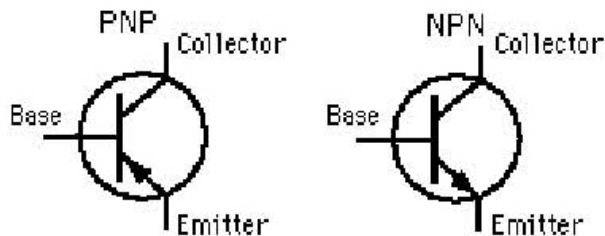
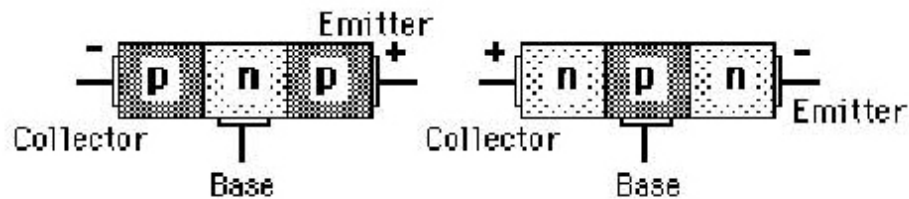


## Bipolar Junction Transistors

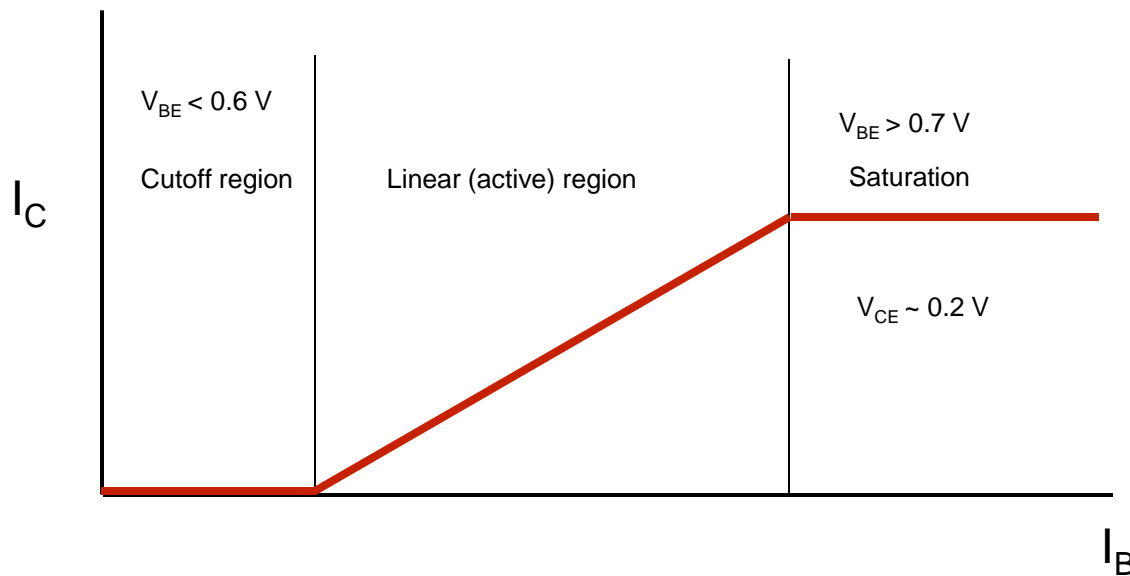
- A three terminal device that allows a small current to control a much larger one
- Essentially two junction diodes



## Bipolar Junction Transistors

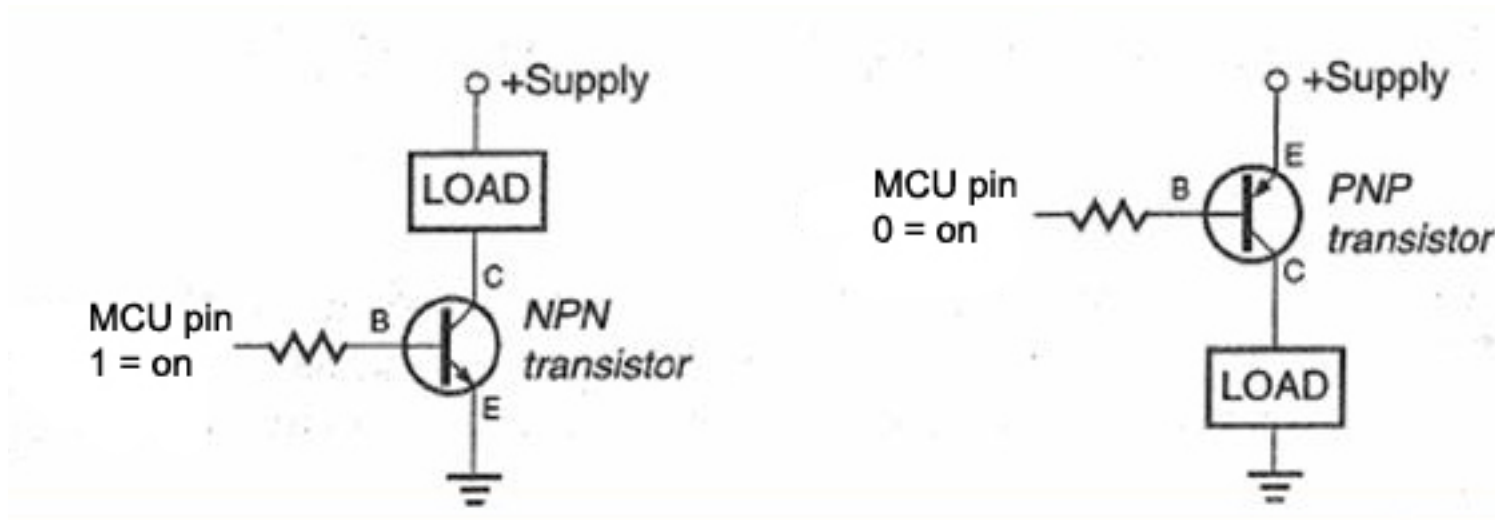
### • What's going on?

- BE diode doesn't turn on until forward biased to  $\sim 0.6\text{ V}$
- In the linear region  $I_C = \beta * I_B$  ( $\beta$  is a bad design parameter!)
- Eventually saturate and  $I_C$  depends solely on the attached load.



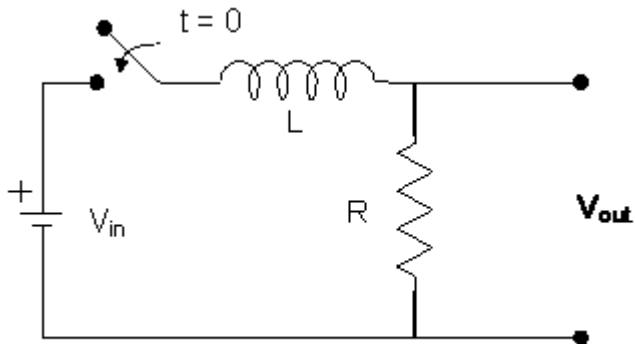
## Bipolar Junction Transistors

- Be sure “switch side” is opposite the load side.

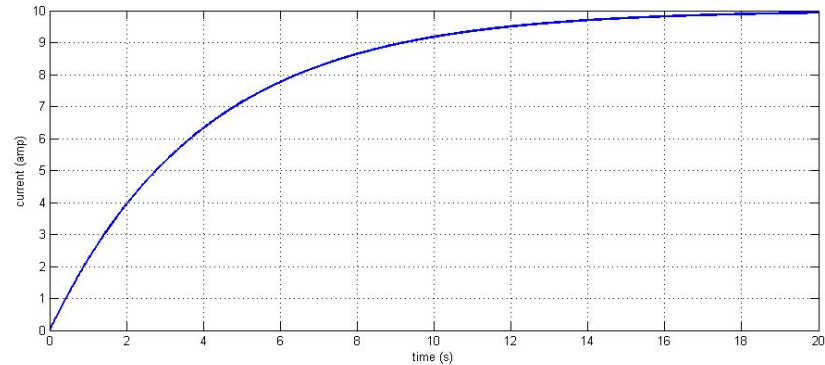


## Circuit Dynamics

- Frequency dependence of impedance is important



- Current through an inductor cannot change instantaneously.



- What happens when the switch is closed?

$$\text{KVL: } V = L \frac{di}{dt} + iR \quad \rightarrow \quad i(t) = \frac{V}{R} \left[ 1 - e^{-t/\tau} \right]$$

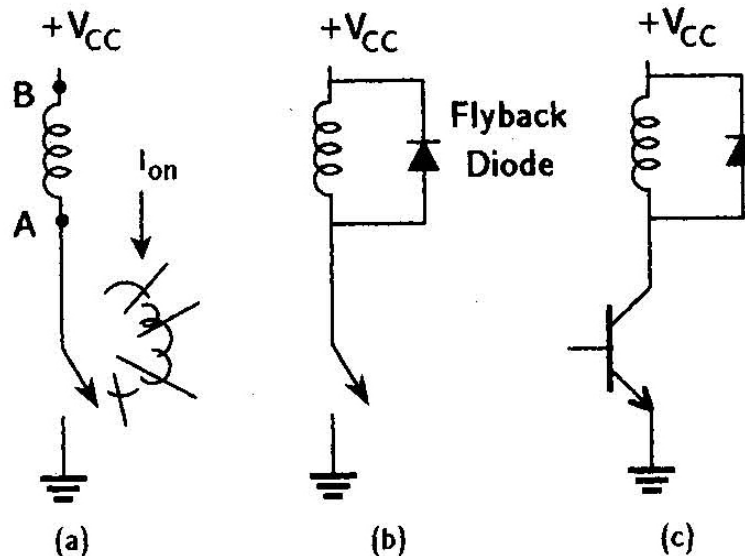
where  $\tau = L/R$  is the time constant

So, as  $t \rightarrow \infty$ ,  $V_L \rightarrow 0$  and the inductor behaves as a short circuit.

## Junction Diodes

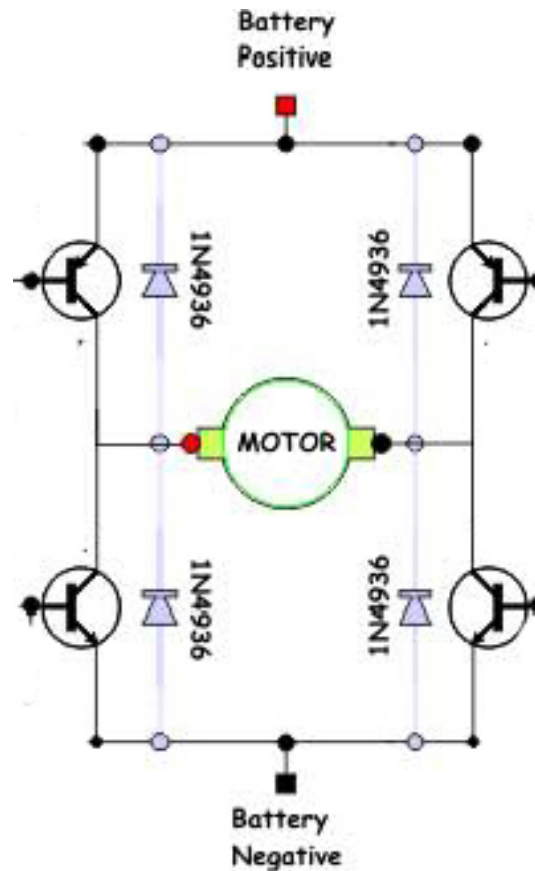
### • Inductive kickback

- Big problem when switching inductive loads (motors, solenoids)
- A changing current induces a voltage across the inductor, making the potential at A greater than at B.
- This can cost you the price of a new switch.
- Flyback diodes protect against this.



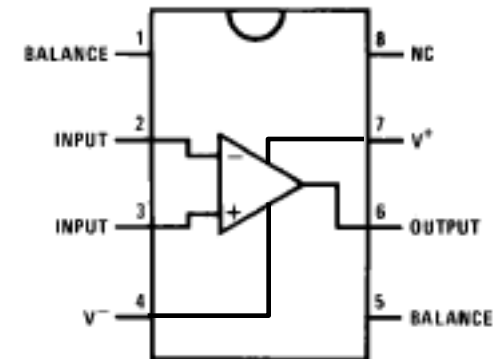
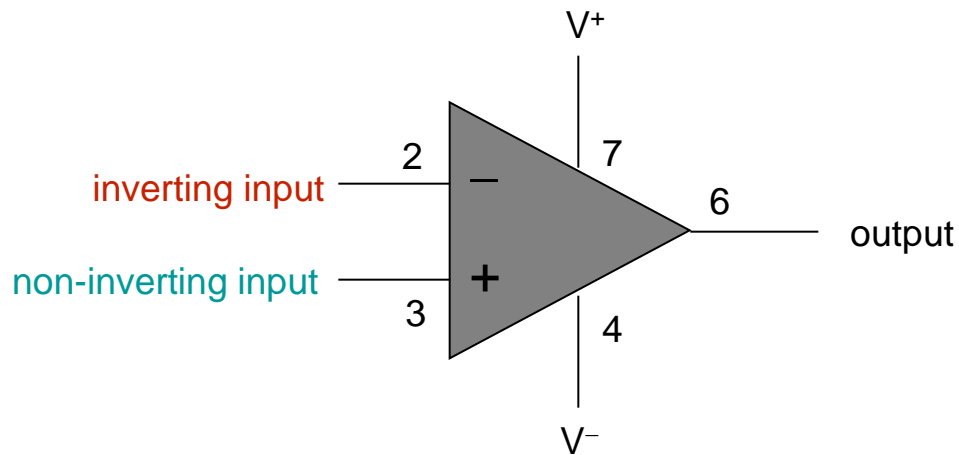
## Bipolar Junction Transistors

- H-Bridge motor drivers



## Operational Amplifier

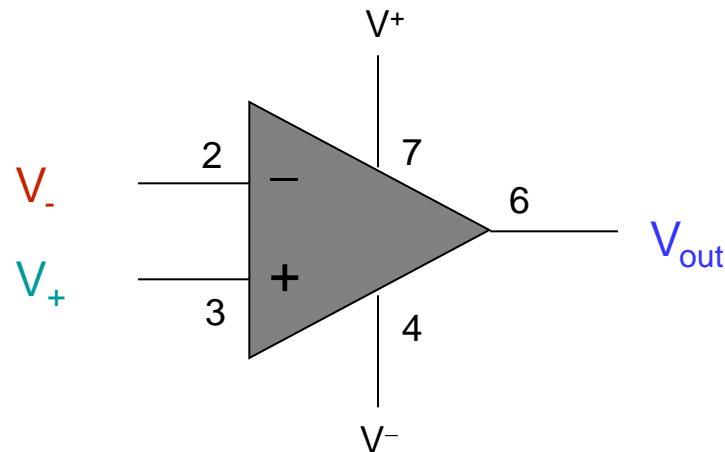
- Two inputs
  - inverting
  - non-inverting
- One output
- External power connections



## Operational Amplifier (w/o feedback)

- The internal op-amp formula is

$$V_{\text{out}} = \text{Gain} * (V_{+} - V_{-})$$

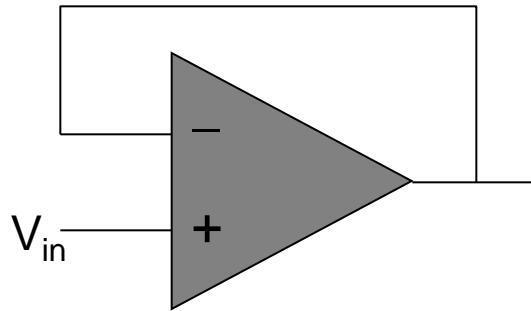


- So if  $V_+$  is greater than  $V_-$ , the output goes positive
- If  $V_+$  is less than  $V_-$ , the output goes negative
- A **Gain** of  $\sim 200,000$  (for a real op-amp) makes this device practically useless (at least as shown here...)



## Operational Amplifier (negative feedback)

- Infinite gain is not generally useful unless used with negative feedback
- Imagine hooking the output to the inverting input

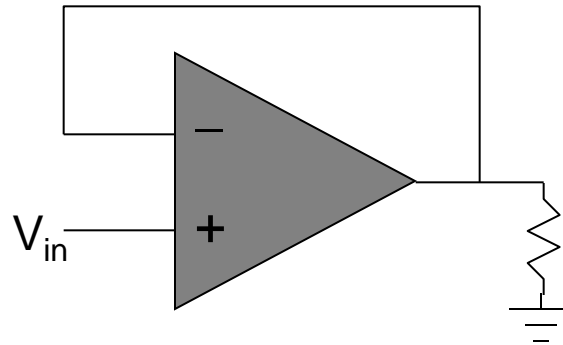


- If the output is less than  $V_{in}$ , it must go positive
- If the output is greater than  $V_{in}$ , it must go negative

The result is that the output quickly forces itself to be exactly  $V_{in}$ .

## Operational Amplifier (negative feedback)

- What happens under load?

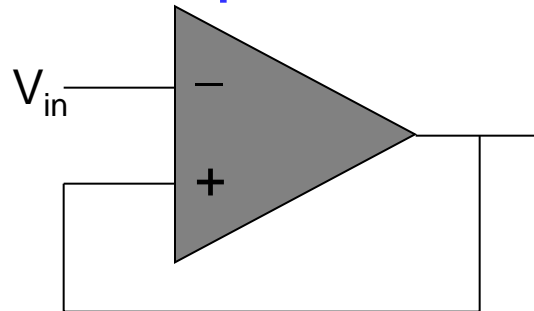


- Load wants to pull output to GND
- Op-Amp will do all it can (within current limitations) to drive output to  $V_{in}$ 
  - In this case, the op-amp drives (or sinks, if  $V_{in}$  is negative) a current through the load until  $V_{out} = V_{in}$

The result is that we have a buffer that can apply  $V_{in}$  to a load without worrying about the characteristics of the source of  $V_{in}$ .

## Operational Amplifier (positive feedback)

- What happens under positive feedback?



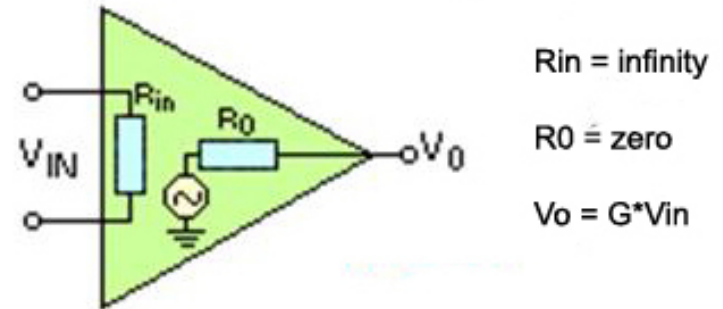
- Now if the non-inverting input is more positive by even a tiny amount, the output tries to drive it still more positive
- The system will immediately “rail” at the supply voltage
  - This could be either positive or negative, depending on the initial offset

## Golden Rules

- The inputs draw no current
- When wired with negative feedback the output does whatever is necessary to make the difference between the input voltages zero.

→ Only KCL, KVL, and Ohm's Law are necessary to completely analyze op amp circuits.

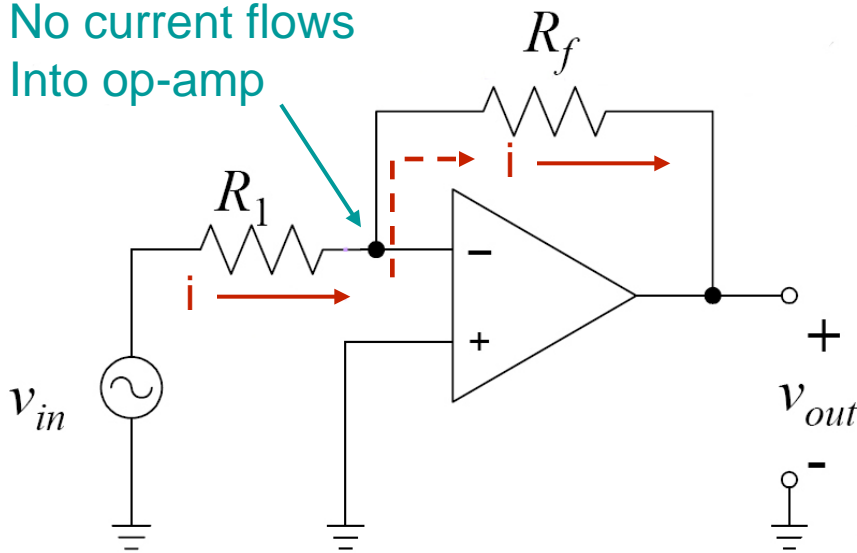
## The Ideal Amplifier



## Inverting Amplifier

- Resistor  $R_f$  is connected to the inverting input and forms a negative feedback loop:

No current flows  
Into op-amp



Using KCL: 
$$\frac{V_{in} - V_-}{R_1} = \frac{V_- - V_{out}}{R_f}$$

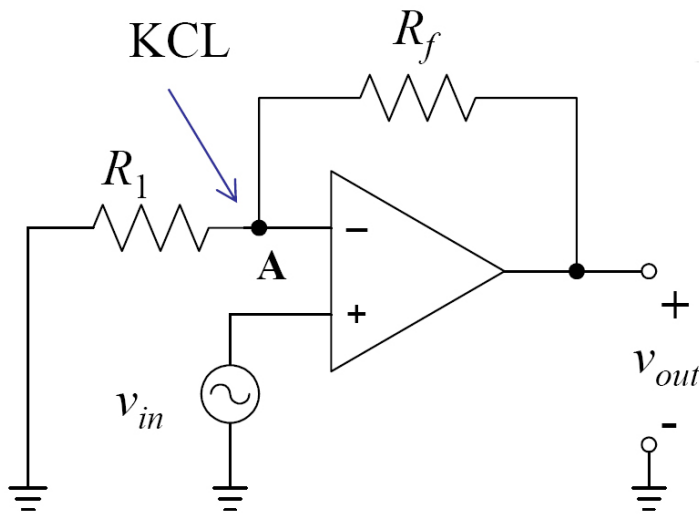
Also: 
$$V_{out} = G * (V_+ - V_-) \text{ and } V_+ = 0$$

$$\rightarrow \frac{V_{in} + \left( \frac{-V_{out}}{G} \right)}{R_1} = \frac{\left( \frac{-V_{out}}{G} - V_{out} \right)}{R_f}$$

$$\rightarrow \frac{V_{out}}{V_{in}} = - \frac{R_f}{R_1}$$

## Non-Inverting Amplifier

- Positive input is held at  $V_{in}$



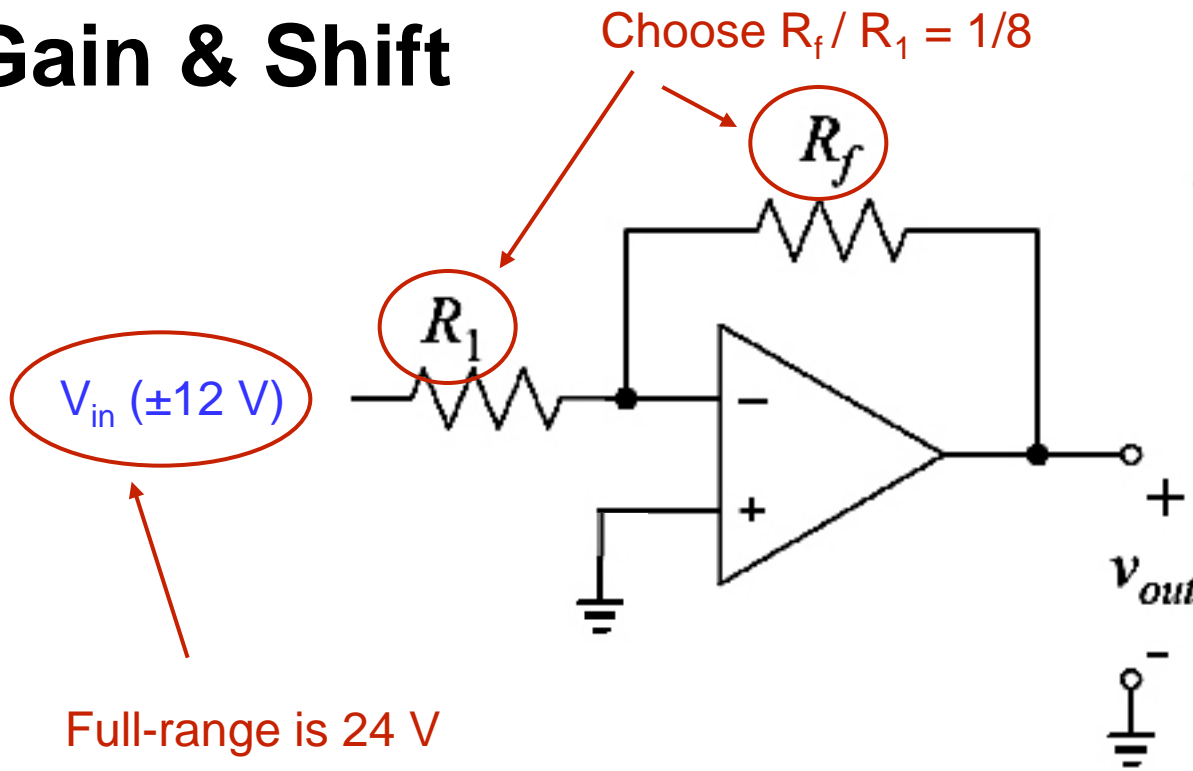
$$V_{out} = G(V_+ - V_-)$$

$$V_+ = V_{in} \text{ and } V_- = \frac{R_1}{R_1 + R_f} V_{out}$$

$$V_{out} = G \left( V_{in} - \frac{R_1}{R_1 + R_f} V_{out} \right)$$

$$\rightarrow \frac{V_{out}}{V_{in}} = \frac{G}{\left( 1 + \frac{GR_1}{R_1 + R_f} \right)} \approx 1 + \frac{R_f}{R_1}$$

## Gain & Shift



$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1}$$

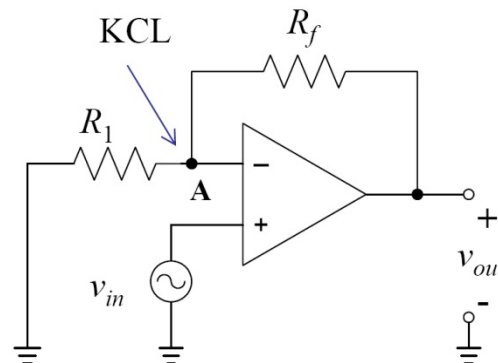
$$V_{out} = \pm 1.5 \text{ V}$$

Now what?

Limited to 0-3 V

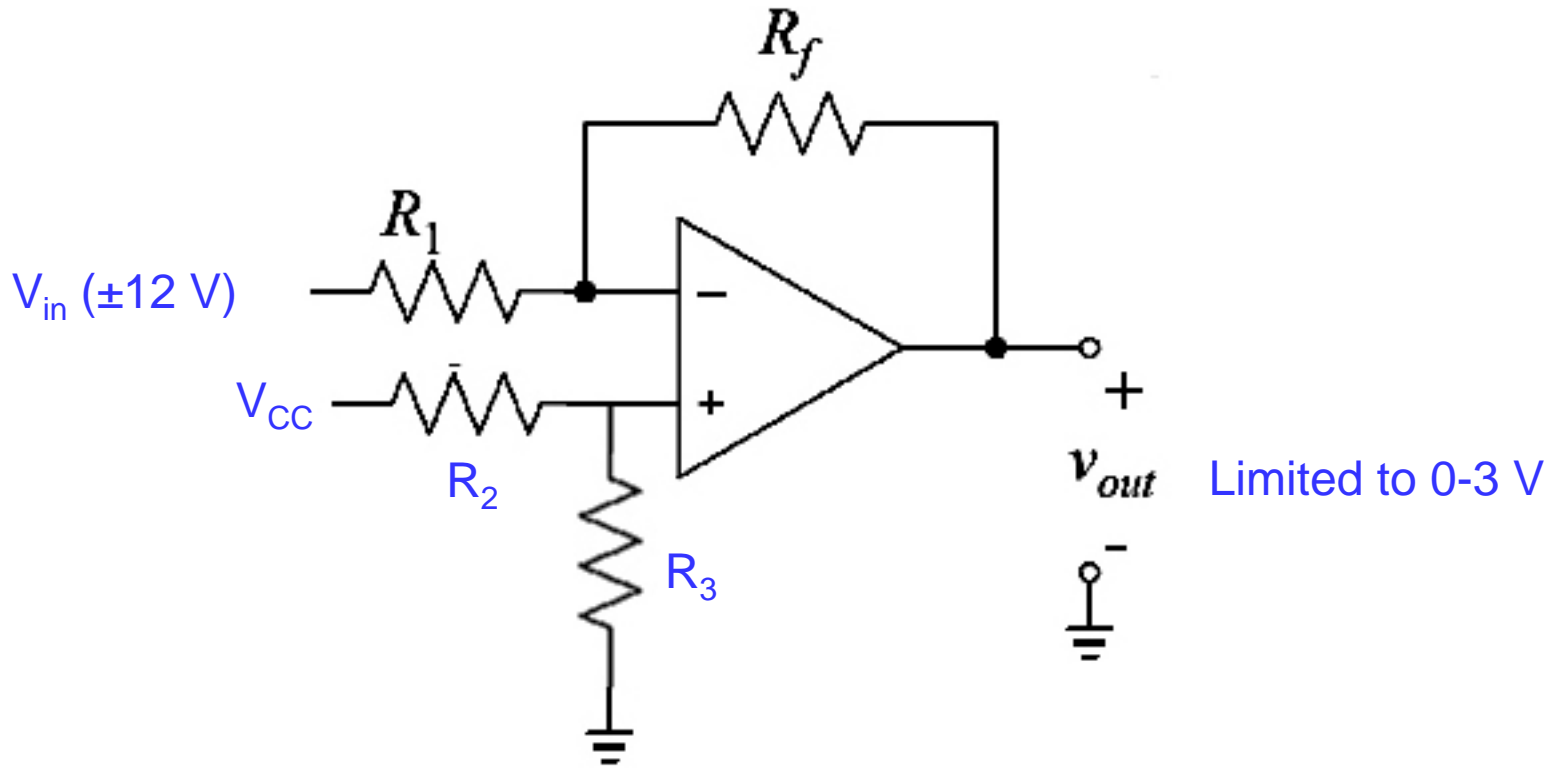
Full-range is 3 V

Recall:



$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}$$

## Gain & Shift



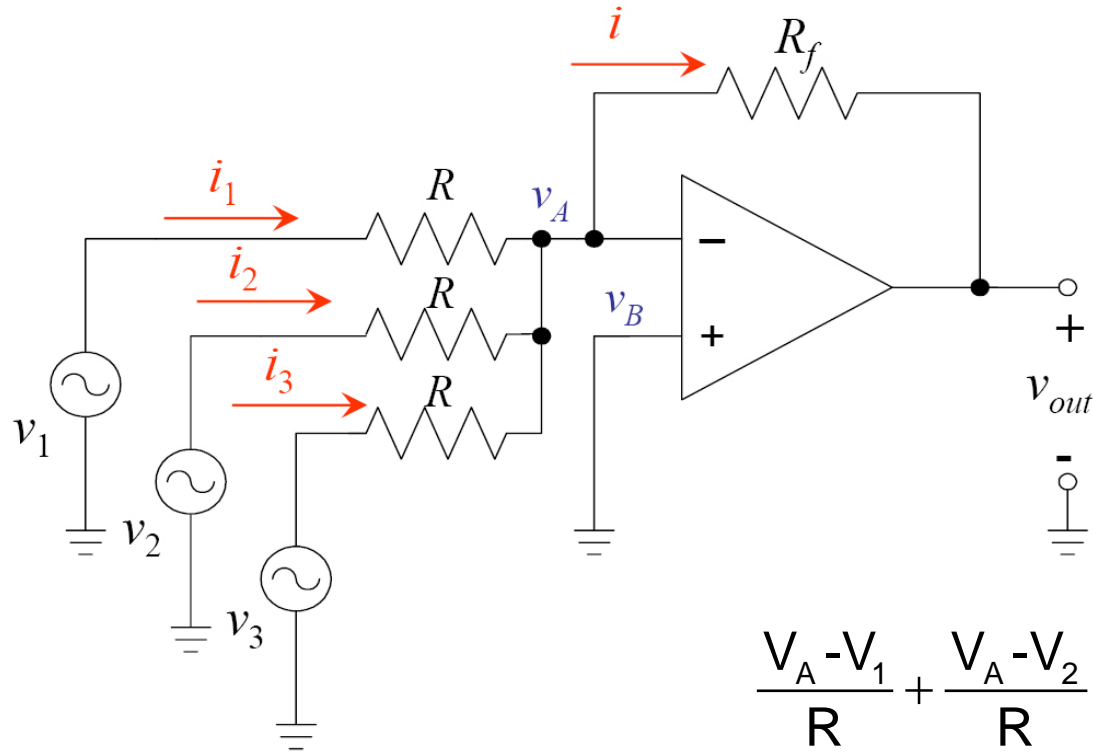
$$V_{out} = \underbrace{-\frac{R_f}{R_1} V_{in}}_{\text{Gain on input voltage}} + \underbrace{\left( \frac{R_3}{R_2 + R_3} + \frac{R_3}{R_2 + R_3} \frac{R_f}{R_1} \right) V_{CC}}_{\text{Shift on reference voltage}}$$

Gain on input voltage

Shift on reference voltage



## Summing Amplifier

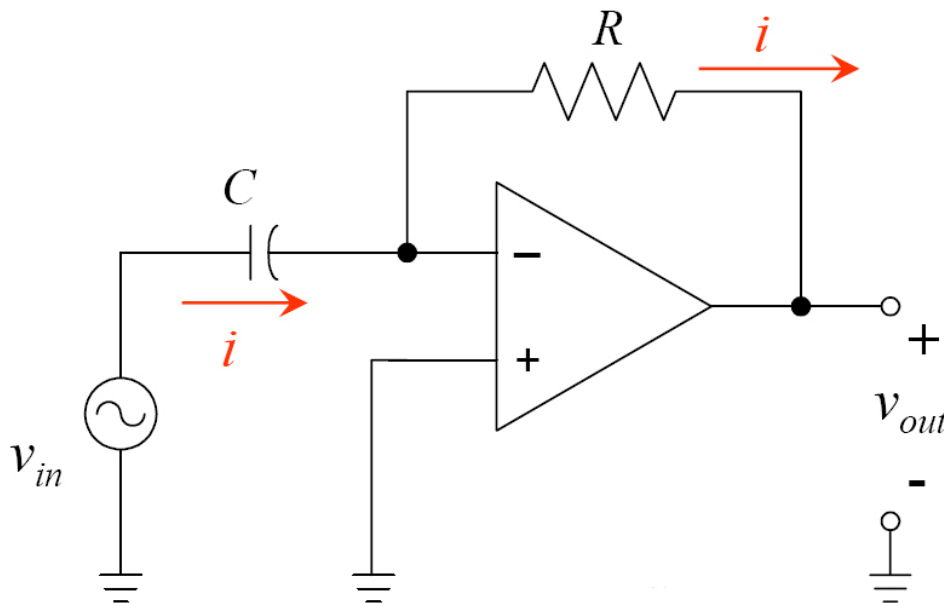


$$\frac{V_A - V_1}{R} + \frac{V_A - V_2}{R} + \frac{V_A - V_3}{R} + \frac{V_A - V_{out}}{R_f} = 0$$

$$\rightarrow V_{out} = -\frac{R_f}{R} (V_1 + V_2 + V_3)$$

## Differentiator

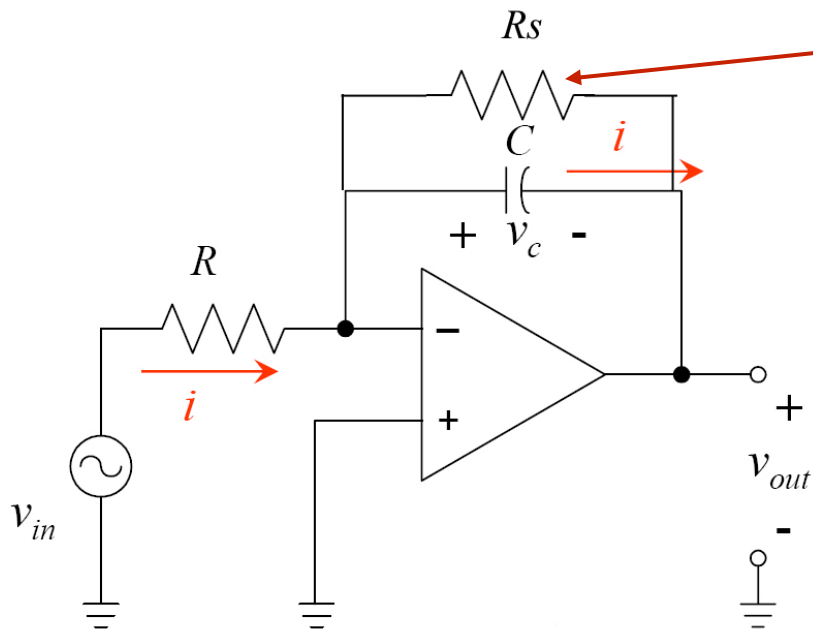
- High-Pass filter
- Tends to accentuate the effects of noise



$$V_{out} = -RC \frac{dV_{in}}{dt}$$

## Integrator

- Low-pass filter
- Tends to smooth signals over time.



Why the shunt resistor?

Without  $R_s$

$$V_{out} = -\frac{1}{RC} \int V_{in}(t) dt$$