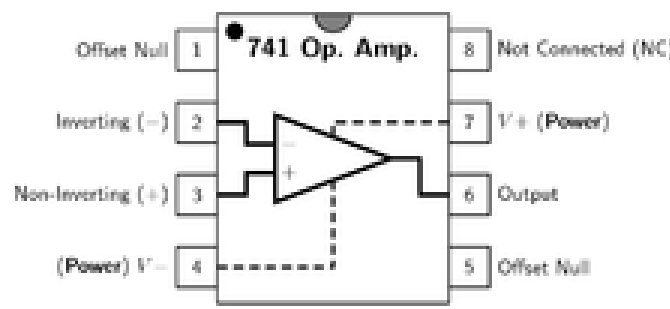
What is an Op-Amp? – The Surface

- An Operational Amplifier (Op-Amp) is an integrated circuit that uses external voltage to amplify the input through a very high gain.
- We recognize an Op-Amp as a mass-produced component found in countless electronics.

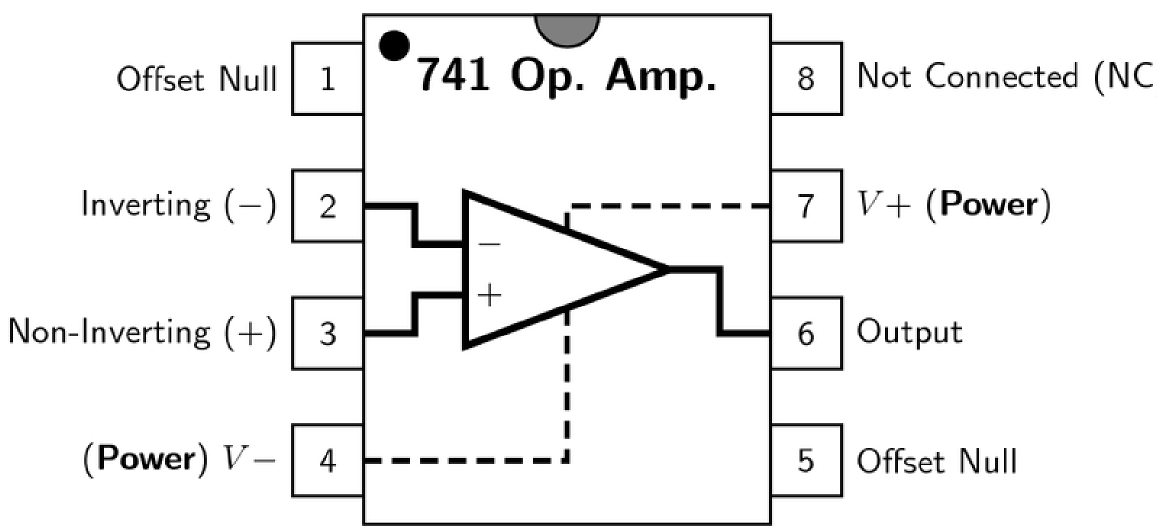
What an Op-Amp looks like to a lay-person



What an Op-Amp looks like to an engineer

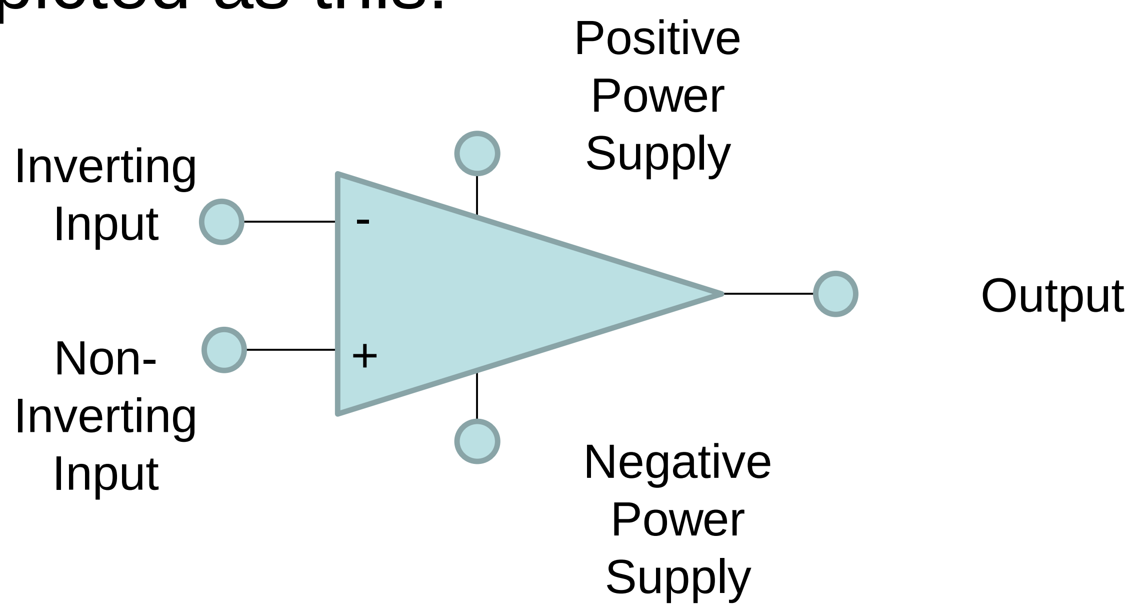
What is an Op-Amp? – The Layout

- There are 8 pins in a common Op-Amp, like the 741 which is used in many instructional courses.



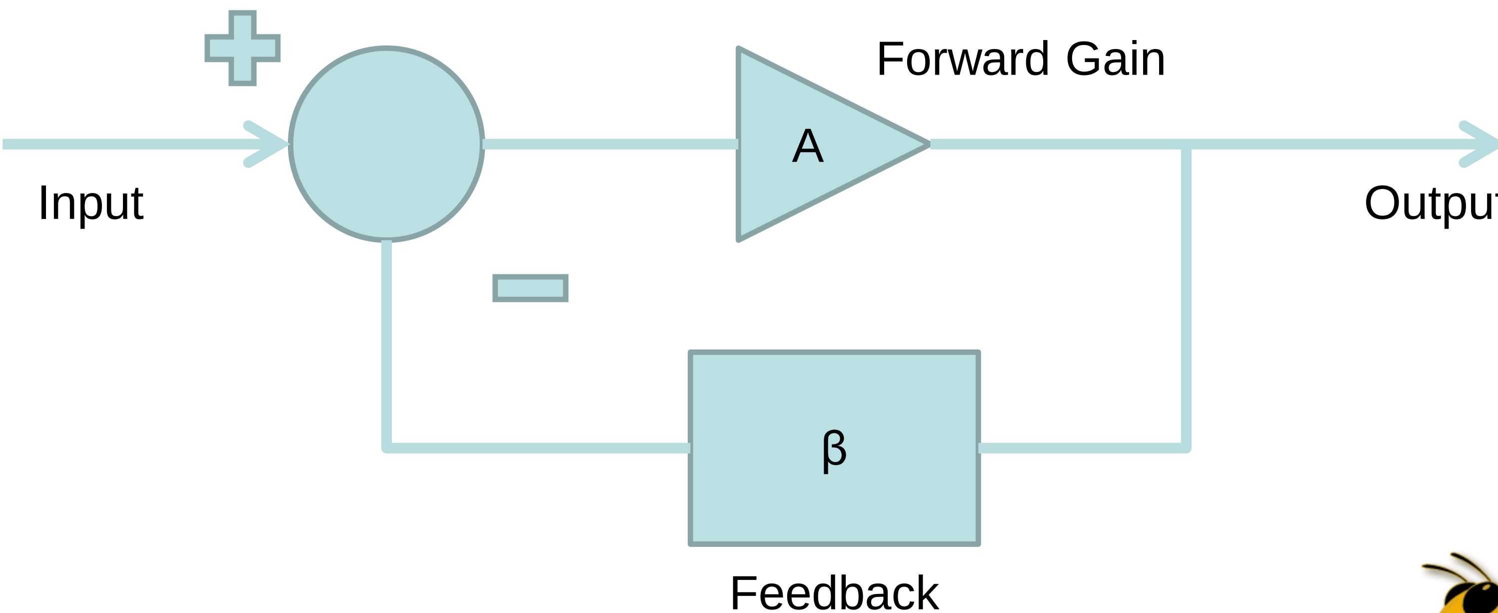
What is an Op-Amp? – The Inside

- The actual count varies, but an Op-Amp contains several Transistors, Resistors, and a few Capacitors and Diodes.
- For simplicity, an Op-Amp is often depicted as this:



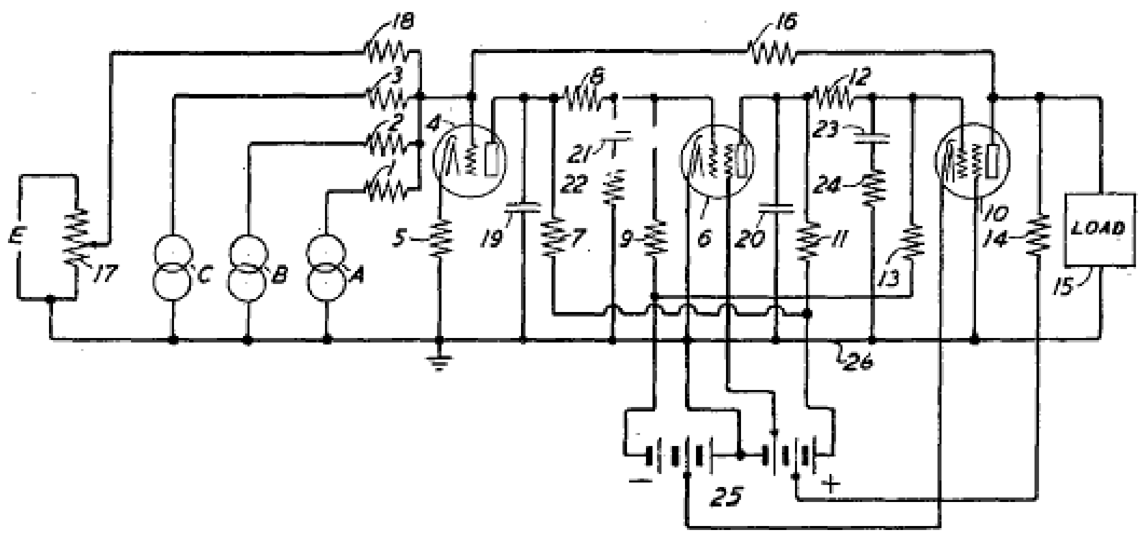
History of the Op-Amp – The Dawn

- Before the Op-Amp: Harold S. Black develops the feedback amplifier for the Western Electric Company (1920-1930)



History of the Op-Amp – The Dawn

- **The Vacuum Tube Age**
- The First Op-Amp: (1930 – 1940) Designed by Karl Swartzel for the Bell Labs M9 gun director
- Uses 3 vacuum tubes, only one input, and ± 350 V to attain a gain of 90 dB
- Loebe Julie then develops an Op-Amp with two inputs: Inverting and Non-inverting



History of the Op-Amp – The Shift

- The end of Vacuum Tubes was built up during the 1950's-1960's to the advent of solid-state electronics

1. The Transistor
2. The Integrated Circuit
3. The Planar Process

History of the Op-Amp – The Shift

- 1960s: beginning of the Solid State Op-Amp
- Example: GAP/R P45 (1961 – 1971)
  - Runs on ± 15 V, but costs $118 for 1 – 4
- The GAP/R PP65 (1962) makes the Op-Amp into a circuit component as a potted module

Mathematics of the Op-Amp

- The gain of the Op-Amp itself is calculated as:

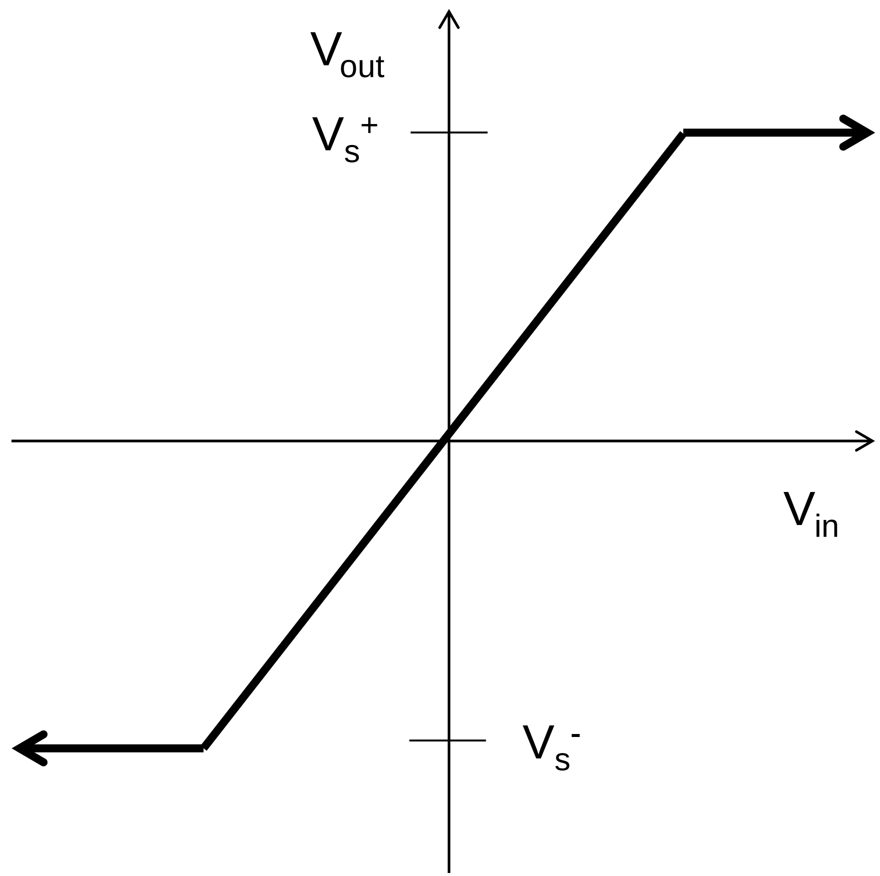
$$G = V_{out}/(V_+ - V_-)$$

- The maximum output is the power supply voltage
- When used in a circuit, the gain of the circuit (as opposed to the op-amp component) is:

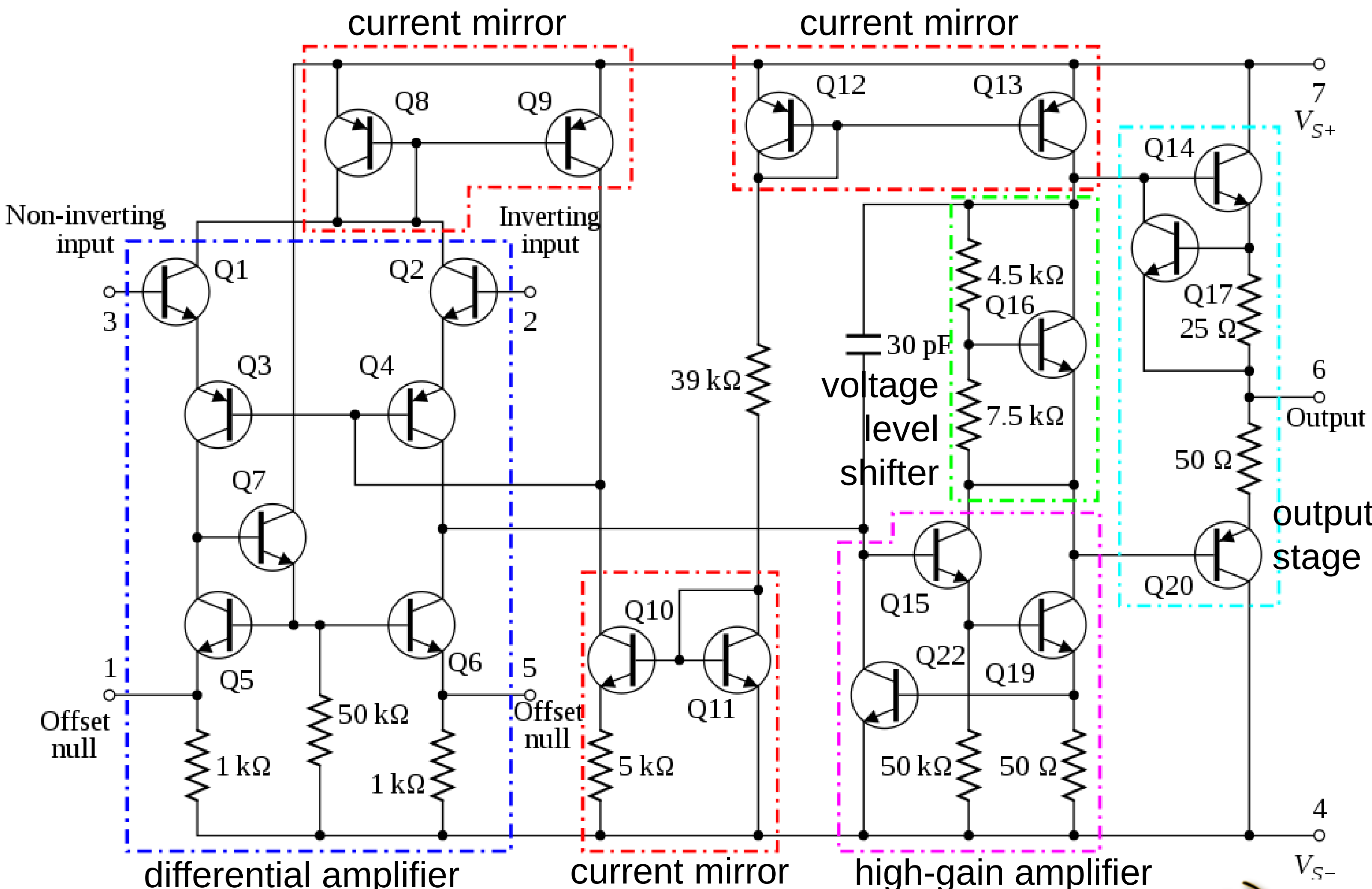
$$A_v = V_{out}/V_{in}$$

Op-Amp Saturation

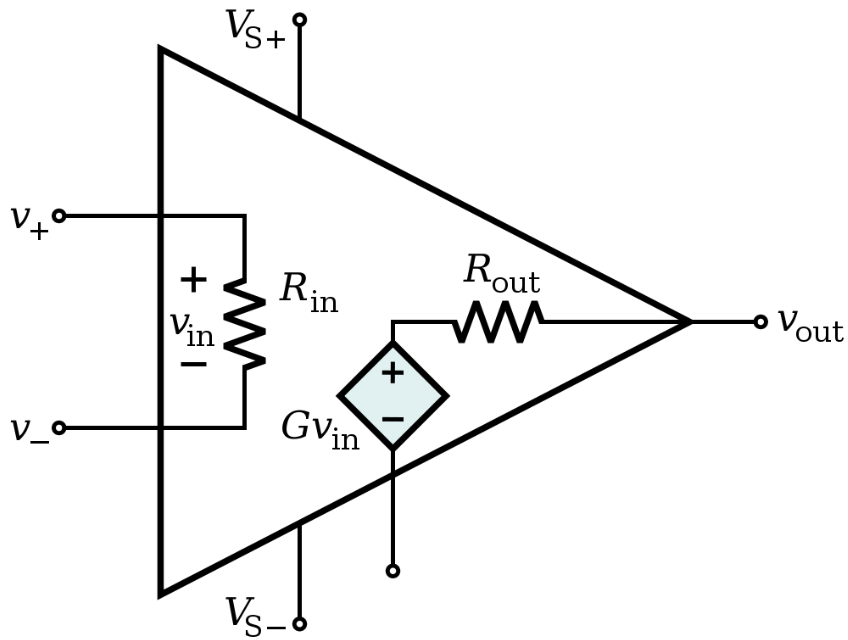
- As mentioned earlier, the maximum output value is the **supply voltage**, positive and negative.
- The gain (G) is the slope between saturation points.



741 Op-Amp Schematic

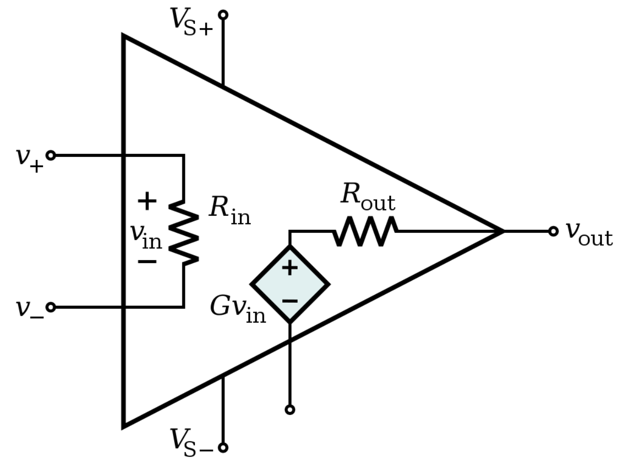


Op-Amp Characteristics



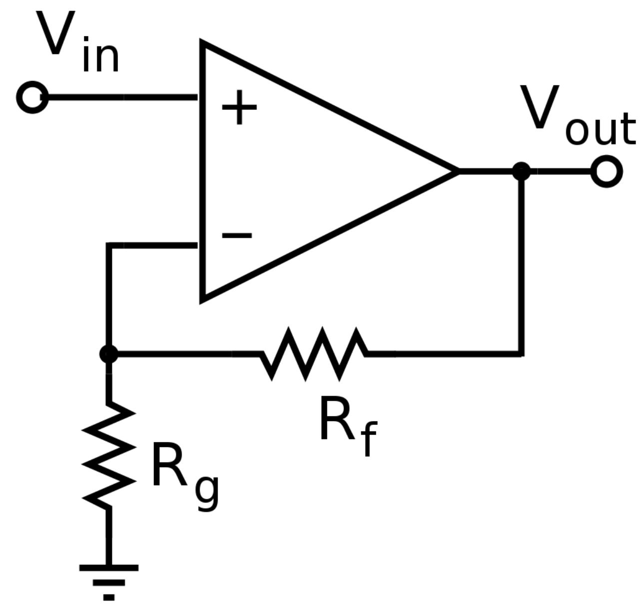
- Open-loop gain G is typically over 9000
    - But closed-loop gain is much smaller
- R_{in} is very large (MΩ or larger)
- R_{out} is small (75Ω or smaller)
    - Effective output impedance in closed loop is very small

Ideal Op-Amp Characteristics



- Open-loop gain G is infinite
- R_{in} is infinite
  - Zero input current
- R_{out} is zero

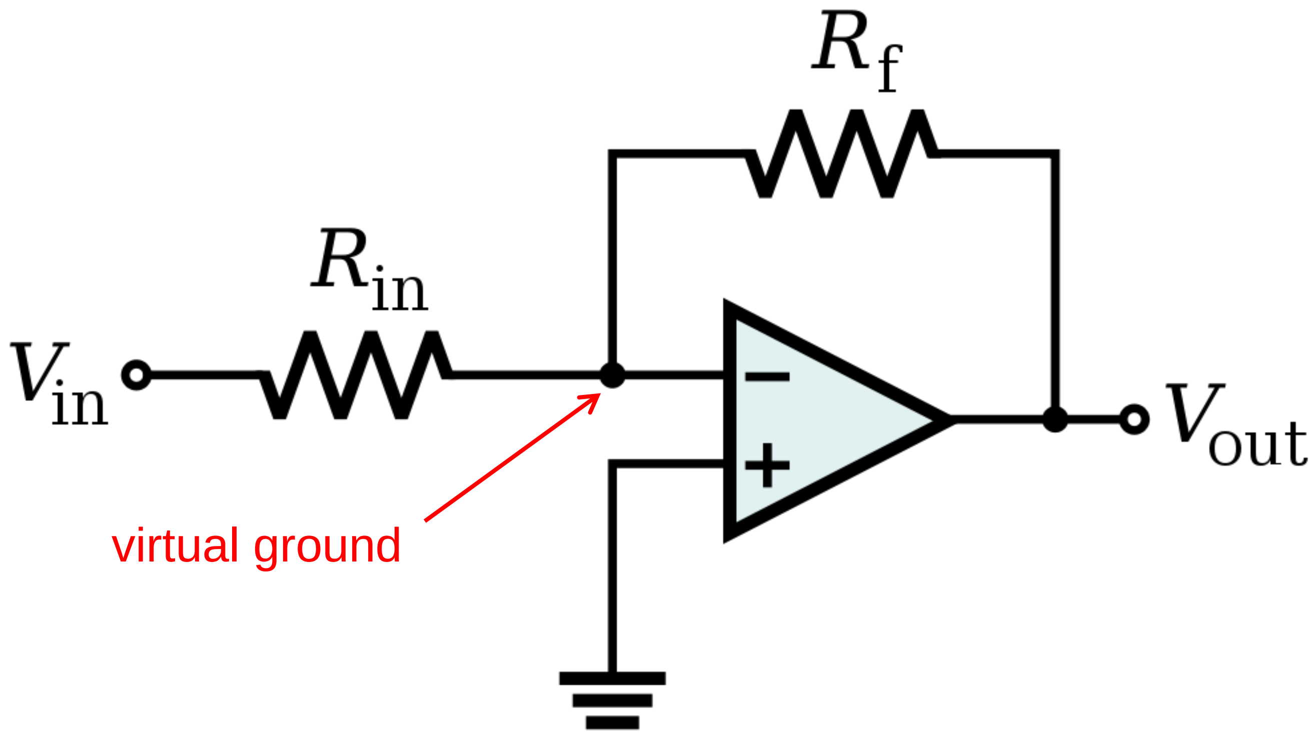
Ideal Op-Amp Analysis



To analyze an op-amp feedback circuit:

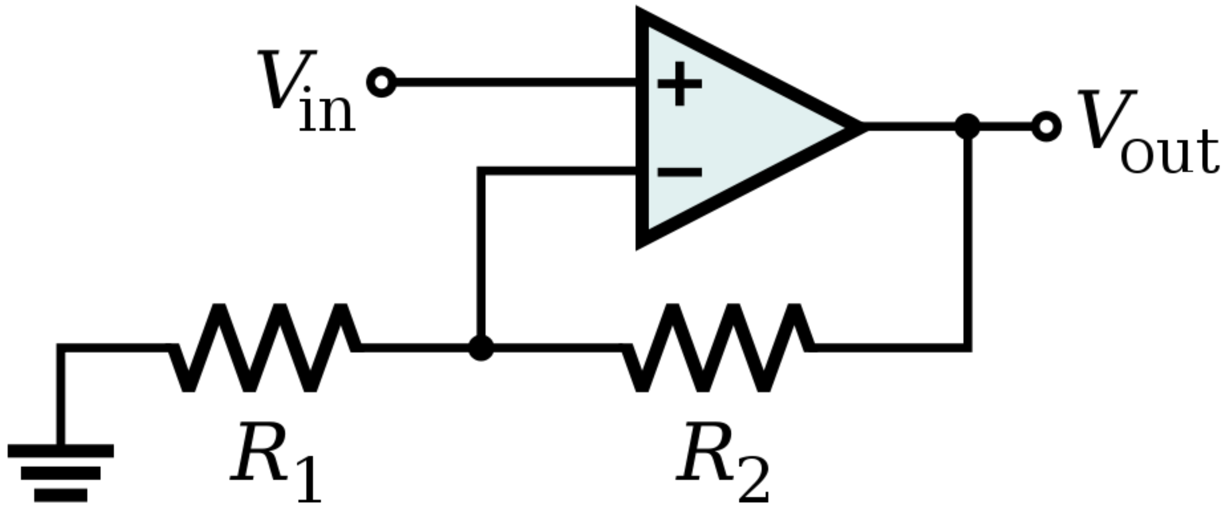
- Assume no current flows into either input terminal
- Assume no current flows out of the output terminal
- Constrain: $V_+ = V_-$

Inverting Amplifier Analysis



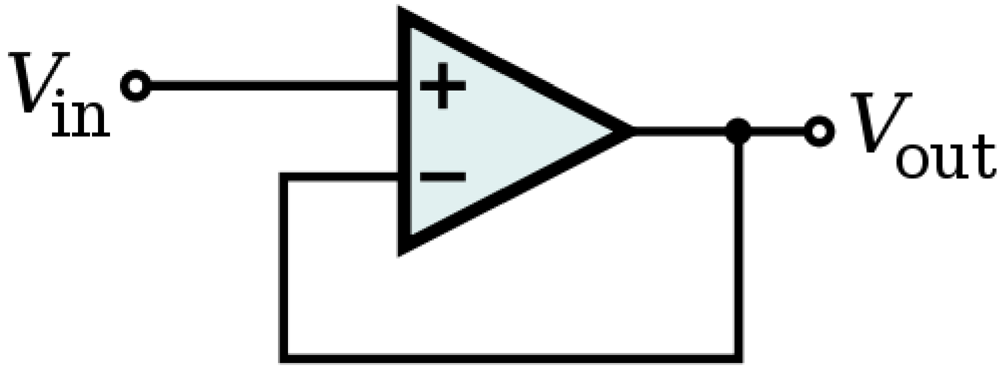
$$V_{out} = -\frac{R_f}{R_{in}} V_{in}$$

Non-Inverting Amplifier Analysis

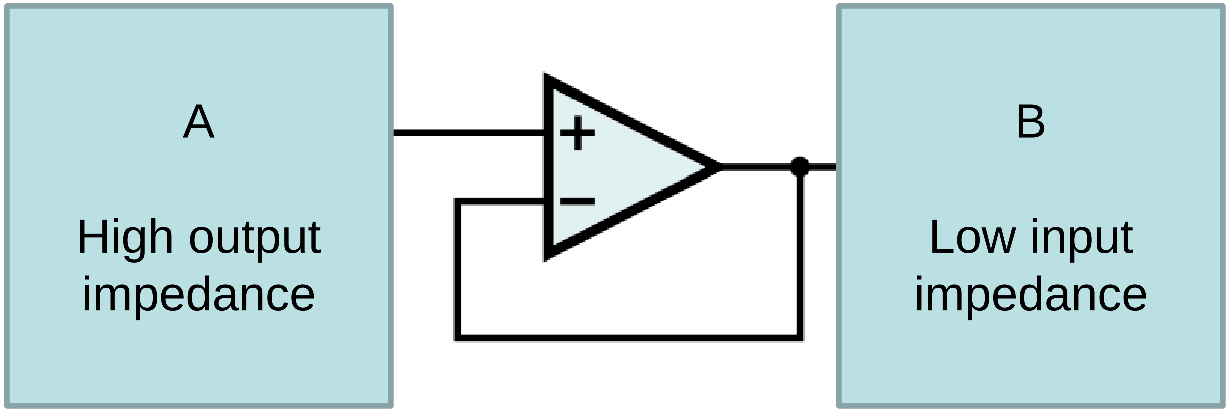


$$V_{out} = V_{in}\left(1 + \frac{R_2}{R_1}\right)$$

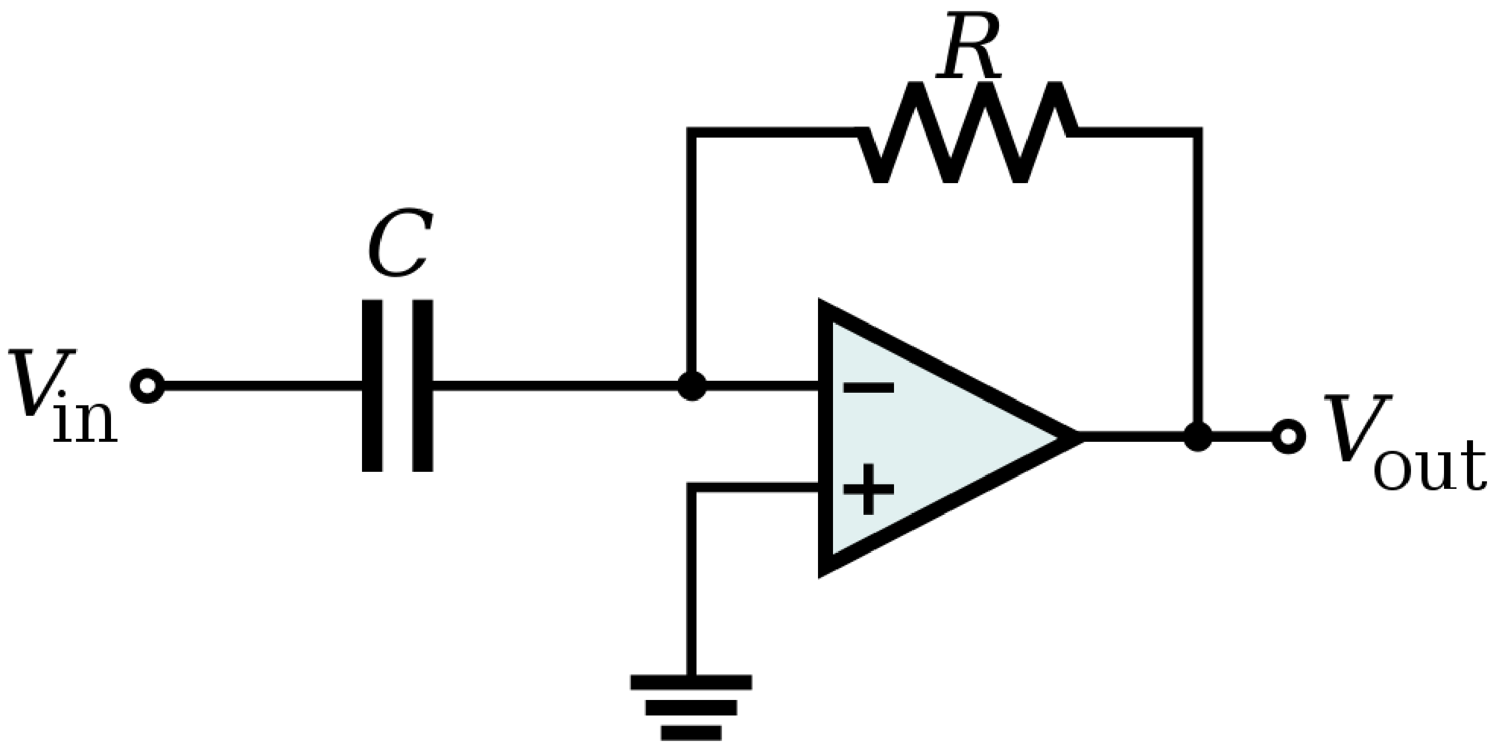
Op-Amp Buffer



Vout = Vin
Isolates loading effects

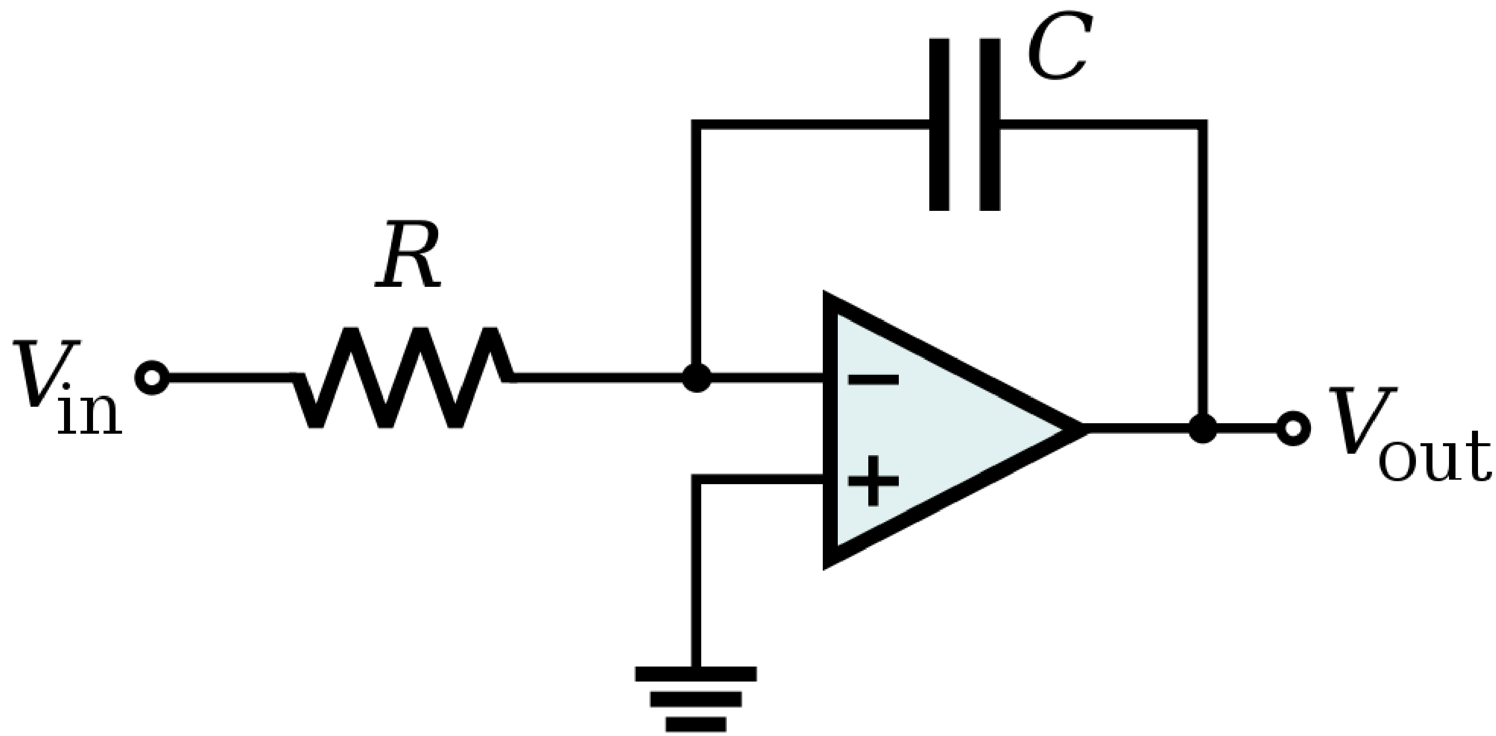


Op-Amp Differentiator



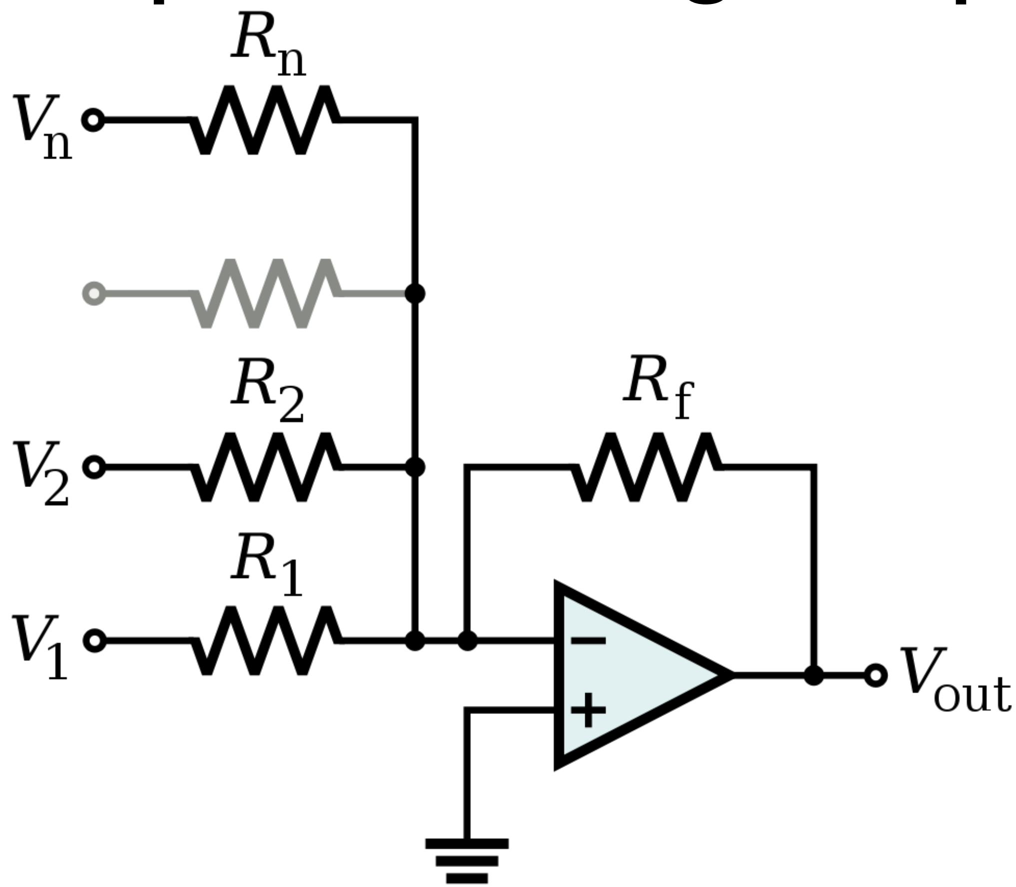
$$V_{\text{out}} = -RC\,\frac{\mathrm{d}V_{\text{in}}}{\mathrm{d}t}$$

Op-Amp Integrator



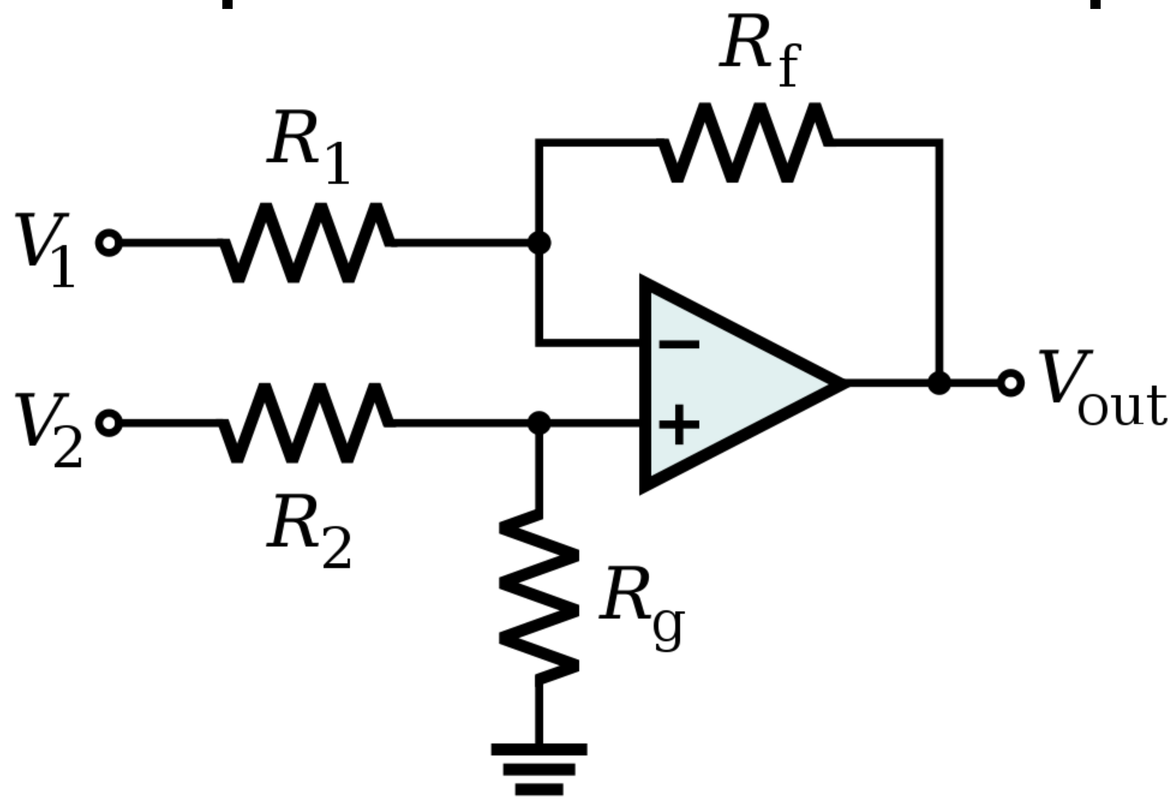
$$V_{\text{out}} = -\int_0^t \frac{V_{\text{in}}}{RC}\,\mathrm{d}t + V_{\text{initial}}$$

Op-Amp Summing Amplifier



$$V_{\text{out}} = -R_{\text{f}} \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n} \right)$$

Op-Amp Differential Amplifier



$$V_{out} = \frac{(R_f + R_1)\,R_g}{(R_g + R_2)\,R_1} V_2 - \frac{R_f}{R_1} V_1$$

If $R_1 = R_2$ and $R_f = R_g$: $$V_{out} = \frac{R_f}{R_1}(V_2 - V_1)$$

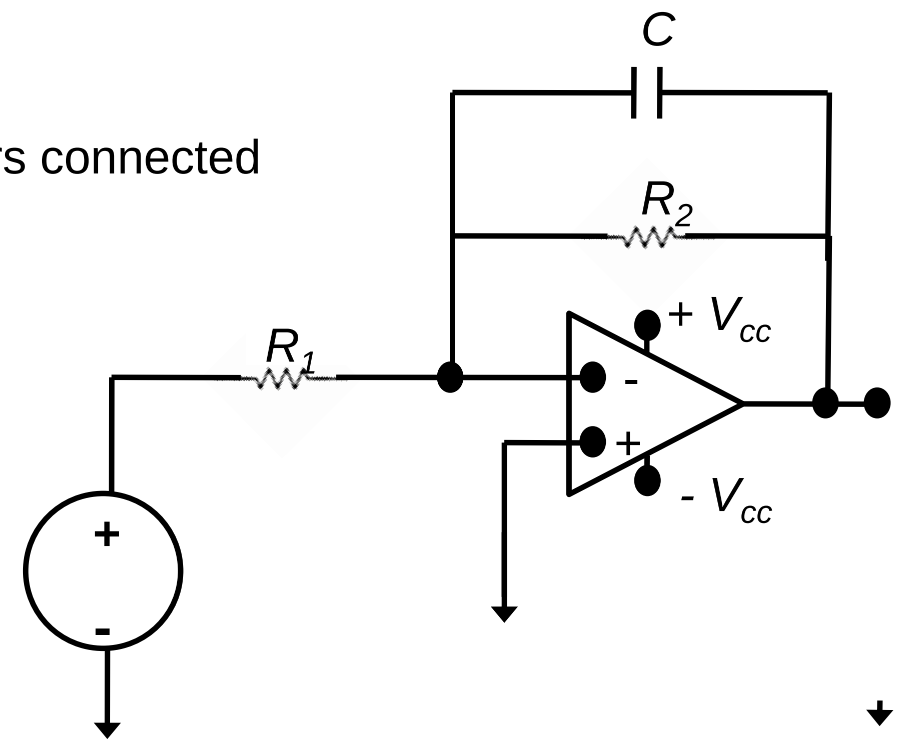
Applications of Op-Amps

Filters

Types:

- •Low pass filter
- •High pass filter
- •Band pass filter
- •Cascading (2 or more filters connected together)

Low pass filter



Low pass filter transfer function➔

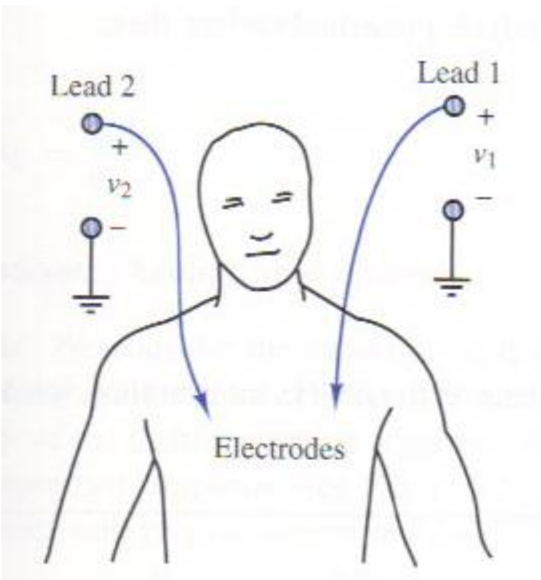
$$H(s) = \frac{-R_2\omega_c}{sR_1 + R_1\omega_c}$$

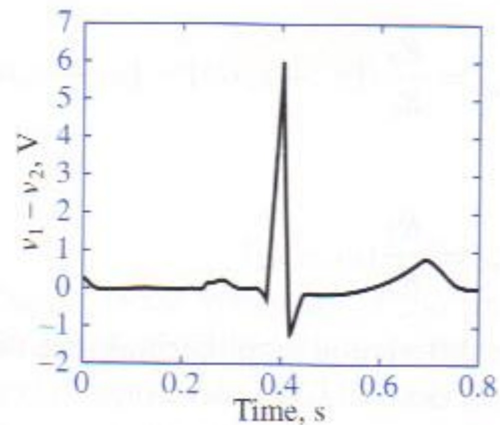
Low pass filter Cutoff frequency ➔

$$\omega_c = \frac{1}{R_2 C}$$

Applications of Op-Amps

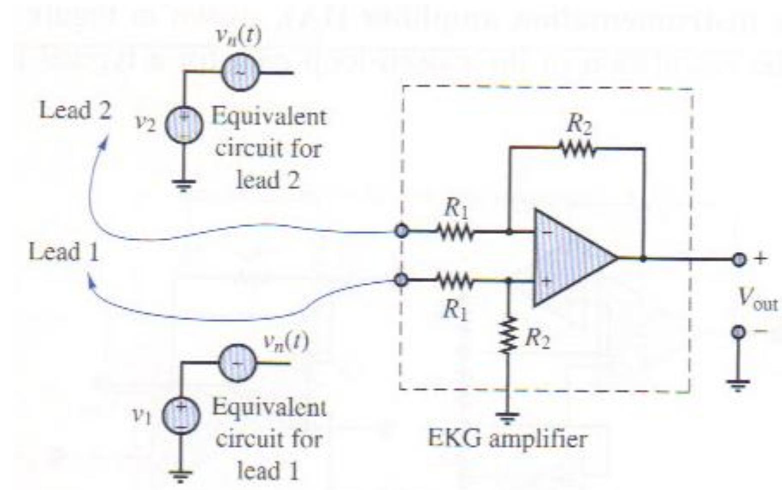
- Electrocardiogram (EKG) Amplification
  - Need to measure difference in voltage from lead 1 and lead 2
  - 60 Hz interference from electrical equipment



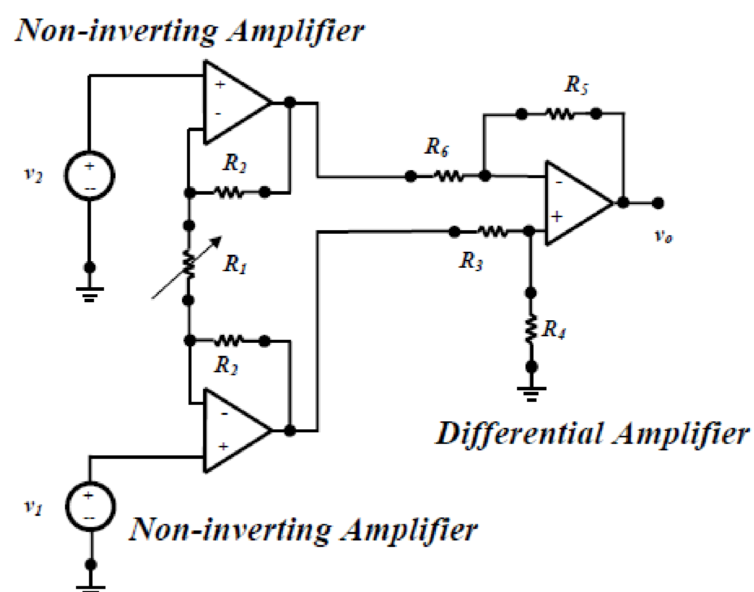


Applications of Op-Amps

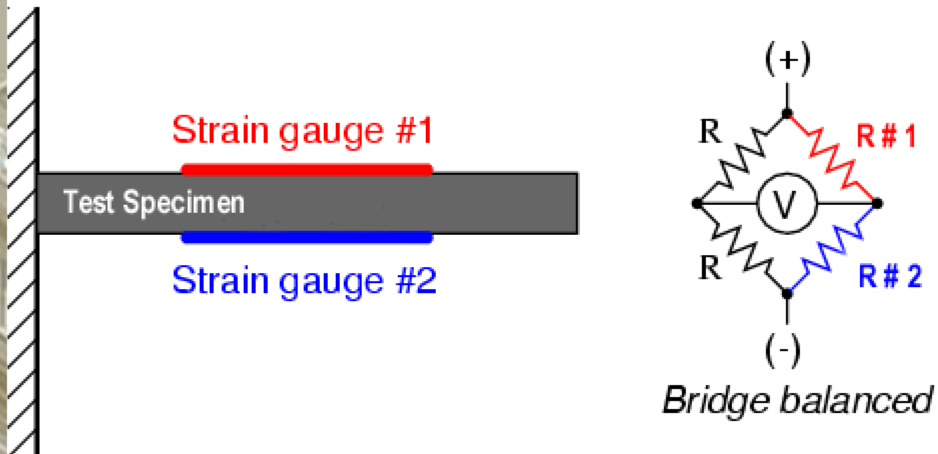
- Simple EKG circuit
  - Uses differential amplifier to cancel common mode signal and amplify differential mode signal



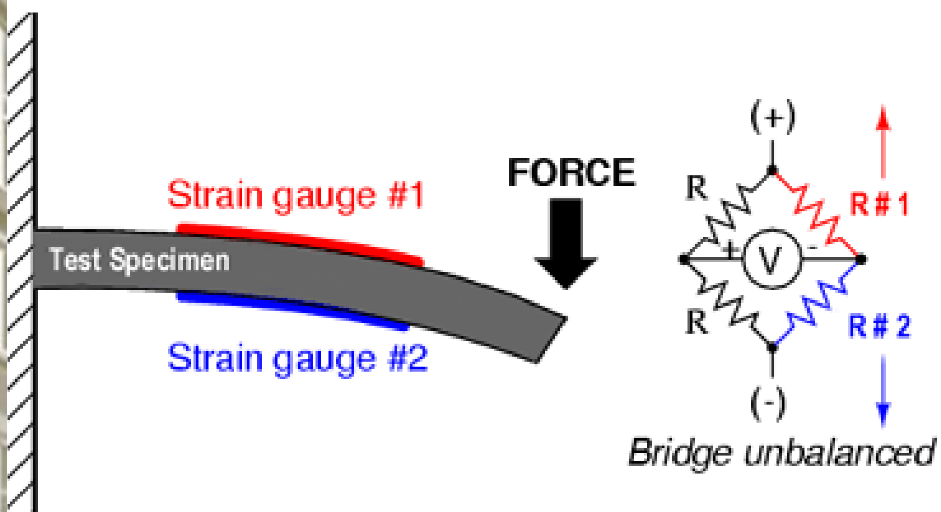
- Realistic EKG circuit
  - Uses two non-inverting amplifiers to first amplify voltage from each lead, followed by differential amplifier
  - Forms an “instrumentation amplifier”



Strain Gauge



Use a Wheatstone bridge to determine the strain of an element by measuring the change in resistance of a strain gauge



(No strain) Balanced Bridge

R #1 = R #2

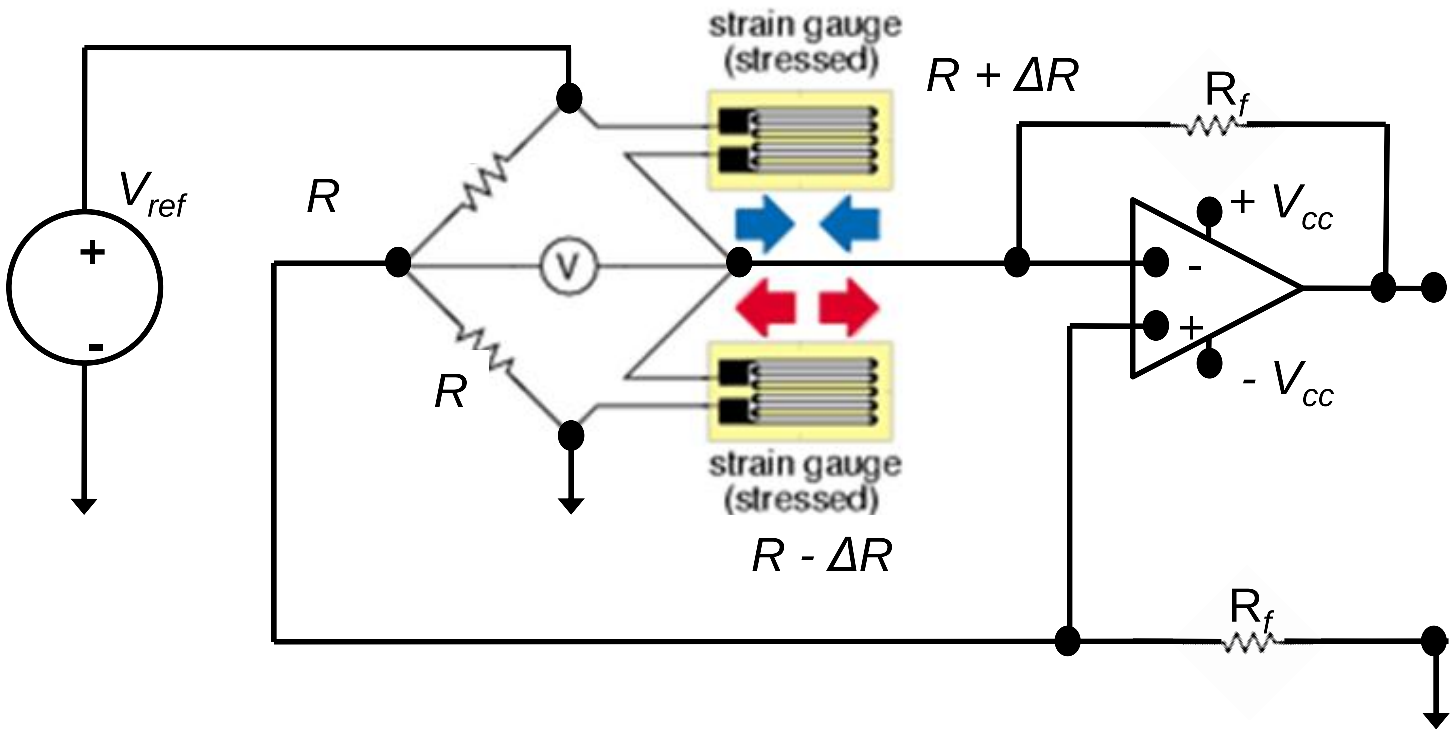
(Strain) Unbalanced Bridge

R #1 ≠ R #2

Strain Gauge

Half-Bridge Arrangement

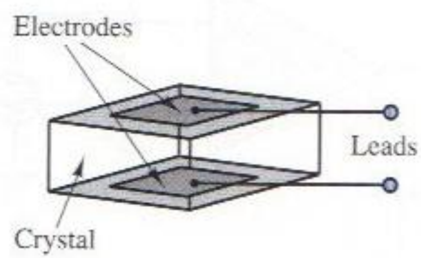
Op amp used to amplify output from strain gauge



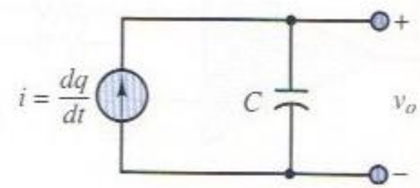
Using KCL at the inverting and non-inverting terminals of the op amp we find that ➔ $\varepsilon \sim V_o = 2\Delta R(R_f/R^2)$

Applications of Op-Amps

- Piezoelectric Transducer
  - Used to measure force, pressure, acceleration
  - Piezoelectric crystal generates an electric charge in response to deformation

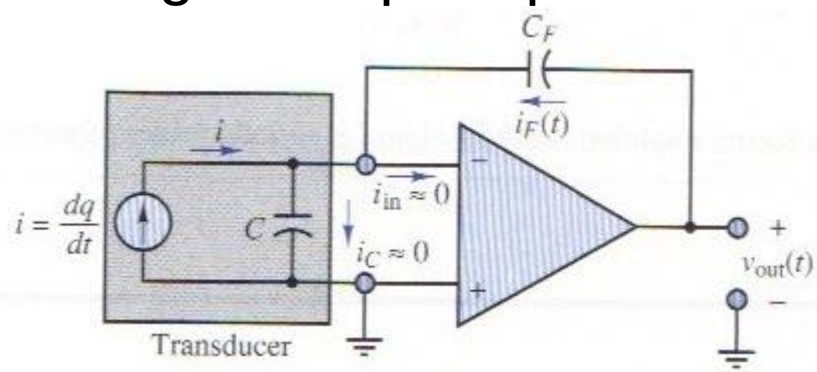


Piezoelectric transducer

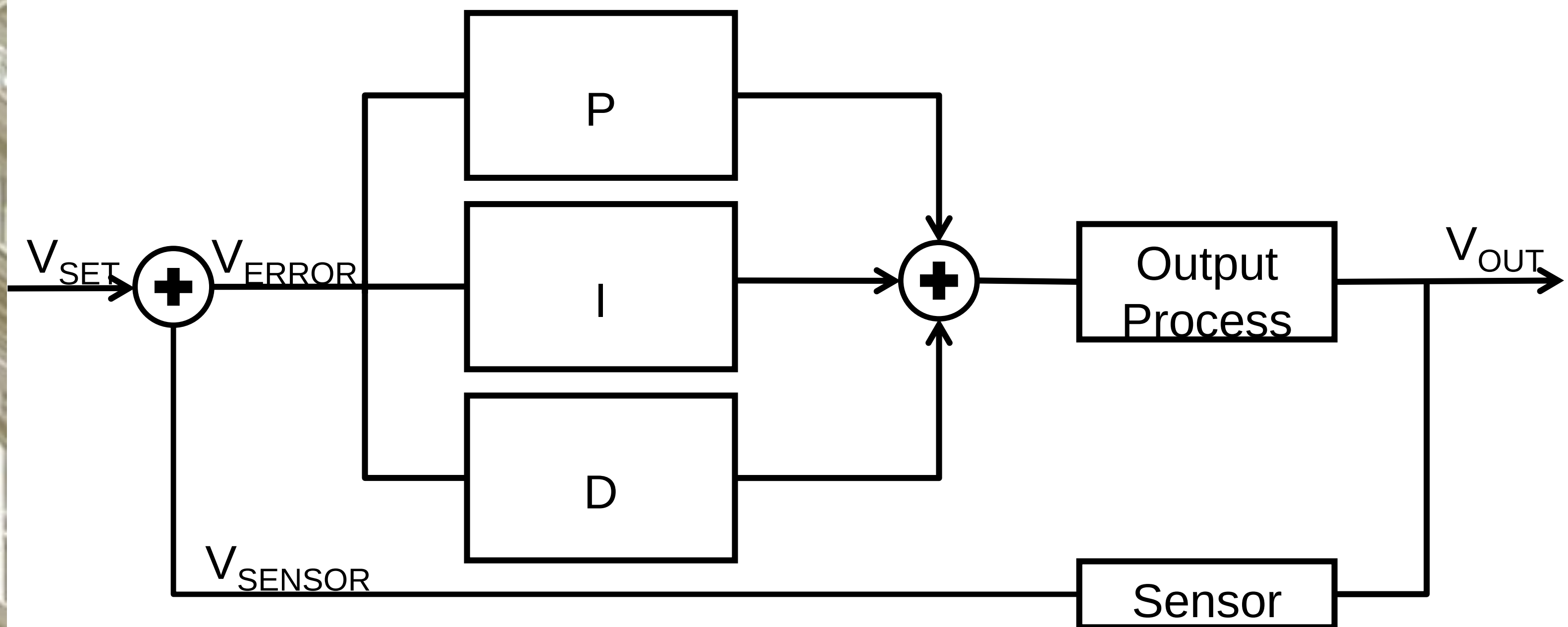


Circuit model

- Use Charge Amplifier
  - Just an integrator op-amp circuit



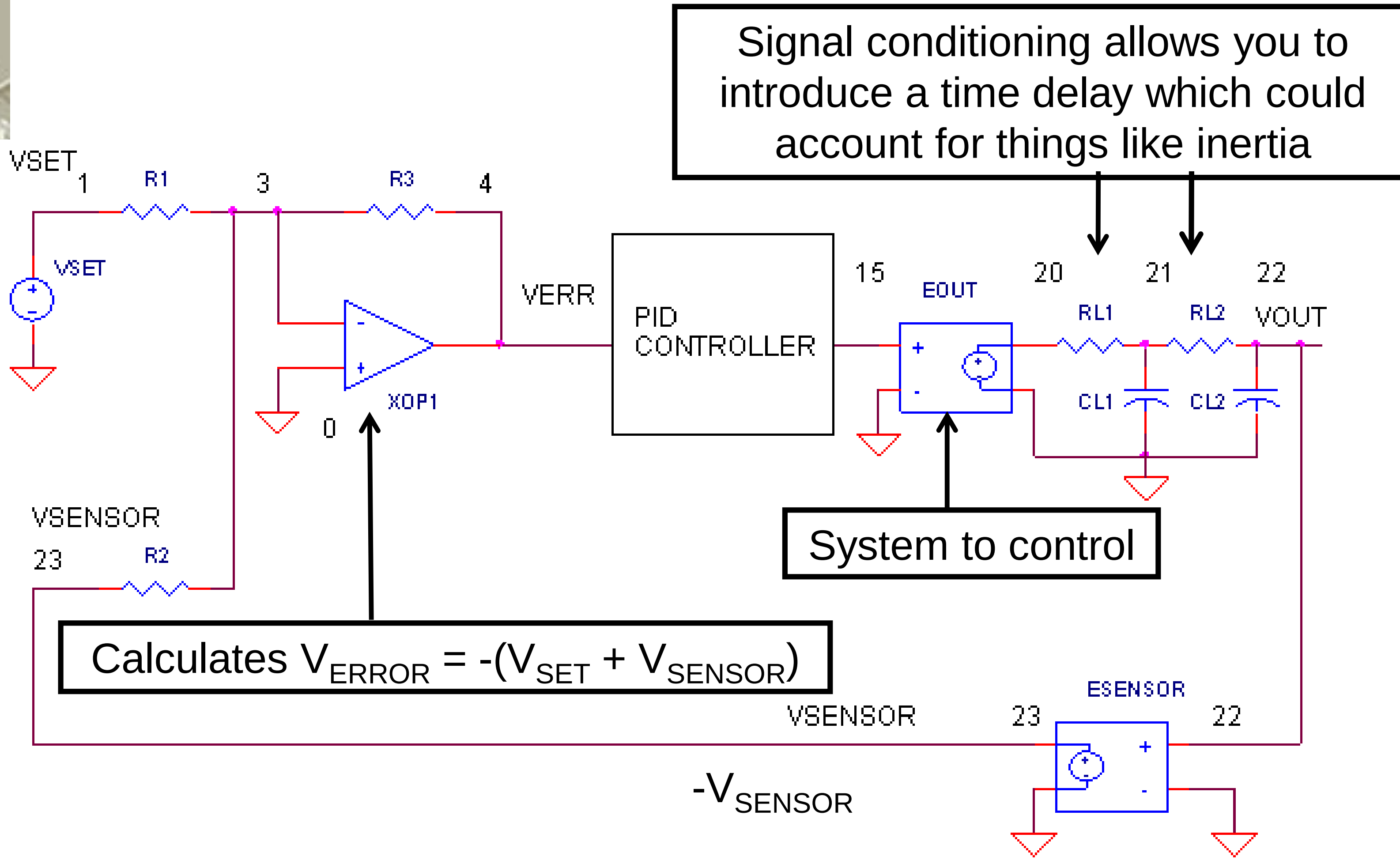
PID Controller – System Block Diagram



- Goal is to have $V_{SET} = V_{OUT}$
- Remember that $V_{ERROR} = V_{SET} – V_{SENSOR}$
- Output Process uses V_{ERROR} from the PID controller to adjust V_{out} such that it is ~V_{SET}

Applications

PID Controller – System Circuit Diagram

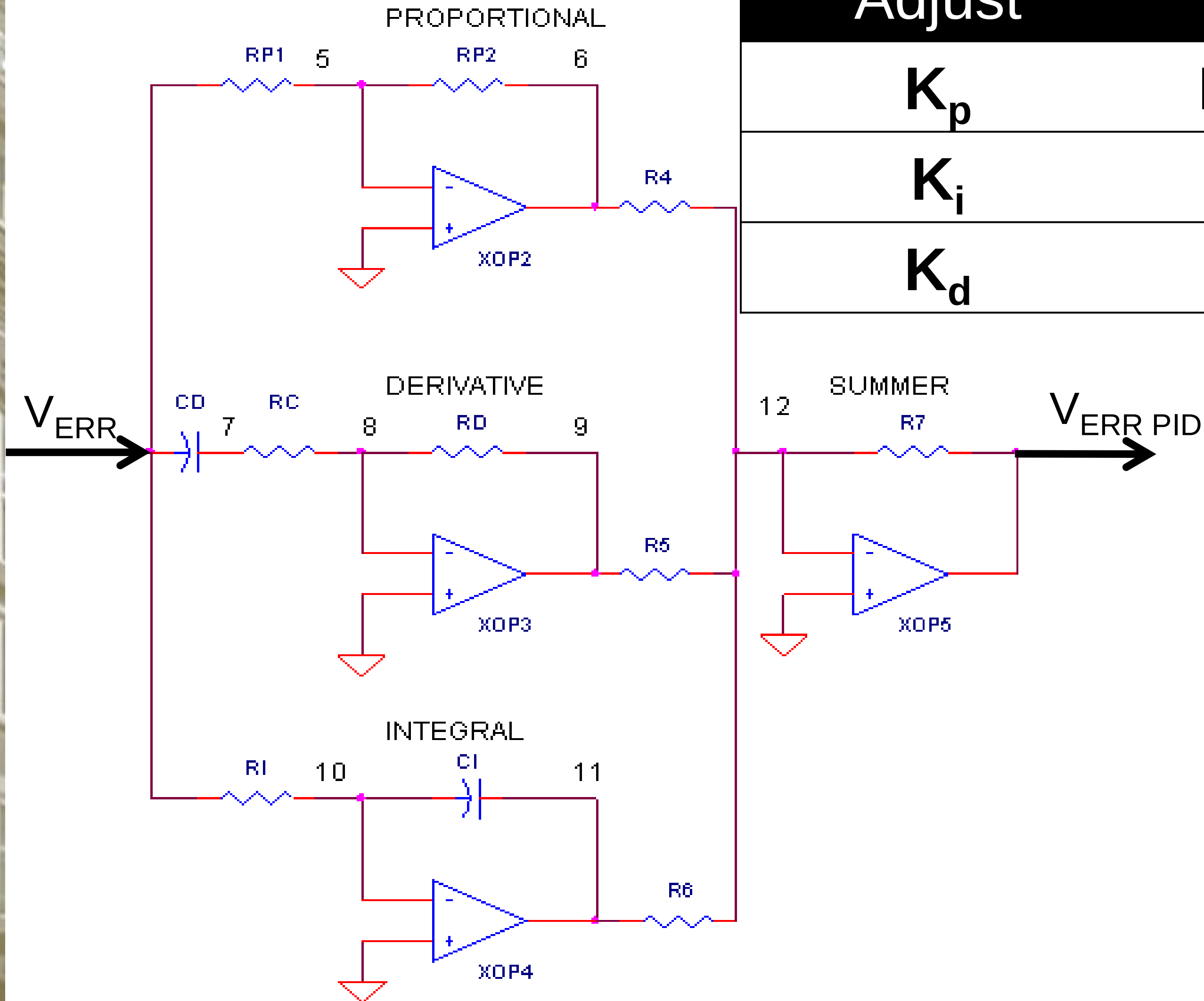


Source:
http://www.ecircuitcenter.com/Circuits/op_pid/op_pid.htm

Applications

PID Controller – PID Controller Circuit Diagram

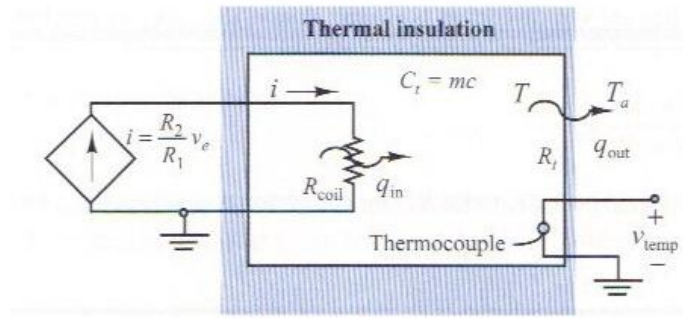
Adjust	Change
K_p	**RP1, RP2**
K_i	**RI, CI**
K_d	**RD, CD**



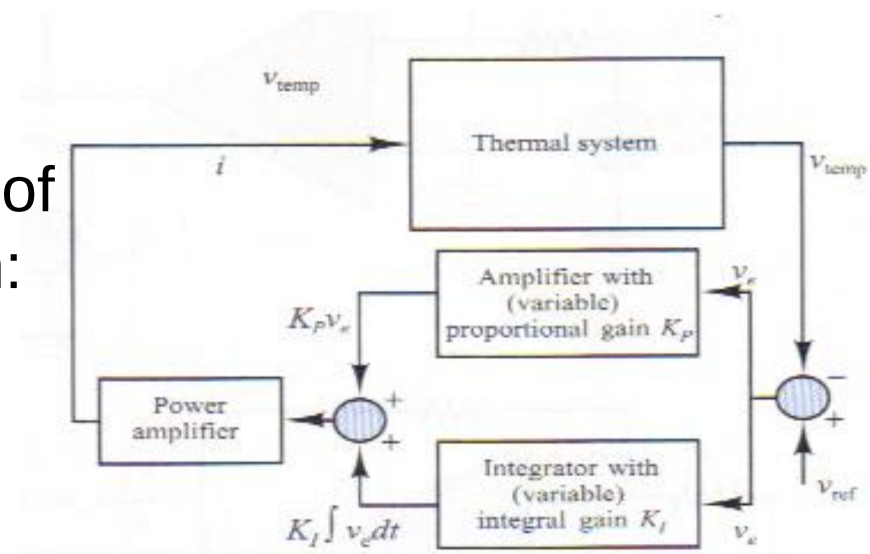
Applications of Op-Amps

- Example of PI Control: Temperature Control

- Thermal System we wish to automatically control the temperature of:



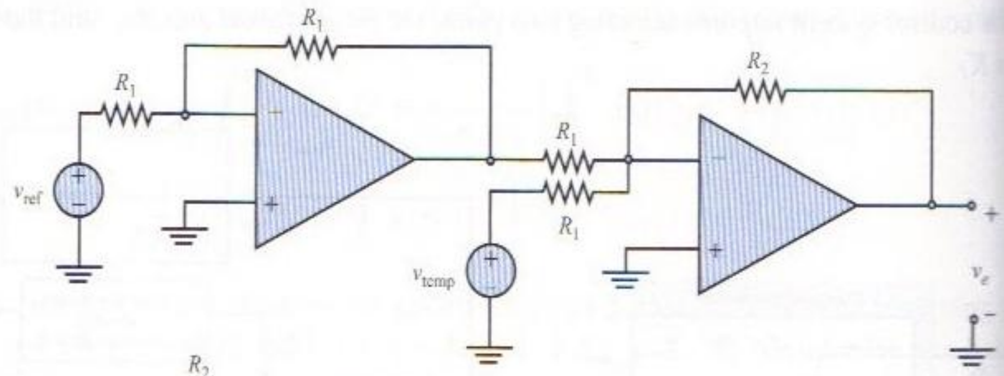
- Block Diagram of Control System:



Applications of Op-Amps

- Example of PI Control: Temperature Control

- Voltage Error Circuit:



- Proportional-Integral Control Circuit: