limited elsewhere.
- V_{CE} settles below the "biased" region, in effect a short circuit doing the best it can.

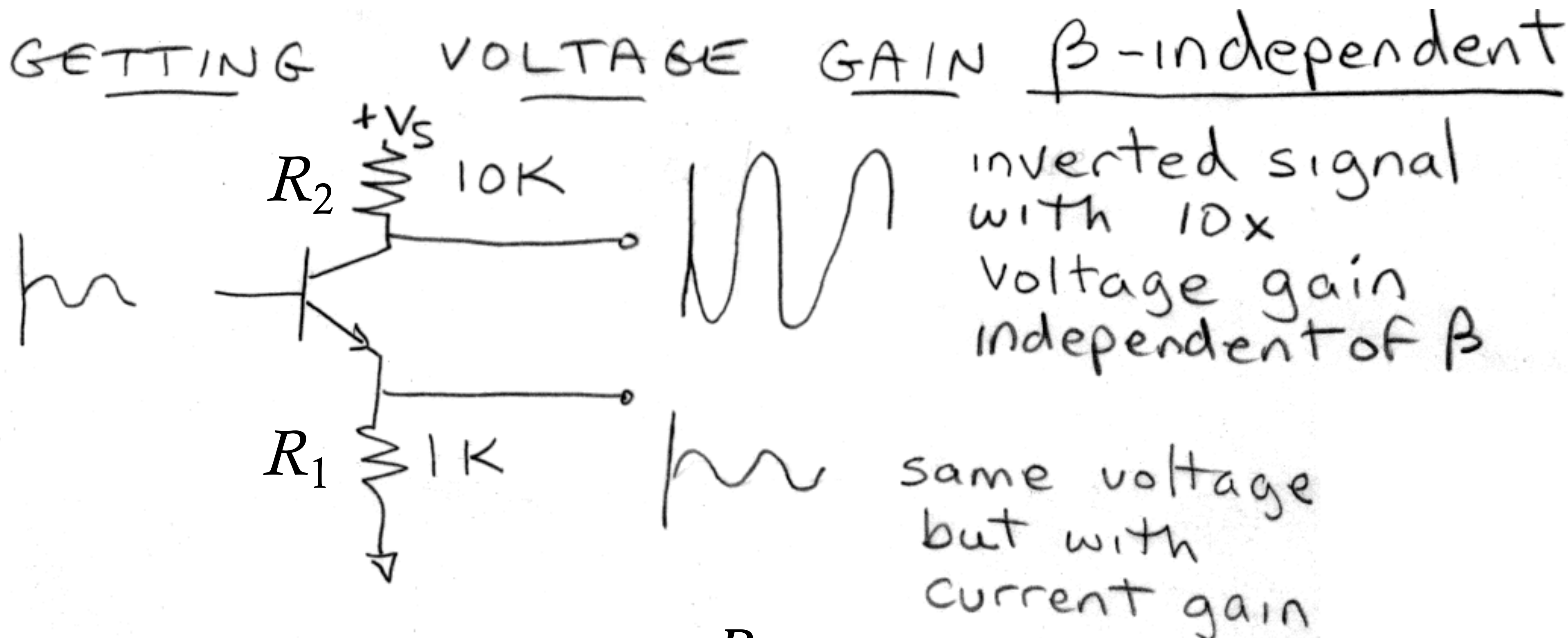


Example: Emitter Follower as “Buffered” Voltage Source



V_{out} acts more like a perfect voltage source because transistor supplies more current as needed

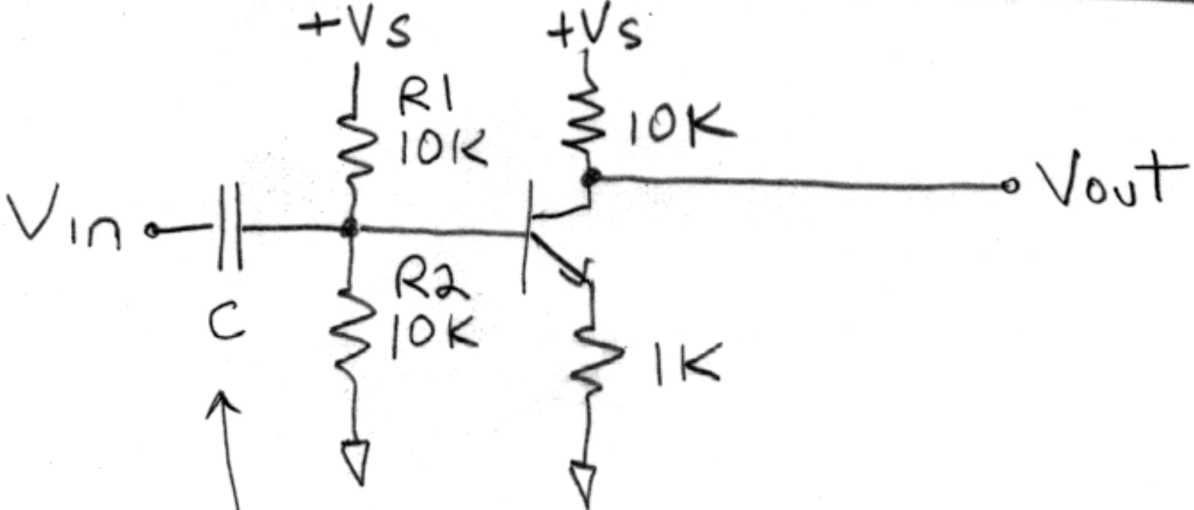
We would like to build amplifiers whose voltage gain only depends on linear components (resistors).



$$\text{Gain} = -\frac{R_2}{R_1}$$

Classic Audio Amplifier

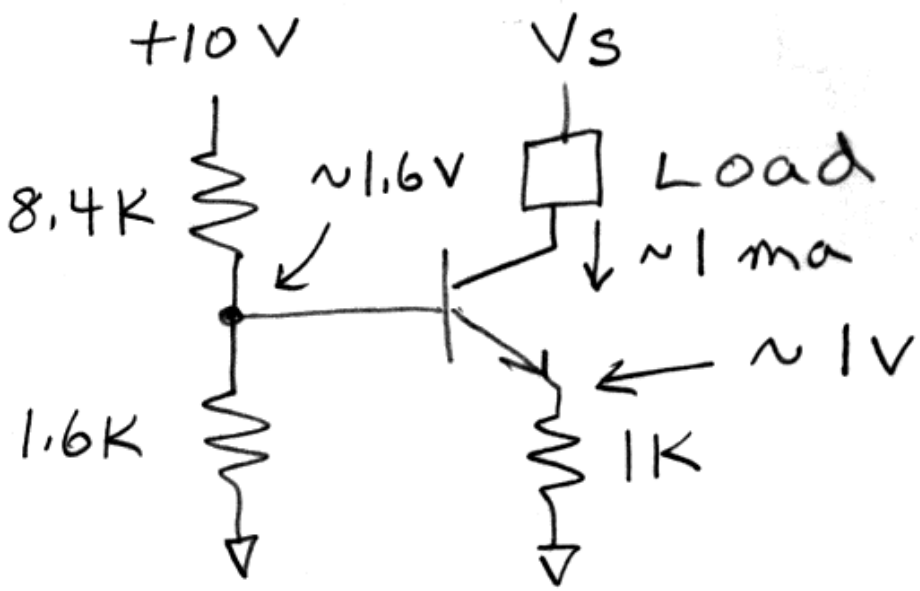
BIASING AND AC COUPLING



THE INPUT CAPACITOR REMOVES THE DC PORTION OF Vin AND ONLY PERMITS THE VARYING PORTION OF Vin TO BE AMPLIFIED (BY −10).

R1 and R2 "BIAS" THE TRANSISTOR, I.E. THEY PROVIDE THE DC CURRENT TO MAKE THE TRANSISTOR OPERATE IN ITS PROPER RANGE

1 mA Current Source



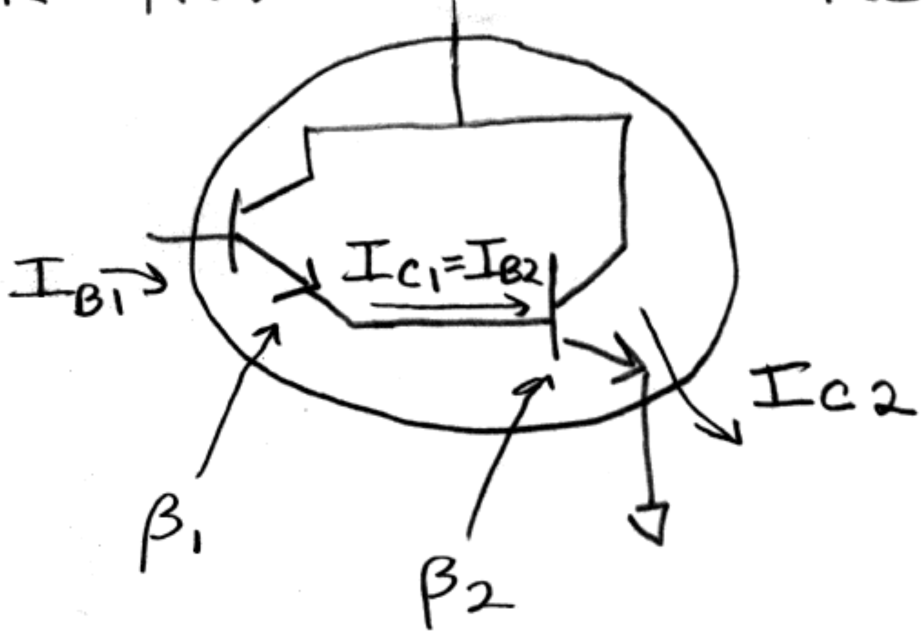
IRRESPECTIVE OF Vs AND THE LOAD RESISTANCE (WITHIN REASON) 1ma will be drawn through the load.

Assumes $V_{BE} = 0.6$ V

Darlington Transistor (two transistors in one)

THE "DARLINGTON"

OR HOW TO GET REALLY BIG β



$$I_{C1} = \beta_1 I_{B1}$$

$$I_{C2} = \beta_2 I_{B2}$$

$$I_{C2} = \beta_1 \beta_2 I_{B1}$$

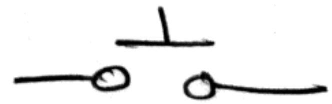
the effective β is the product of the two individual β's

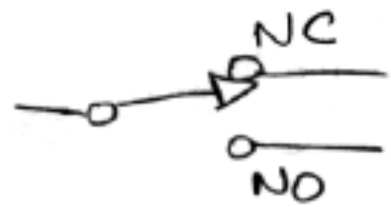
Gain

- Before transistors, our circuits (with resistors, capacitors, coils, and diodes) had just one stable equilibrium.
- Transistors add *gain*, the ability to control a large voltage or current with a smaller voltage or current.
- This leads to *bistable* and *unstable* circuits.
- We will demonstrate this next with *relays*, which are magnetically activated switches, and which therefore have gain.

Switches and Relays

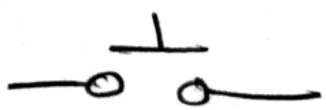
toggle vs. momentary

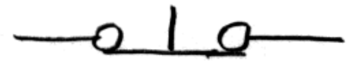




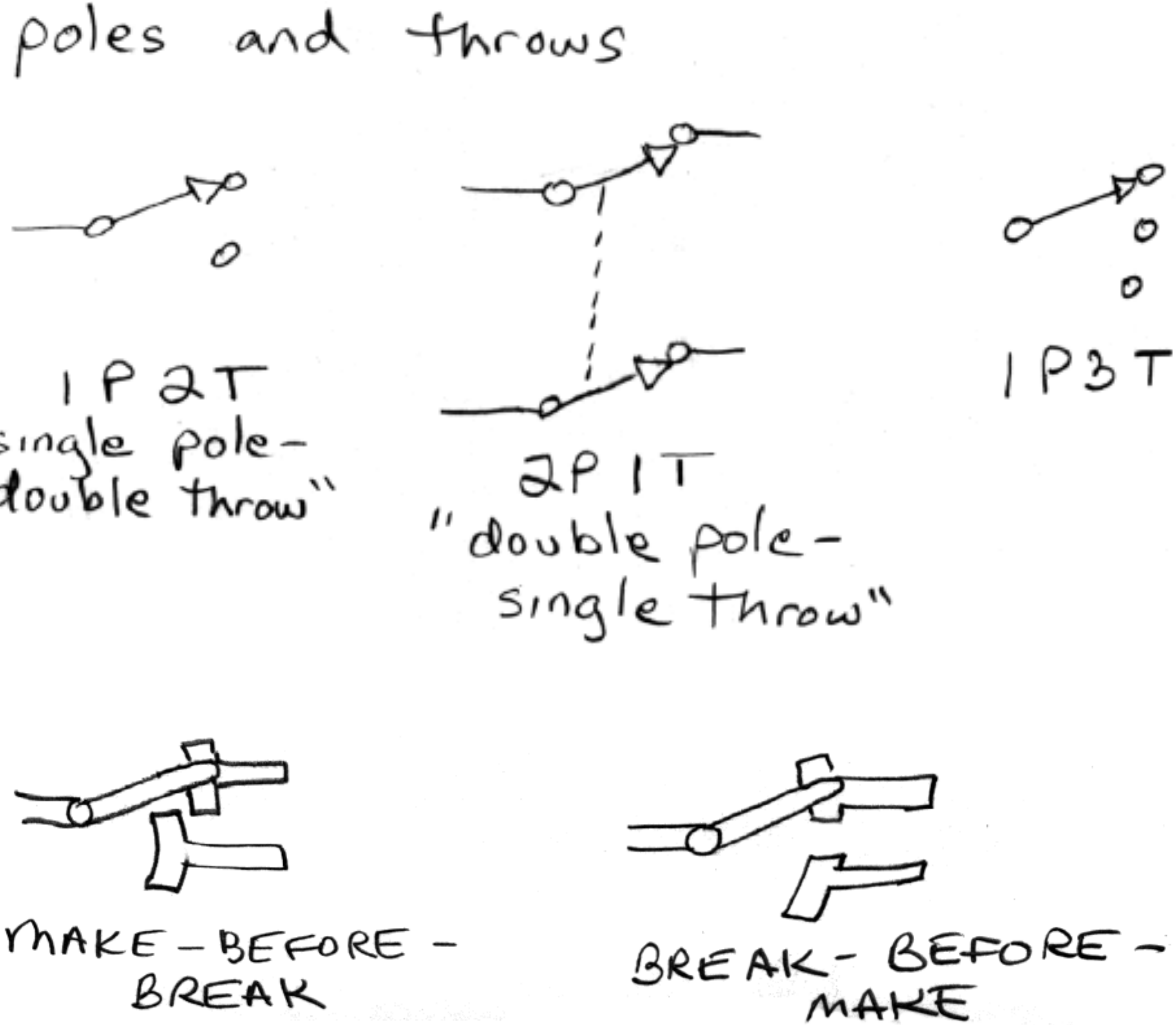
a spring is implied

Normally open (NO) vs. normally closed (NC)

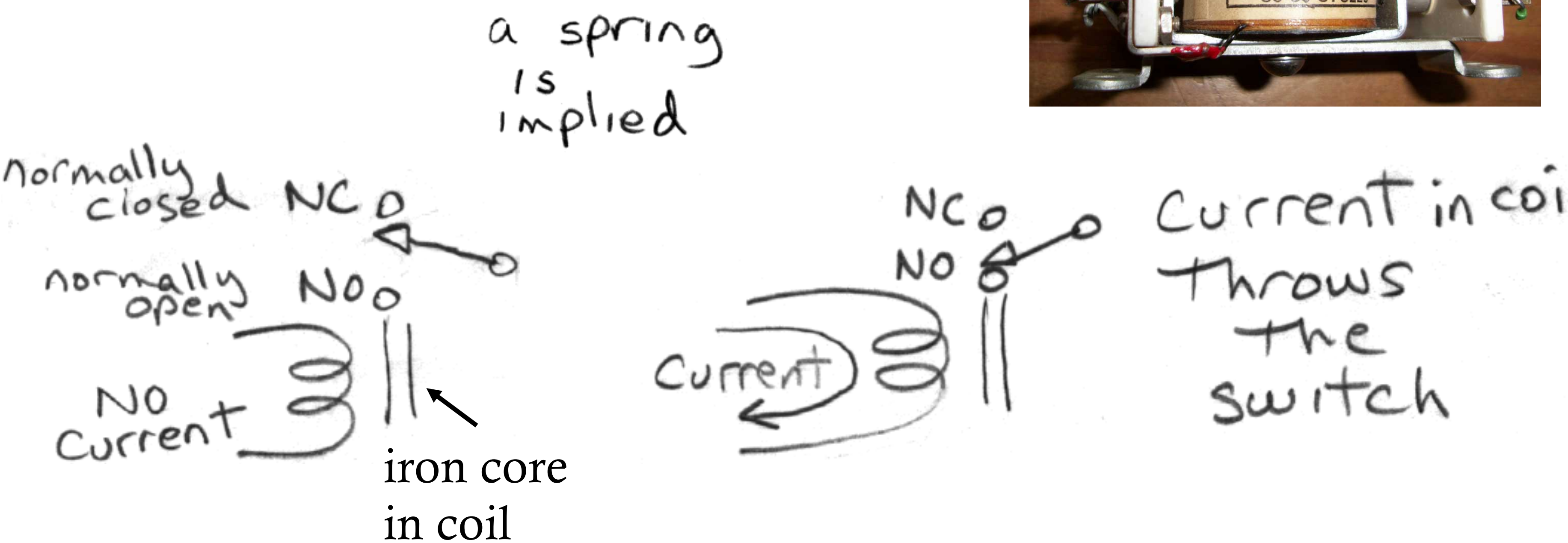




More Switches



Relays

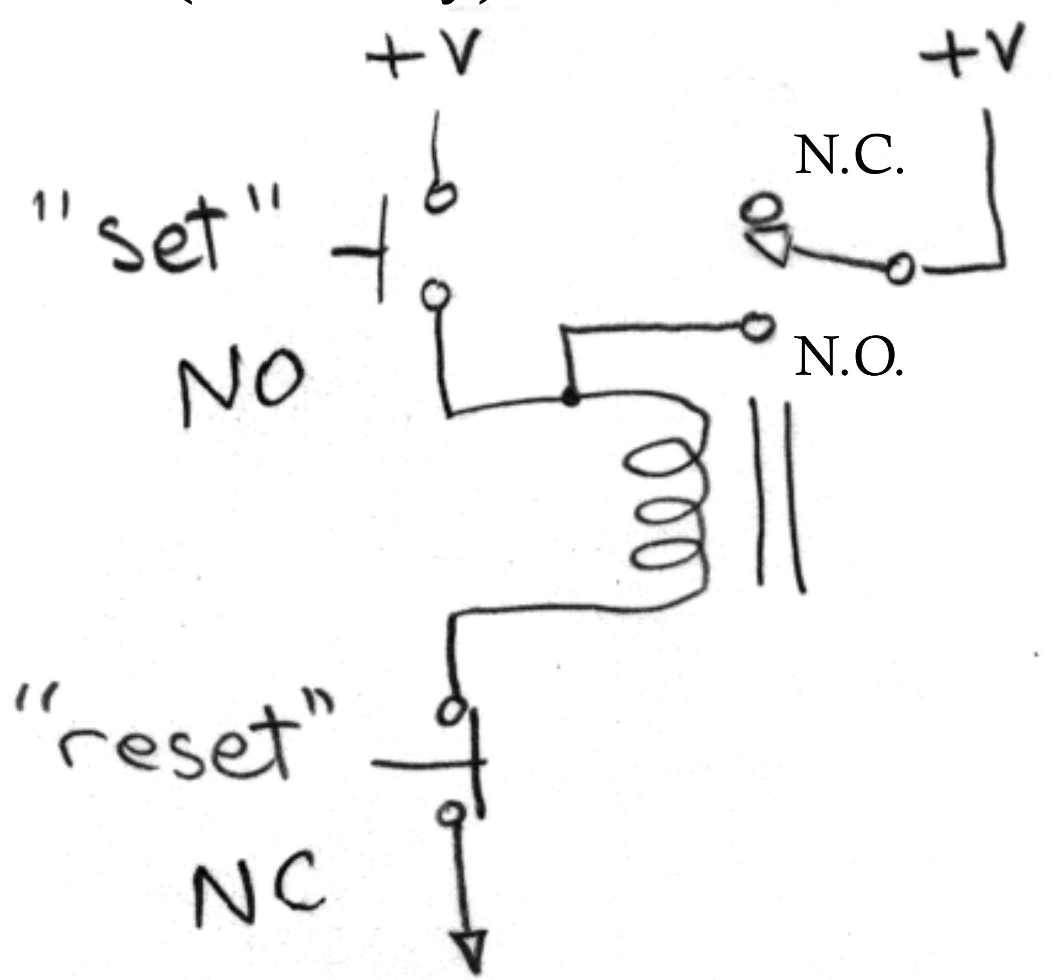


- Switch thrown by electromagnet pulling iron in the switch lever against a spring.
- Like transistors, relays introduce *gain*.
- Gain permits circuits that are either:

<u>Bistable</u> (with memory) or <u>Unstable</u> (that oscillate)

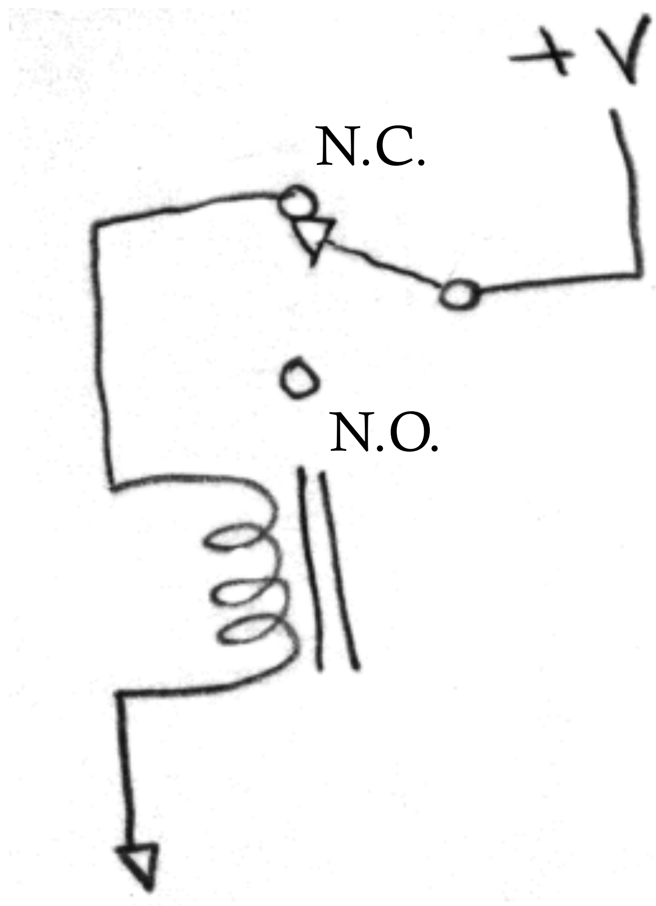
Bistable Relay Circuit

- the Latch
  - *Positive* feedback: reinforces its present state, whichever it is (memory)

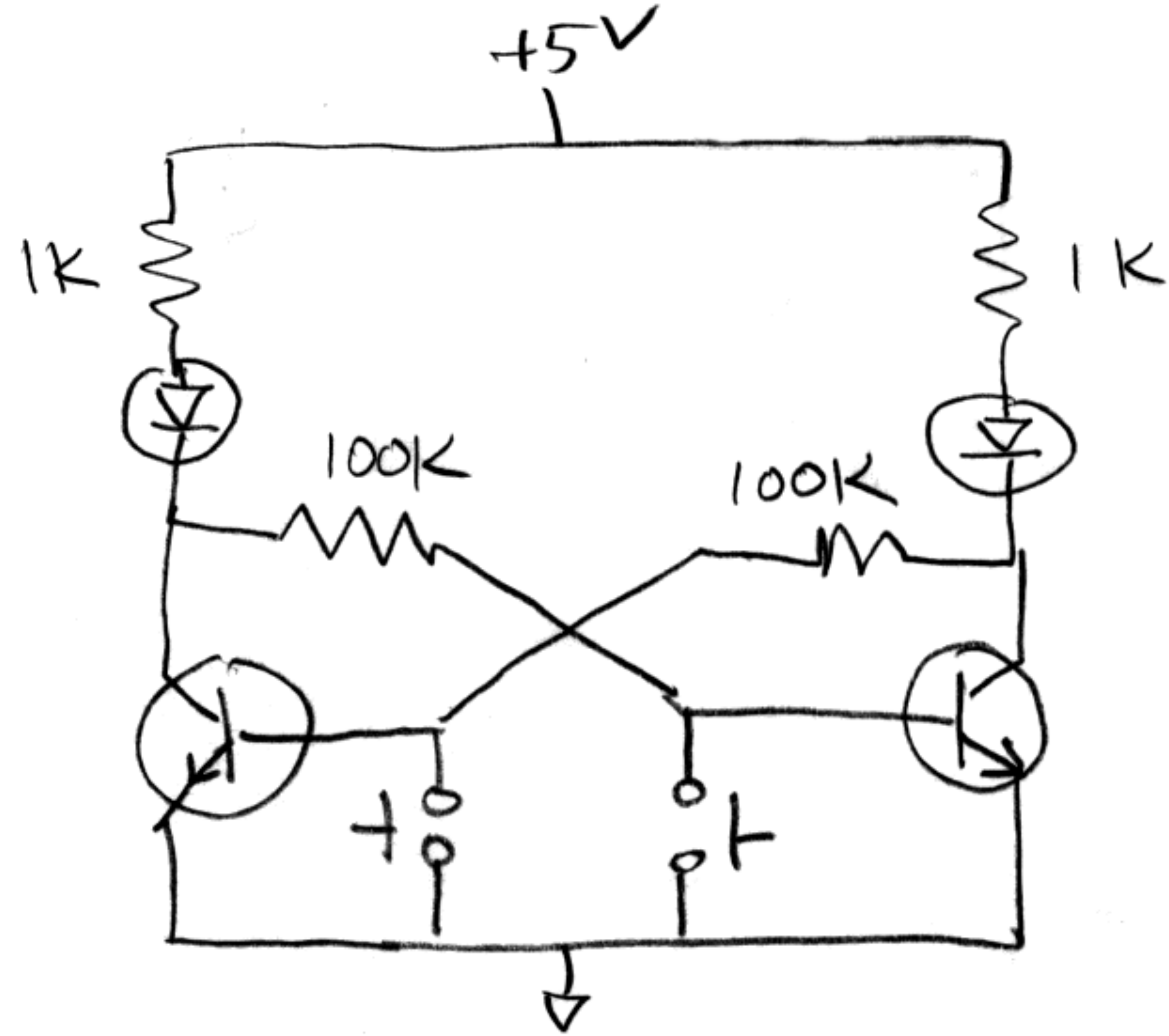


Unstable Relay Circuit

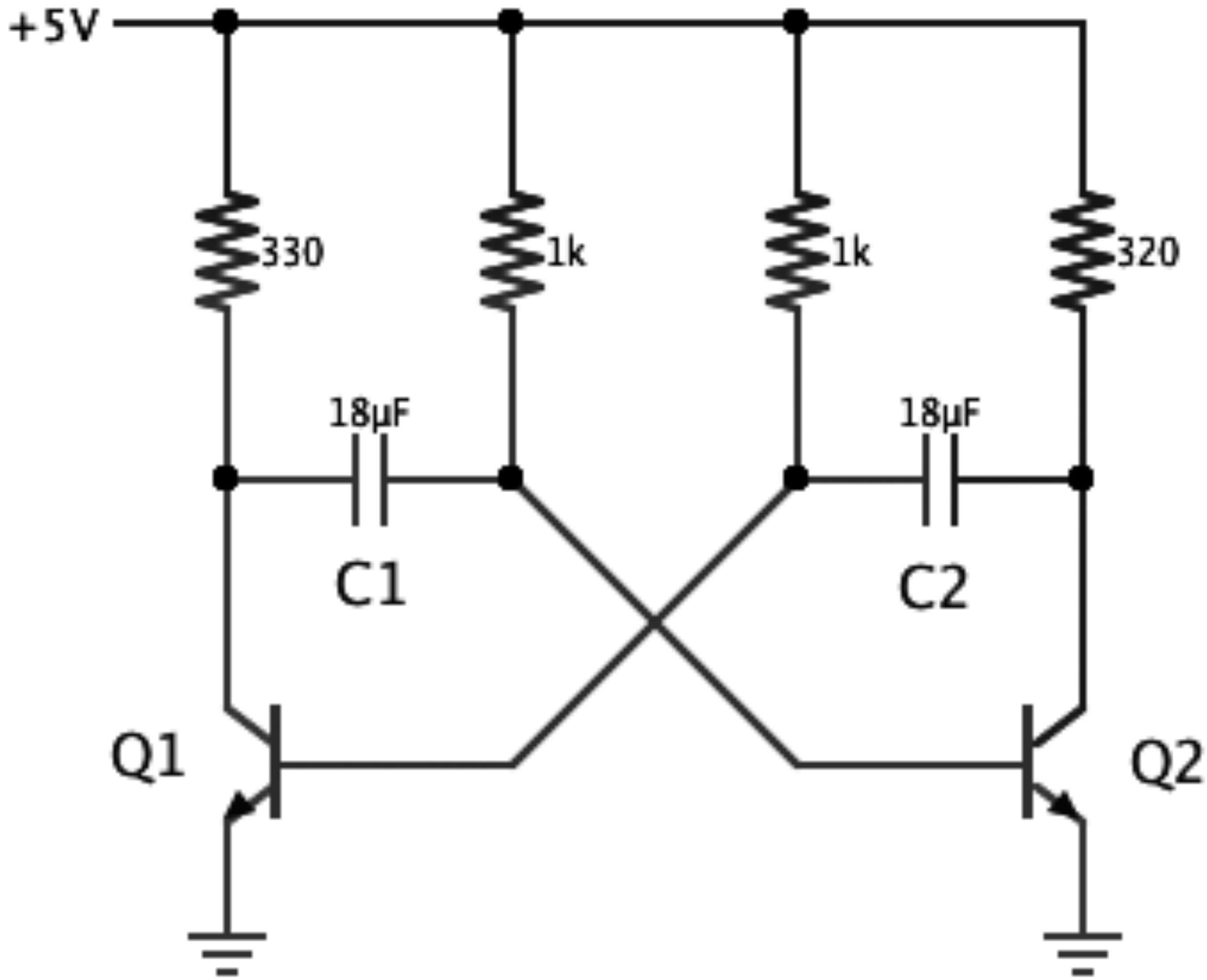
- the Buzzer
  - *Negative* feedback: disavows its present state, oscillates (although negative feedback can also converge to a single midpoint in some systems)



Bistable Transistor Circuit (Flip Flop)



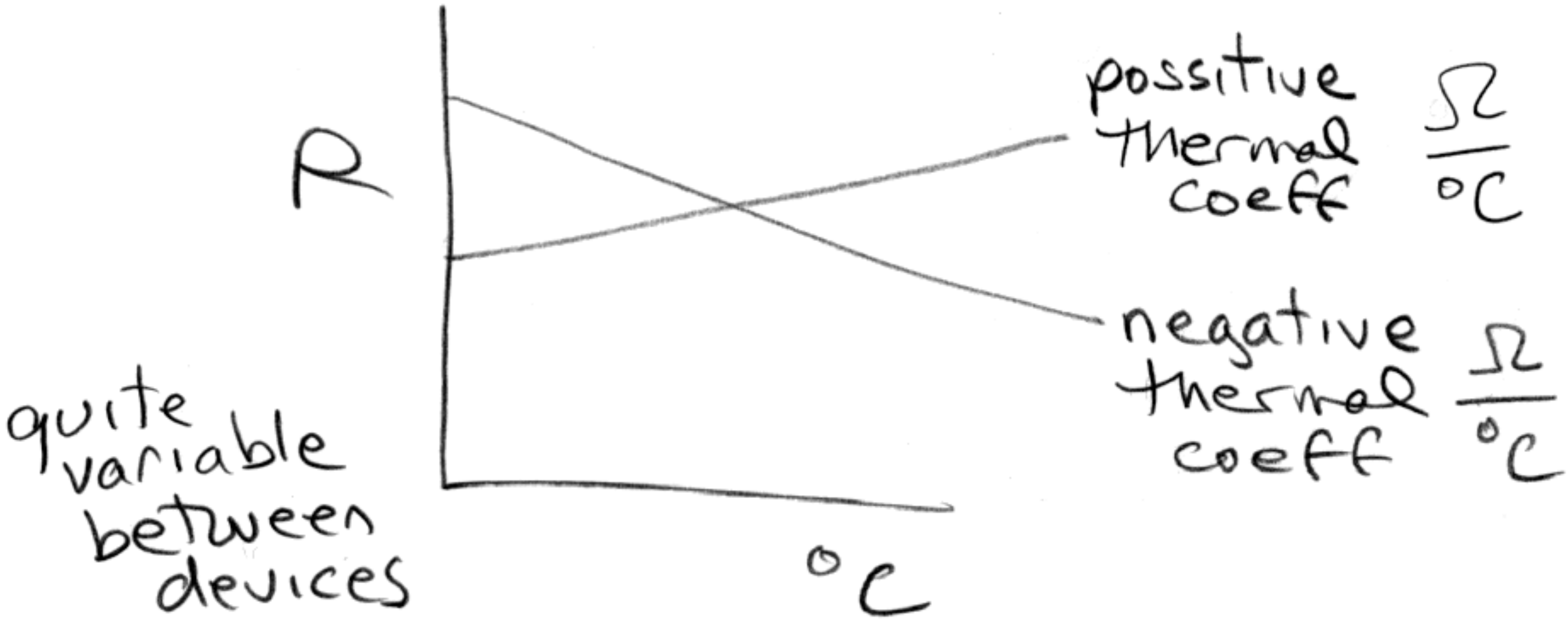
Unstable Transistor Circuit (Multivibrator)



With Q1 on, C1 charges, until base of Q2 high enough to turn on.
For animation see www.falstad.com/circuit/e-multivib-a.html

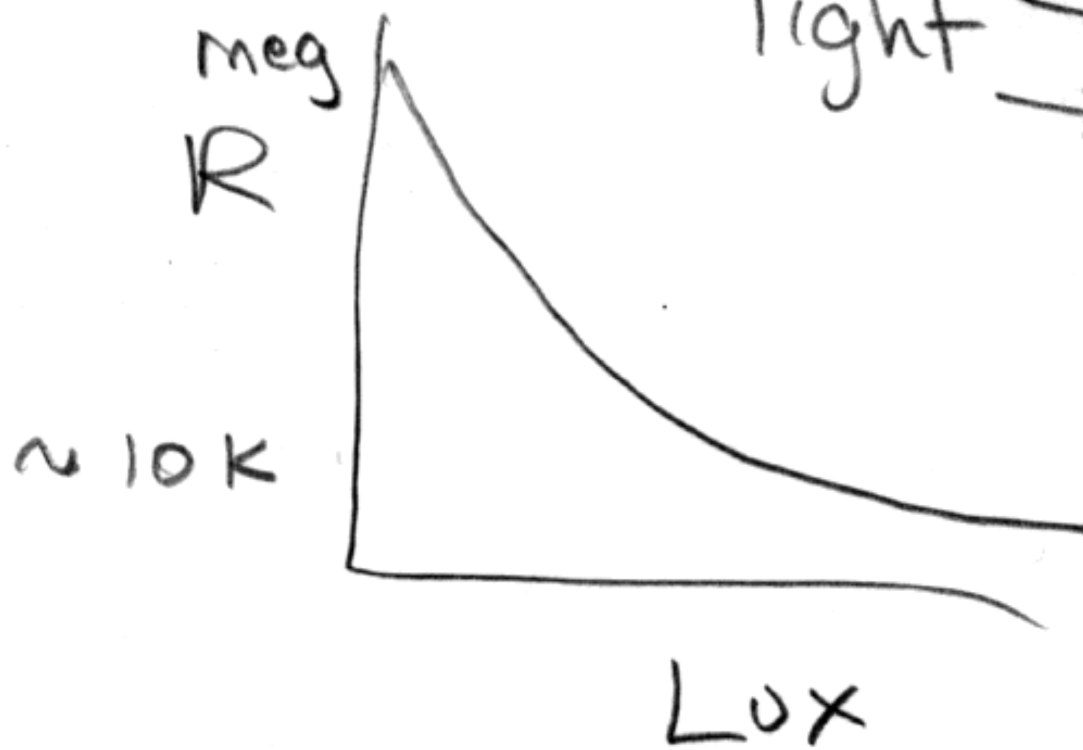
Thermistor

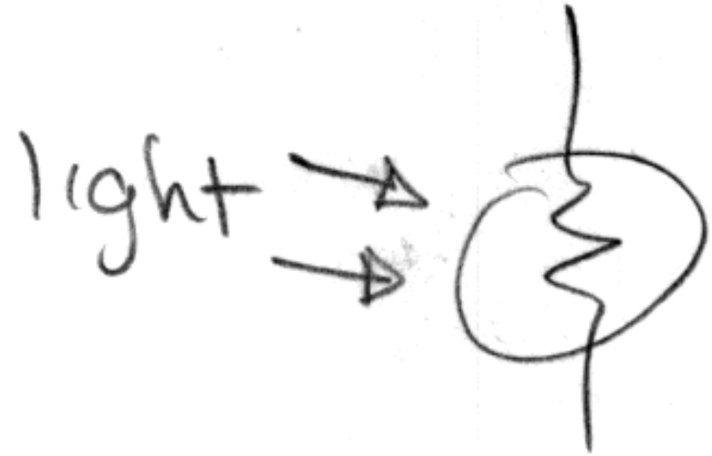
- All resistors have temperature coefficient, usually considered bad.
- Bug becomes feature.



Photoresistor

- Cadmium sulfide between electrodes.
- Photons create free electrons.



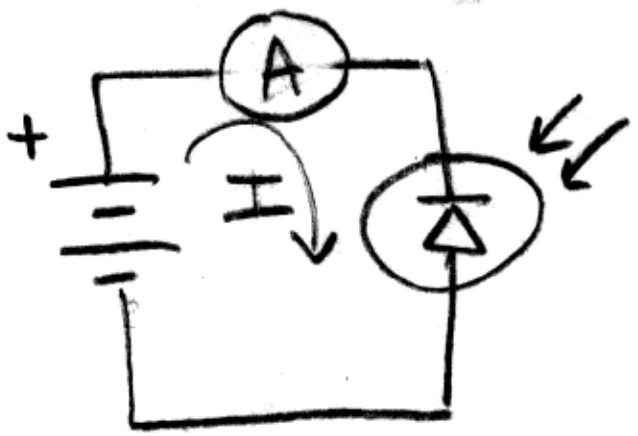


cheap
sturdy
slow
~100 Hz

Photodiodes

- Faster and more sensitive than photoresistors
- Two modes:
  - Photoconductive vs. Photovoltaic

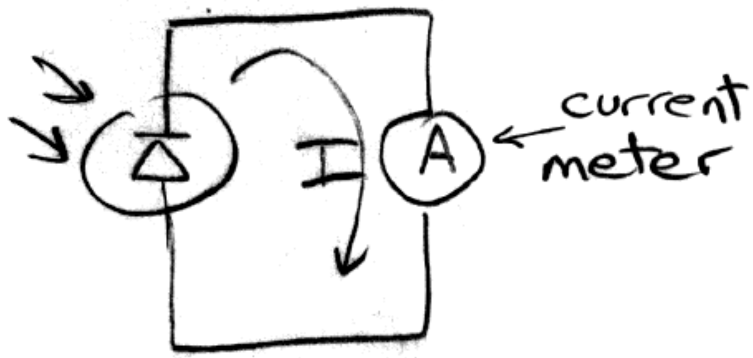
Photoconductive



strong signal
leakage current
("shot" noise)

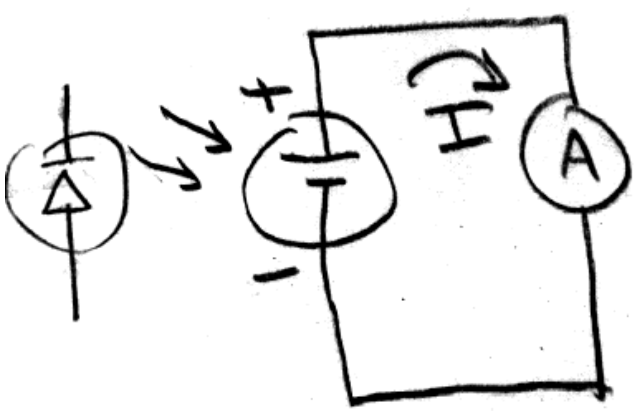
Photodiodes

Photovoltaic



greatest sensitivity (low noise) but can be very small currents

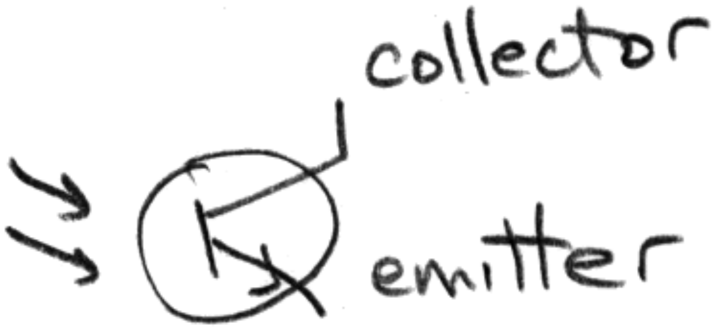
Solar Cells – Photovoltaic with large surface area



Phototransistors

- Faster than photodiodes

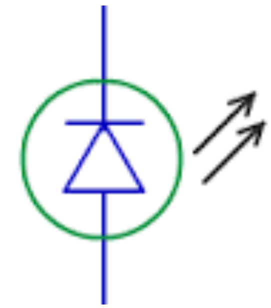
very sensitive

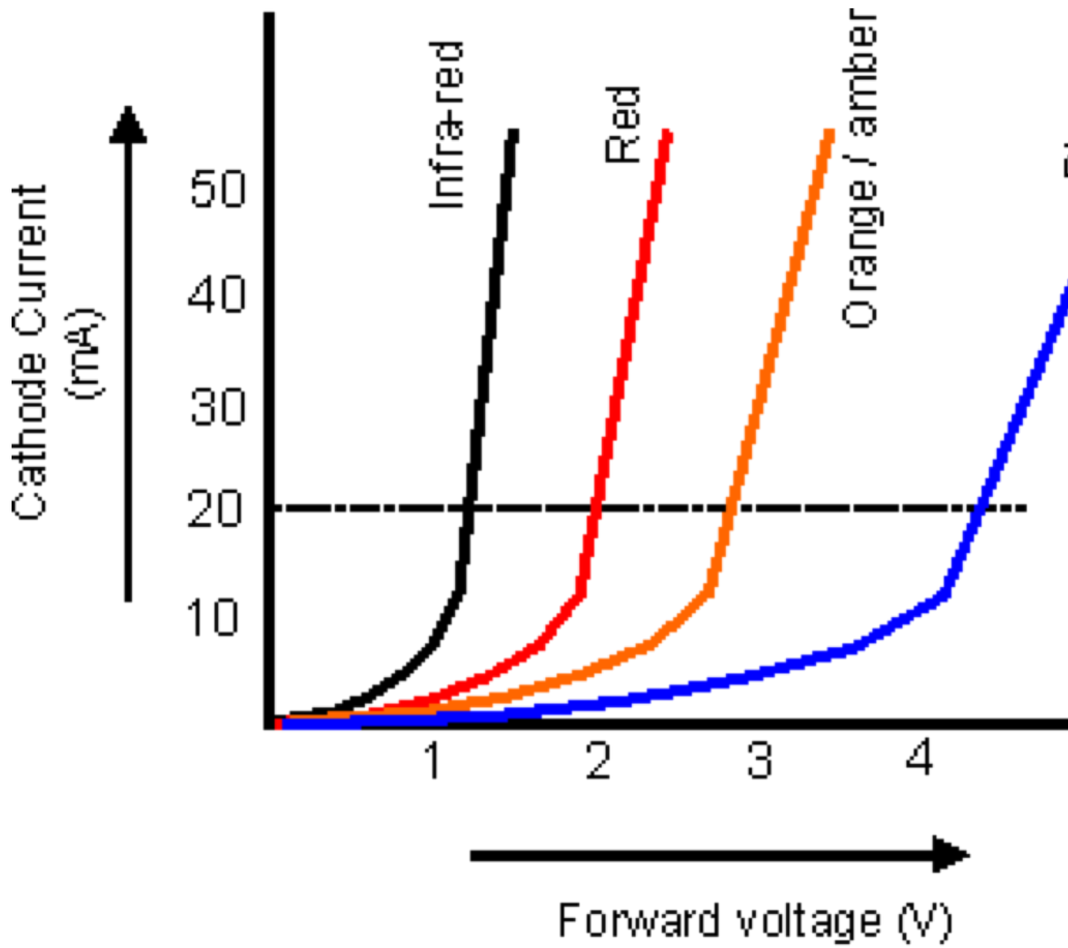


light generates the base current

Light Emitting Diode (LED)

- Forward bias voltage is higher and varies with color since photon energy $E = h\nu$, where ν is frequency and h is Planck's constant.

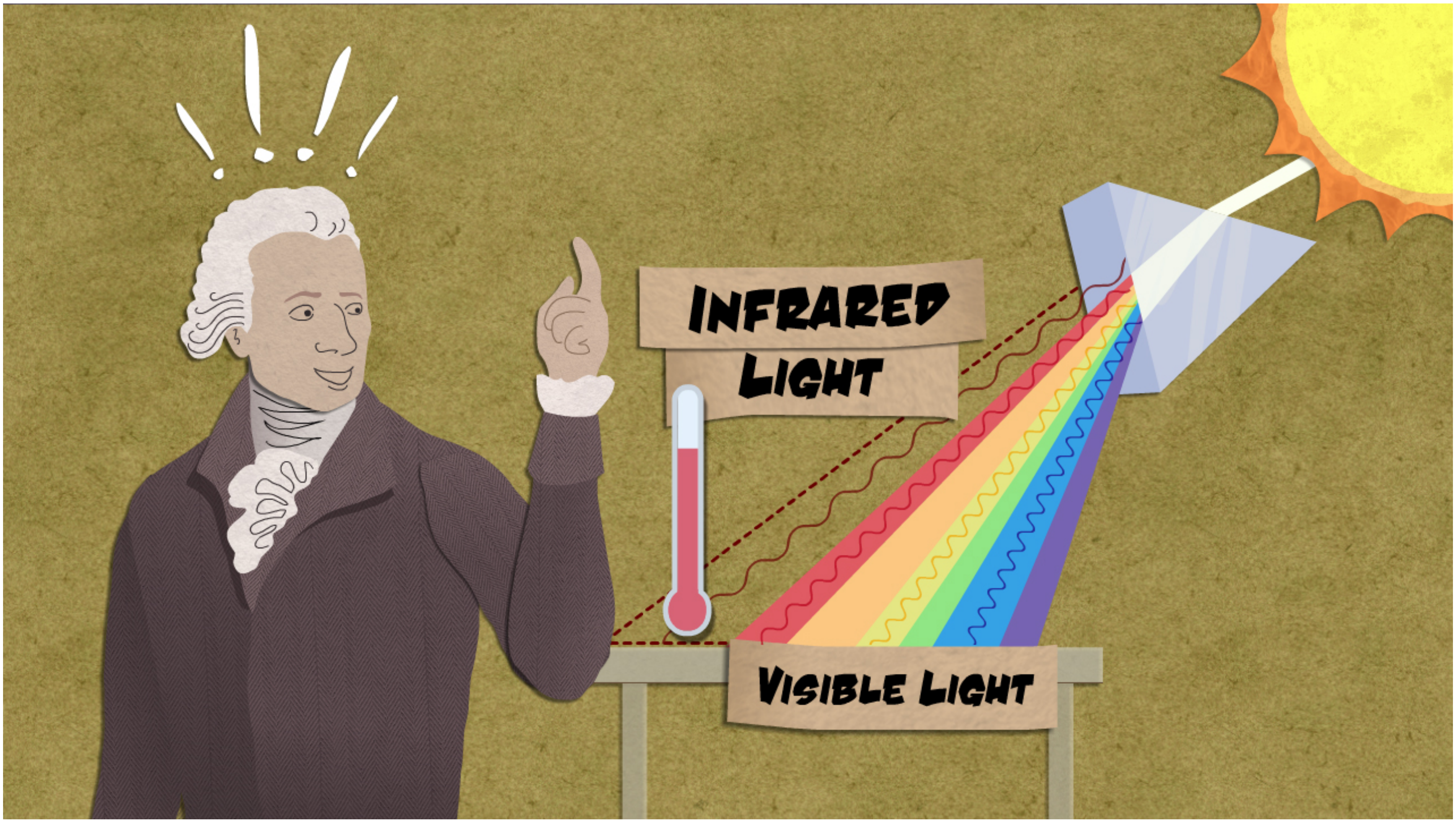




Discovery of Infrared

- William Herschel 1800 with a prism and a thermometer

(also discovered Uranus)



https://www.nasa.gov/images/content/685627main_IMAGE3-beyond-visible.jpg