Measurement Systems

3. Amplifiers

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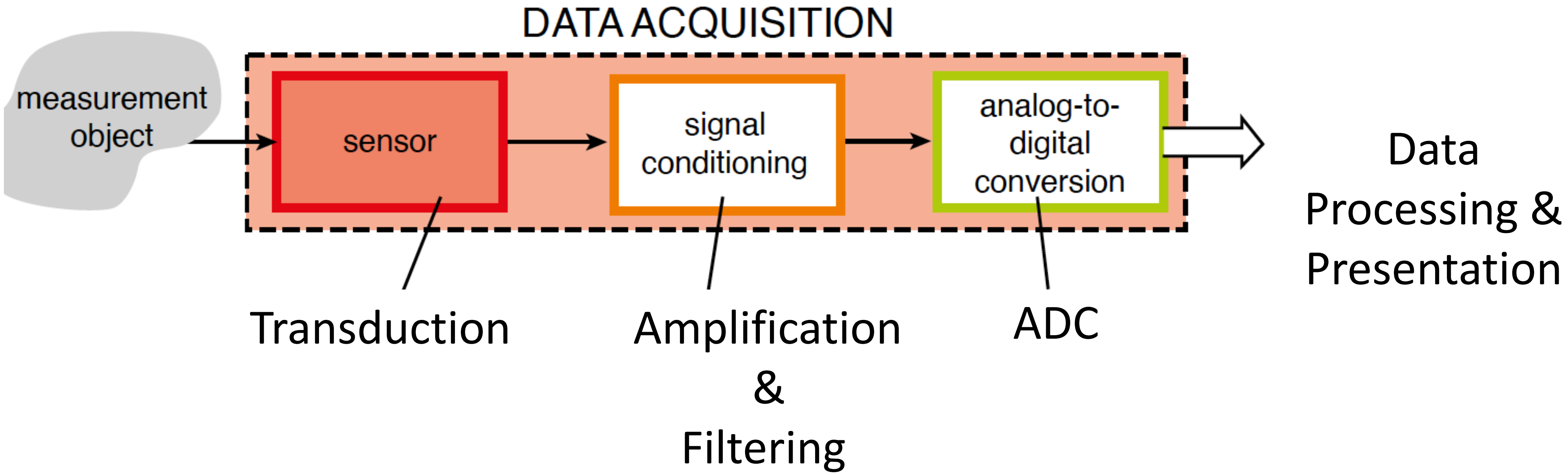
Section 2 – Recap

- Sensors can transduce physical quantities to electrical signals
- Electrical principles can be resistive, capacitive, inductive… etc.
- Output from the sensor is a voltage or current which may be time varying or static
- Often sensors provide very small mV or mA signals which are too small to work with effectively

Overview of measurement systems



Signal Conditioning

Output signal of sensors is often not suitable for ADC input

- too small - input range ADC not used effectively
- too sensitive - load of sensor by ADC yields errors
- too much interference / noise - ADC saturates without filtering
- wrong format - e.g. resistive sensor on voltage-input

Signal conditioning adapts the sensor signal to the ADC

- amplification (scaling)
- buffering
- filtering
- conversion

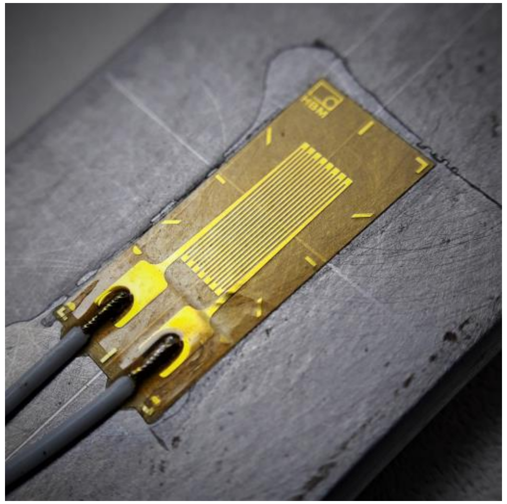
Devices and voltages

Thermocouple:

- Output: ~50μV/°C; at 25°C, output is ~1.25mV.

Strain Gauge:

- Output: Typically outputs <10mV under load.



Photodiode:

- Output: Generates current; typical output voltage can be in the range of 0.1 to 1V under illumination.

Amplification

Thermocouple:

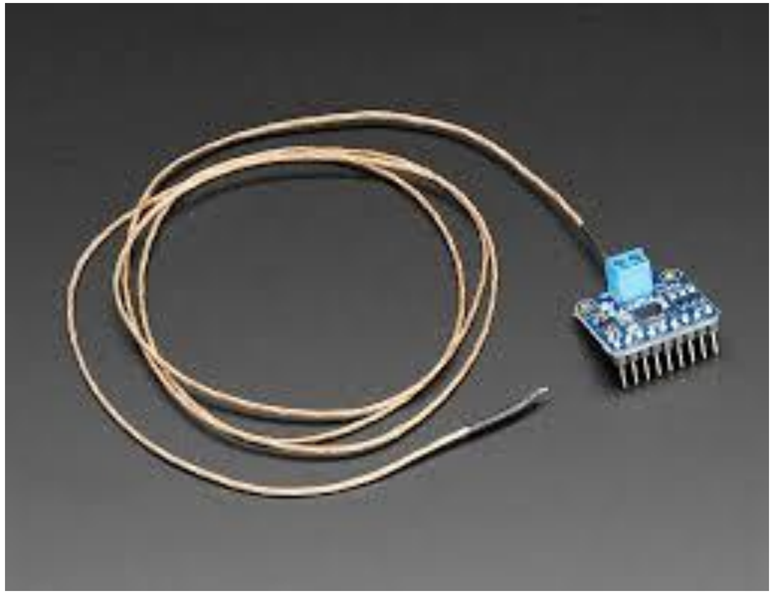
- Requires a gain of 1000 to reach 1.25V for better processing.

Strain Gauge:

- Needs at least 1000x gain to produce a usable signal (e.g., to reach 10V for ADC input).

Photodiode:

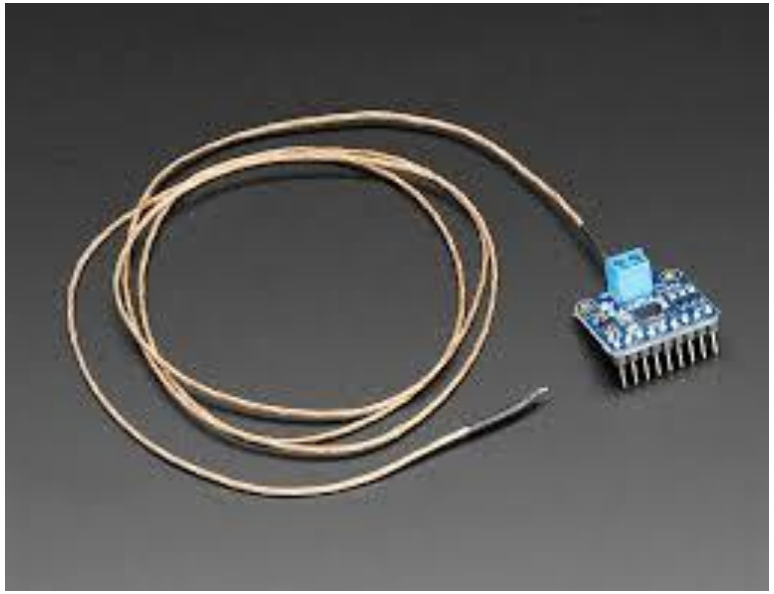
- Often requires a transimpedance amplifier to convert current to voltage, with gains adjustable based on the expected light intensity.



Amplification

Amplification is the process of increasing the amplitude of a signal, whether in terms of voltage, current, or power, e.g.

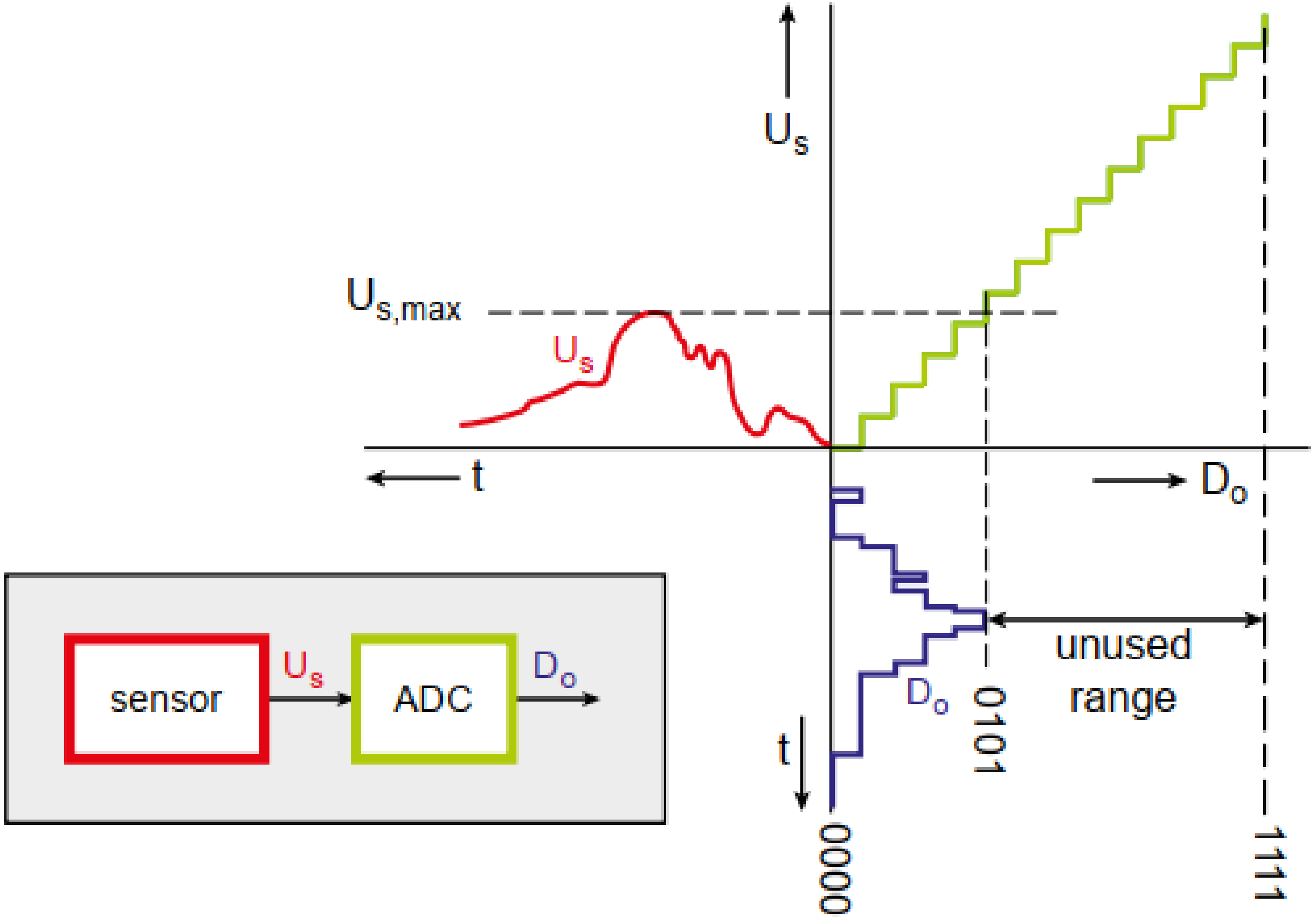
$$V_{out} = A \times V_{in}$$



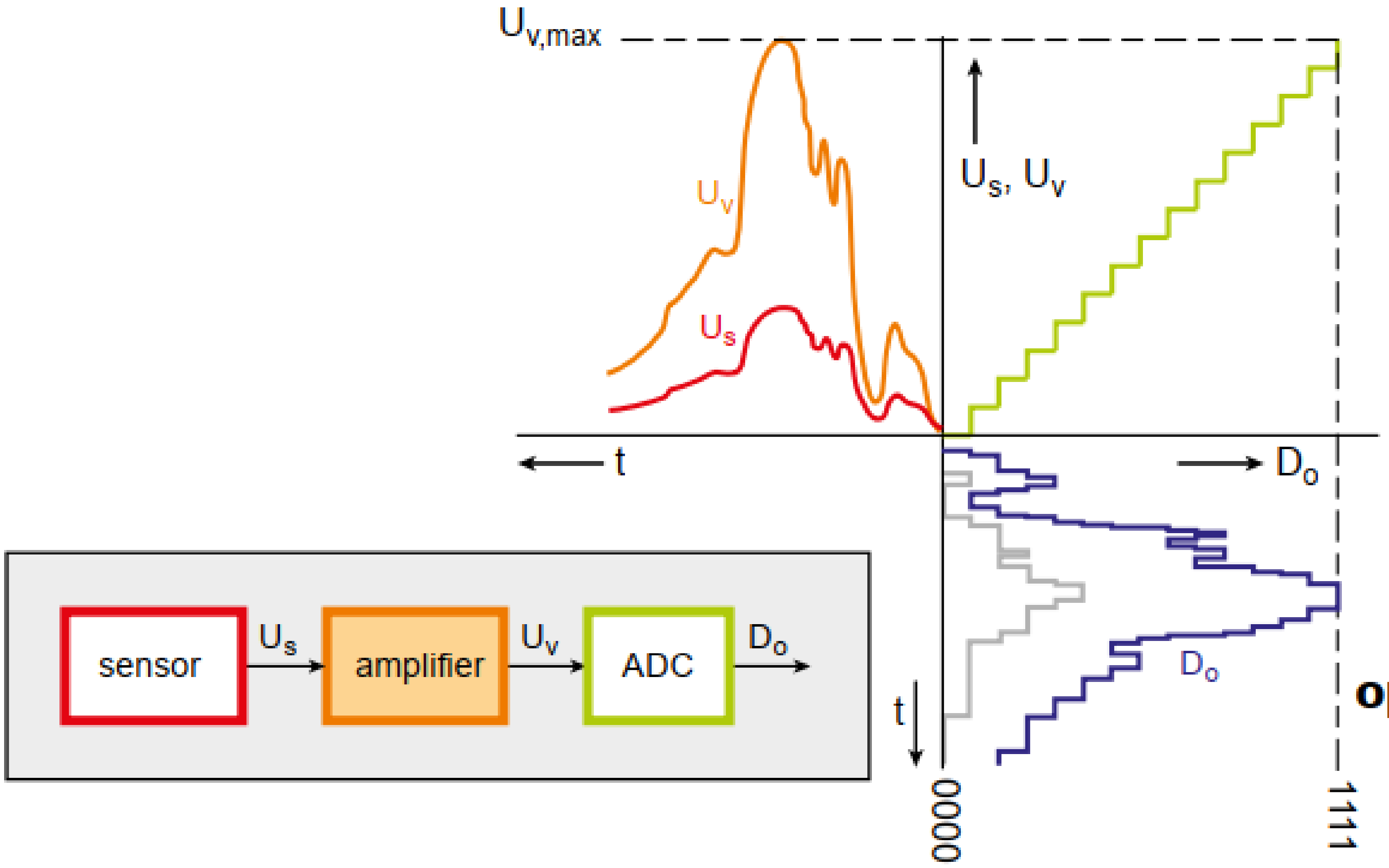
Why Amplification is Important

- **Signal Enhancement:** Strengthens weak signals for better processing, analysis, and transmission.
- **Application Scope:** Essential in audio equipment, communication systems, and measurement devices.

Signal Conditioning



Signal Conditioning

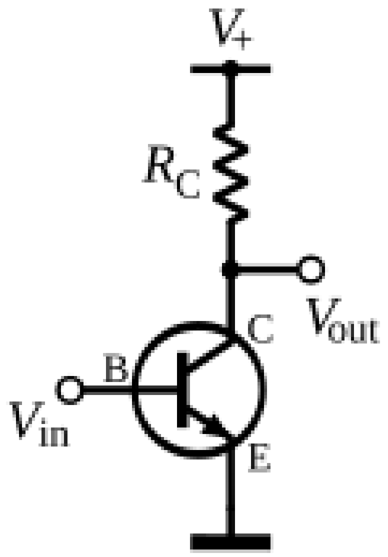


How?
often using
opamp circuits!

Amplification

- **Transistors**: Act as amplifiers in various configurations (e.g., common emitter, common source).

- **Operational Amplifiers (Op-Amps)**: Versatile devices for signal conditioning and processing.

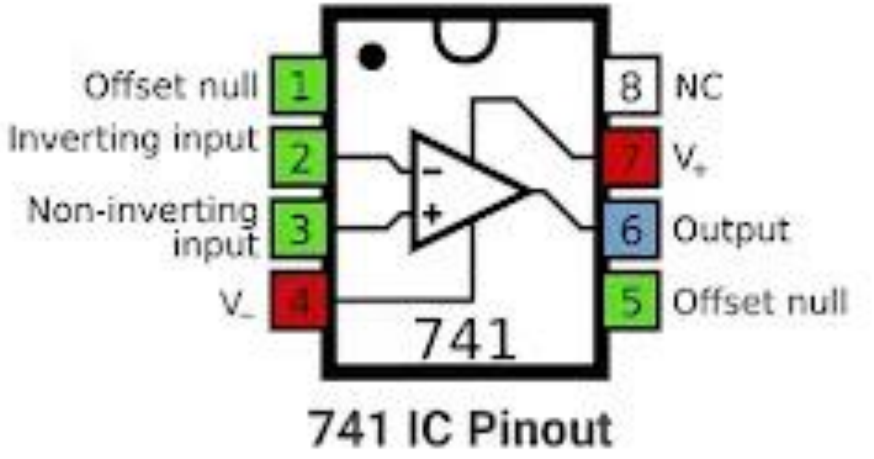


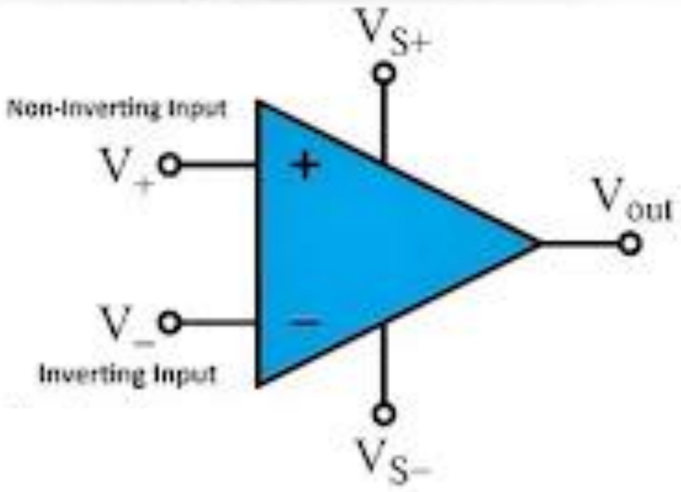
Operational Amplifiers

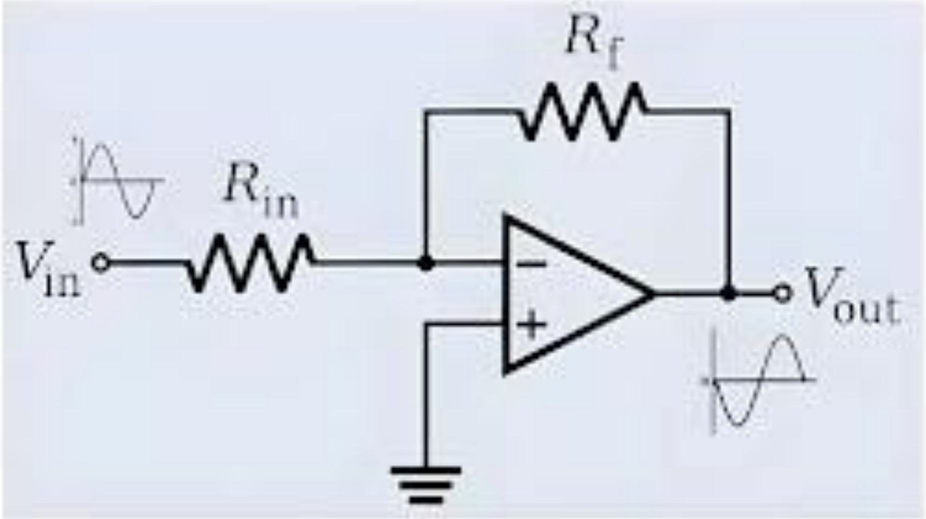
- One of the most common amplierier types is called an Operational Amplifier (op amp)

- The most common (the 741 op amp) is fundamental building block in analog electronics, introduced in the 1960s. Known for its versatility and reliability, the 741 has become a standard reference for understanding operational amplifier principles.

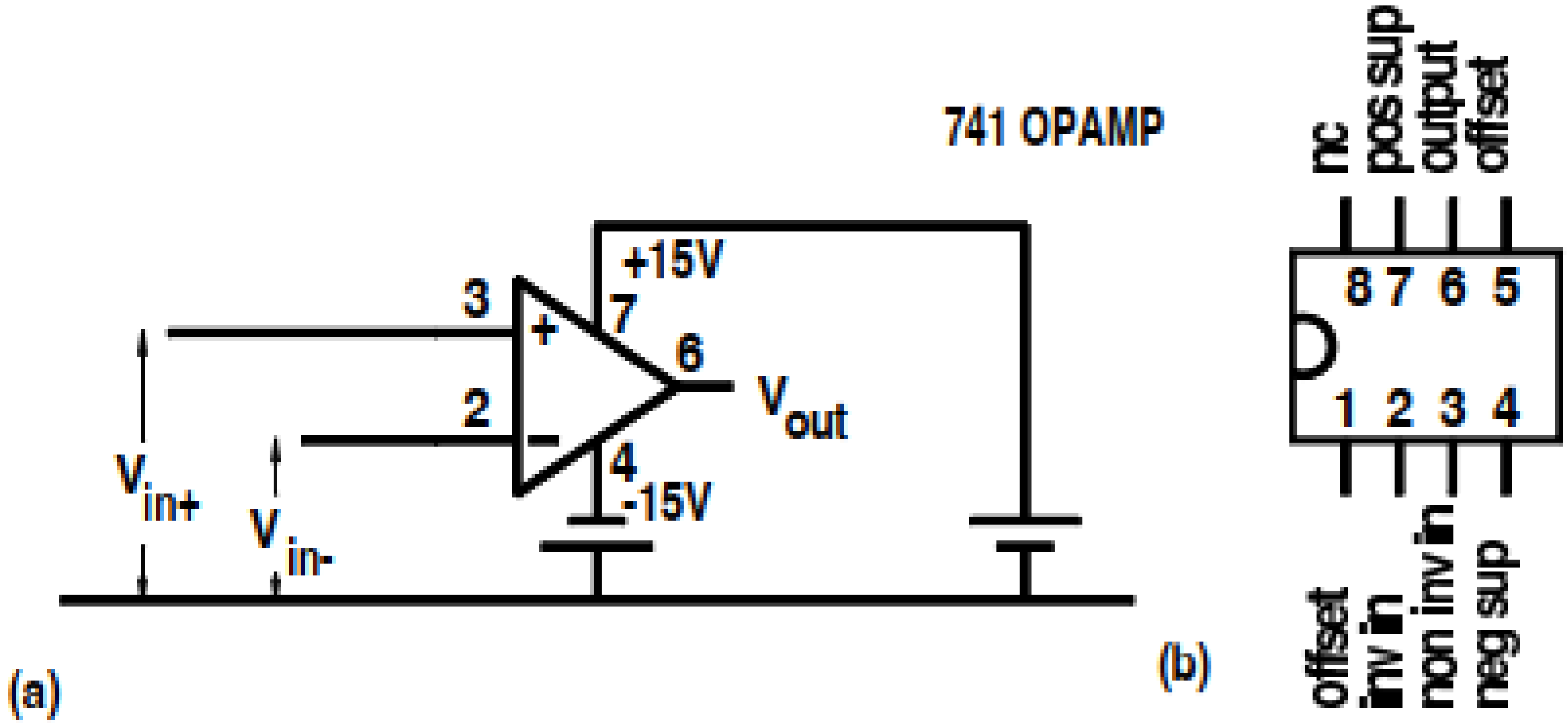
Operational Amplifiers







Operational Amplifiers

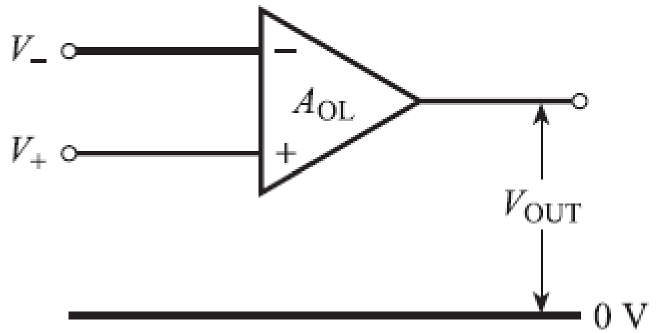


Operational Amplifiers

- An amplifier is an electronic device that produces at its output an amplified version of the signal at its input.

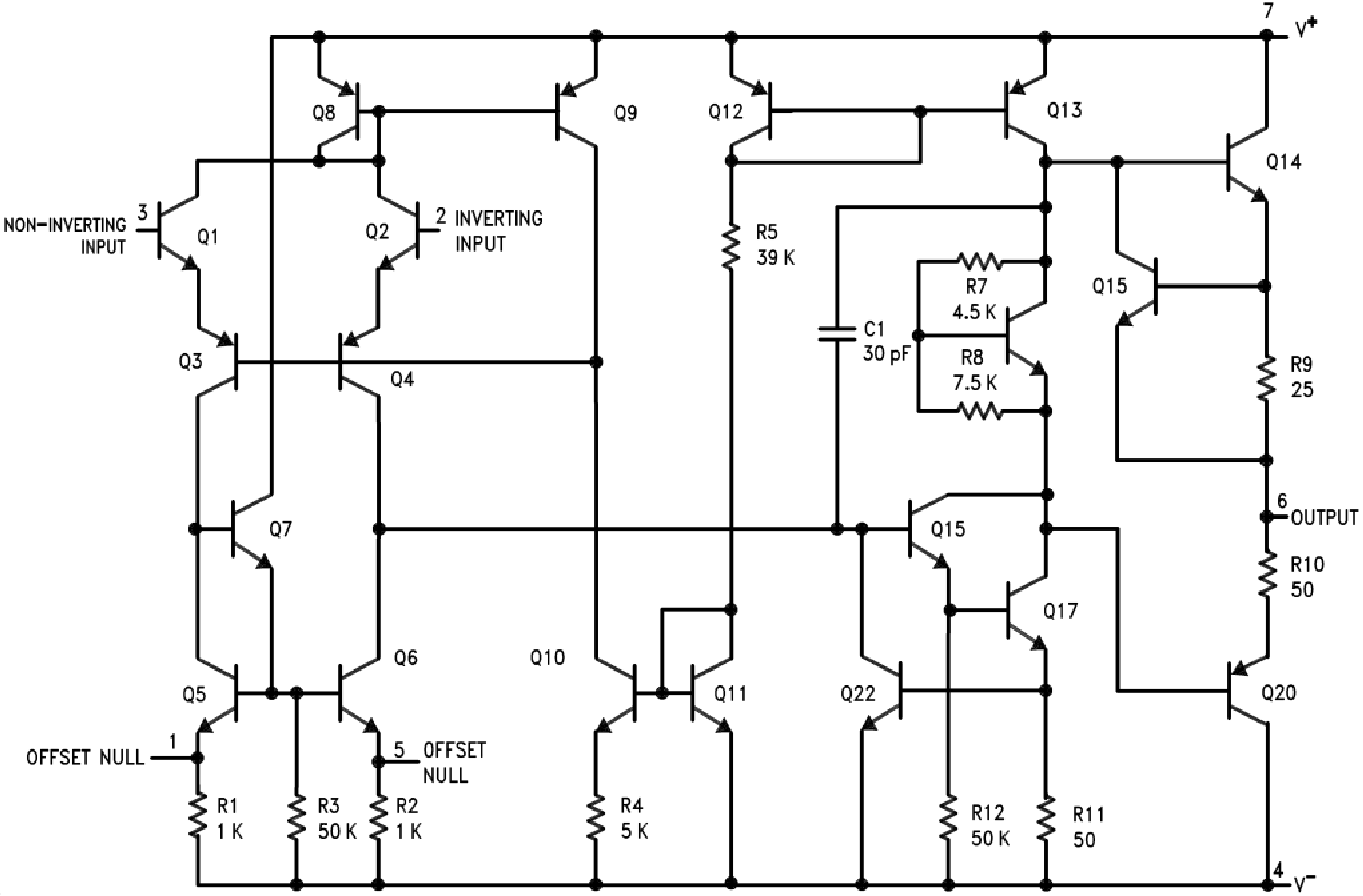
- Forms a basic building block of modern amplification systems and works from DC to >10 kHz AC

- Differential amplifier (op-amp)
  A differential amplifier is one which has two inputs (inverting and non-inverting) and produces at its output an amplified version of the difference between its two inputs



$V_{OUT} = A_{OL}(V_+ - V_-)$

Circuit Diagram



Basic Specifications (741 op amp)

741 Op Amp Properties

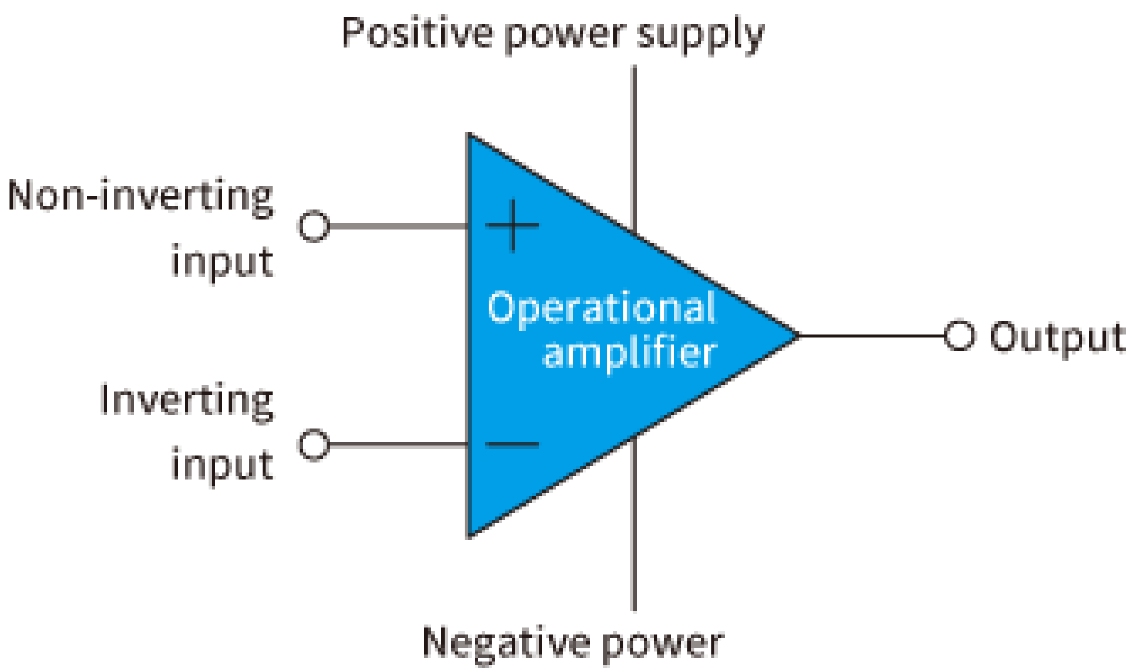
Supply Voltage: $V_{cc} < \pm 15\ \mathrm{V}$

Open Loop Gain: $A_0 = 10^5$

Input Impedance: $Z_i = 10^6\ \Omega$

Output Impedance: $Z_o = 100\ \Omega$

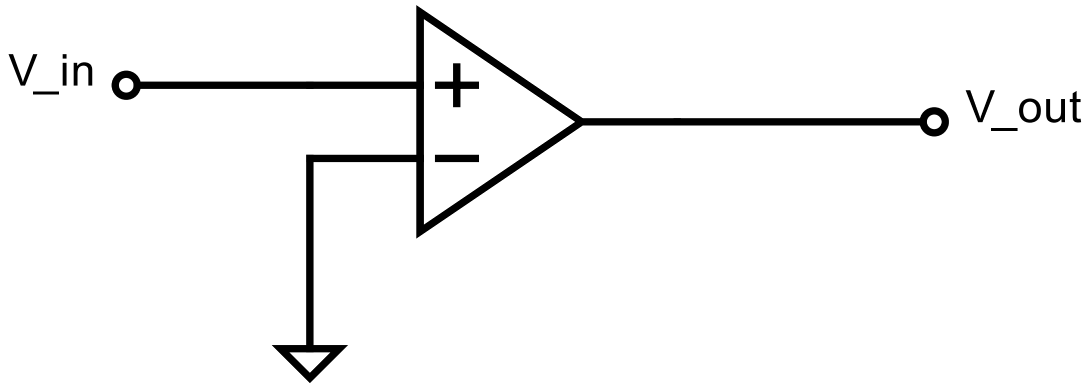
Unity Gain Bandwidth: 10^6



Voltage and Gain

- By default, the op amp will output a voltage of the difference of the two inputs, multiplied by the gain

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

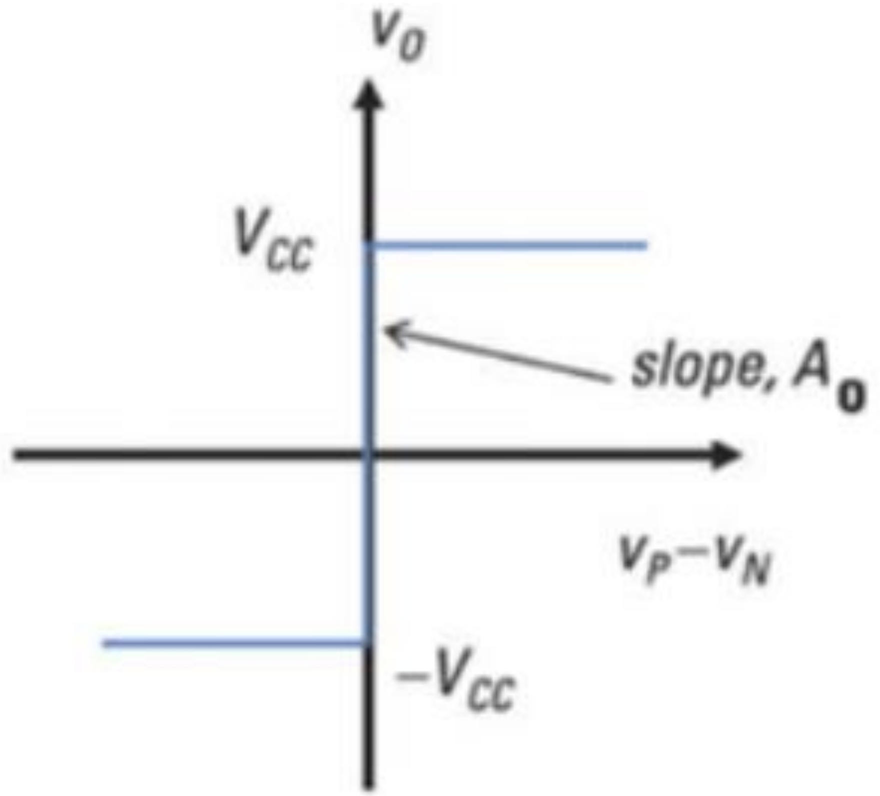


- If V_- is set to 0V, then:

$$V_{out} = A_o V_{in}$$

Open Loop Gain and Saturation

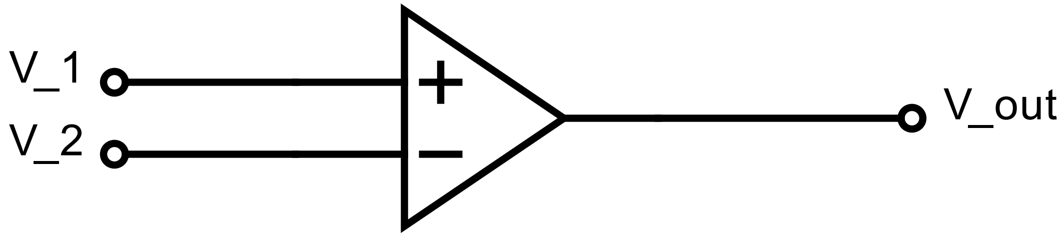
- The open loop gain of 10^5 is quite high, resulting in high sensitivity
- If V_{out} exceeds V_{cc} then the output will saturate at V_{cc}
- Any input voltage of 15 mV or more, will result in an output of 15 V



Application: Comparator

We can exploit open loop gain to compare two voltage inputs

- $Vcc = \pm 5\ \mathrm{V}$
- $V_1 = 2\ \mathrm{V}$
- $V_2 = 1\ \mathrm{V}$



What is the output from the op amp?

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

Voltage and Gain

- Consider the voltage difference between two input terminals in open loop gain

$$V_+ - V_- = \frac{5\mathrm{V}}{A_o} = \frac{5}{10^5} = 10^{-4}\mathrm{V}$$

- Rule 1: When an op amp is in the linear region, the difference between the inverting and non-inverting inputs is approximately zero

Input Impedance

- The op amp has been designed to have an impedance between the two inputs of at least $1\ \mathrm{M\Omega}$

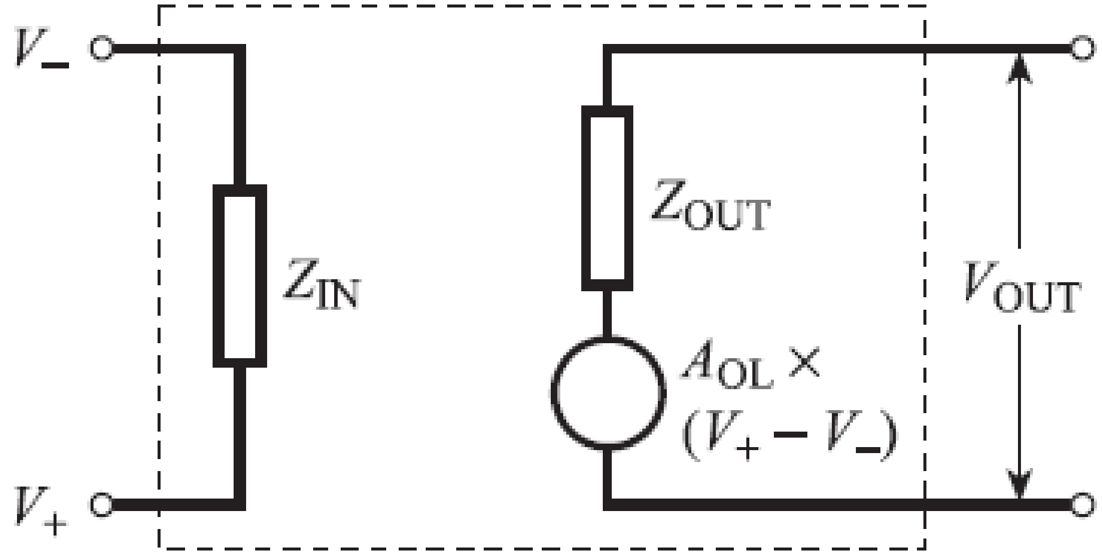
- Since the difference between the two inputs is $\approx 100\ \mu\mathrm{V}$, this means the current flowing is negligible

$$\frac{100\ \mu\mathrm{V}}{10^6\Omega} = 10^{-10}\mathrm{A}$$

- Rule 2: No current flows into the input terminals of the op amp.

- These two rules allow for a large amount of simplification of circuit analysis when using op amps versus transistor-based amplifiers

Equivalent Circuit

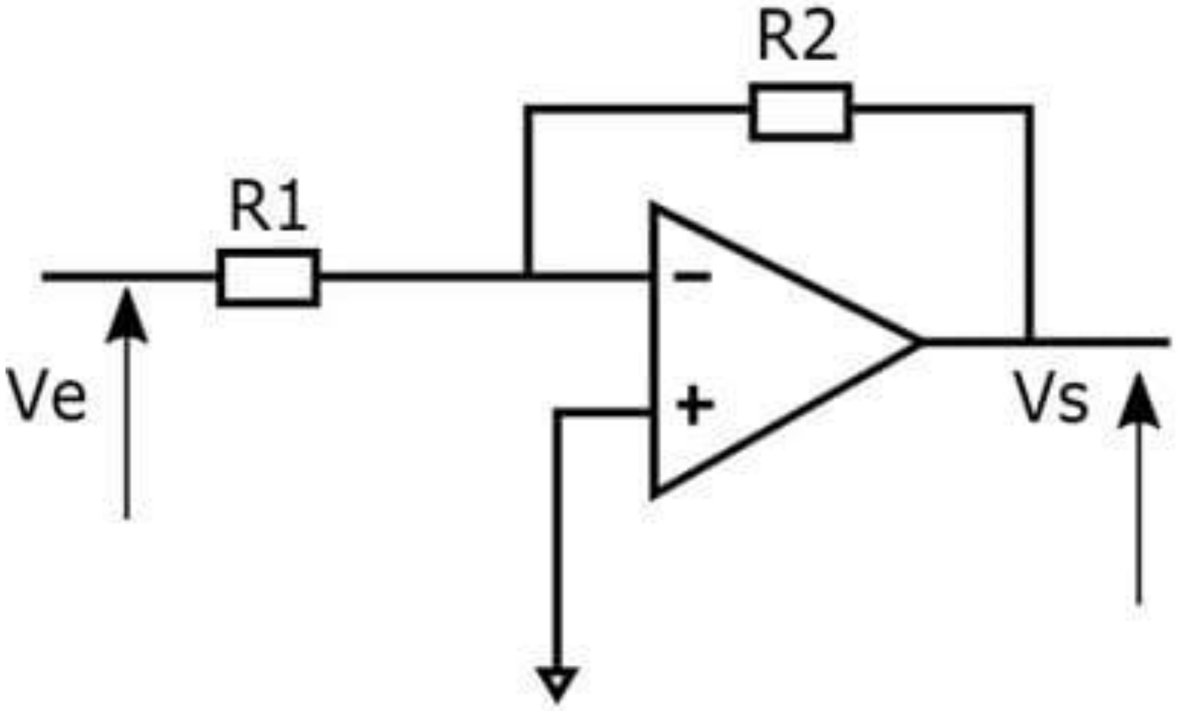


Therefore simplicity we can split an pm amp into two sections:

1. The amplifier input with impedance Z_i
2. The amplifier output: Voltage V (input impedance multiplied by gain of the amplifier: $V = A_V V_i$) in series with an output impedance Z_o

Inverting op amp

- The following arrangement is called an “inverting op amp”



$$V_S = -V_e \frac{R_2}{R_1}$$

Inverting op amp

- From Rules 1 and 2: $V_{in\_+} \approx V_{in\_} = 0V$ and $I_{in} = I_f$

$$\frac{V_{in} - V_{in\_}}{R_{in}} = \frac{V_{in} - 0}{R_{in}} = I_{in}$$

$$\frac{V_{in} - V_{out}}{R_f} = \frac{0 - V_{out}}{R_f} = I_f$$

Therefore:

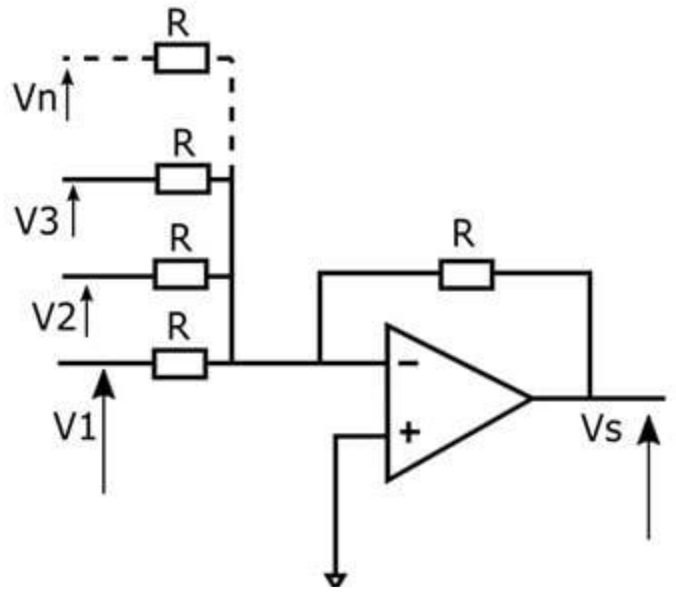
$$\frac{V_{in}}{R_{in}} = -\frac{V_{out}}{R_f}$$

Or:

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

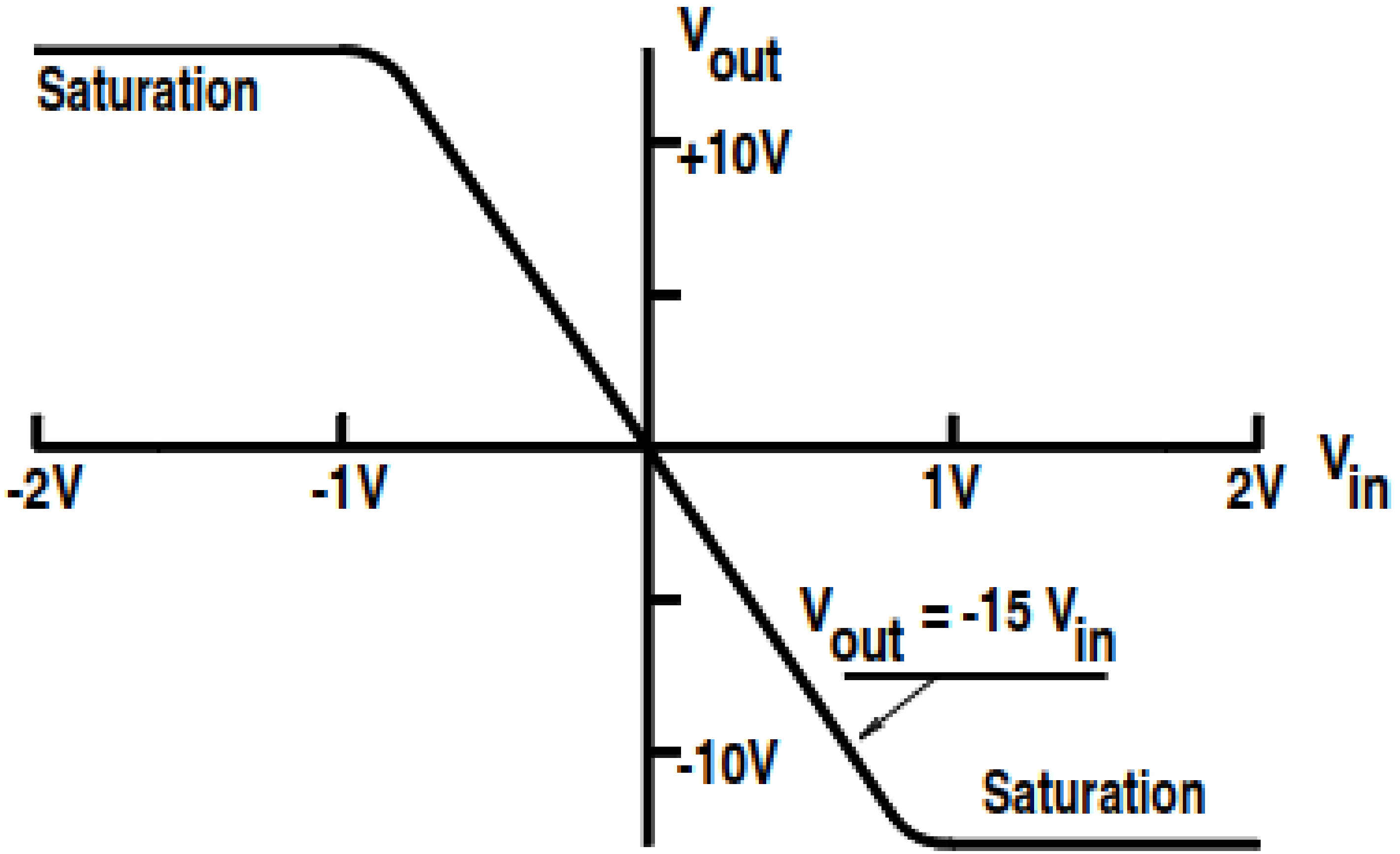
Summing Amplifiers

- By adding resistors in parallel on the inverting input pin of the inverting operation amplifier circuit, all the voltages are summed.



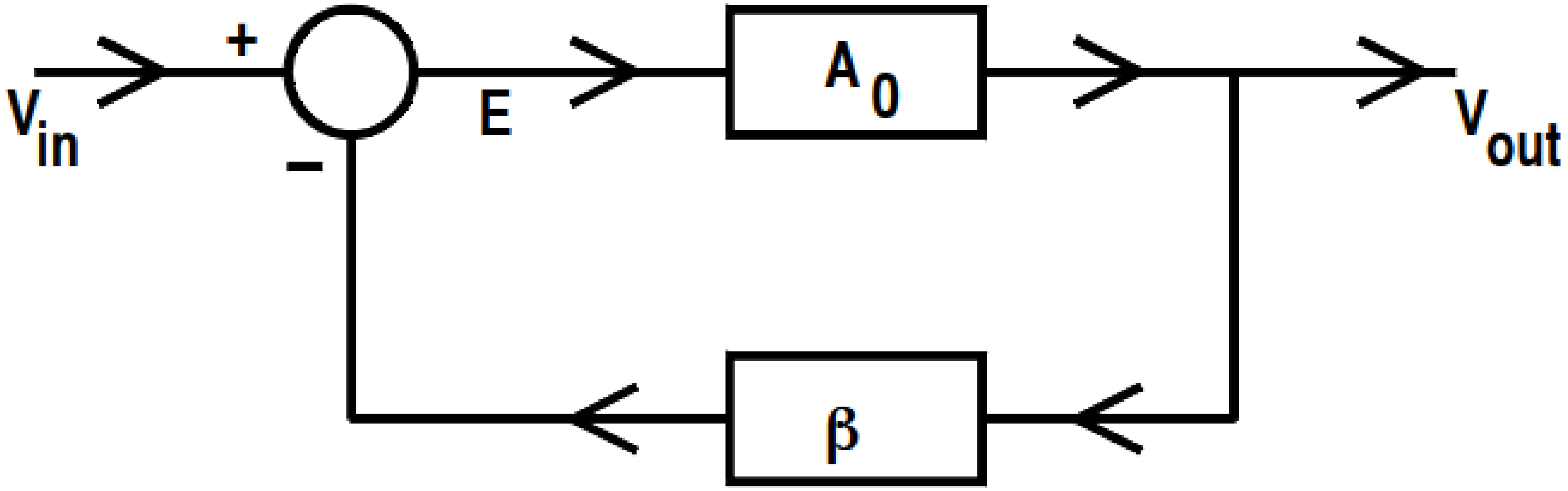
$$V_S = -(V_1 + V_2 + V_3 + \cdots + V_n)$$

Inverting op amp



Feedback

- If we want to increase the range of the linear behaviour of the op amp, we can feed a portion of the output back to the inverting input of the op amp.



$$V_o = E \times A_o = (V_{in} - \beta V_{out}) \times A_o$$

Feedback

- Or more simply:

$$A_v = \frac{V_{out}}{V_{in}} = \frac{A_o}{1 + A_o\beta} = \frac{1}{\frac{1}{A_o}\beta}$$

- Where A_v is the closed-loop gain (sometimes referred to as A_c) and β is the feedback fraction.

- For a 741 op amp, $A_o = 10^5$, then $\frac{1}{A_0}$ is very small compared to β, thus the gain simplifies to:

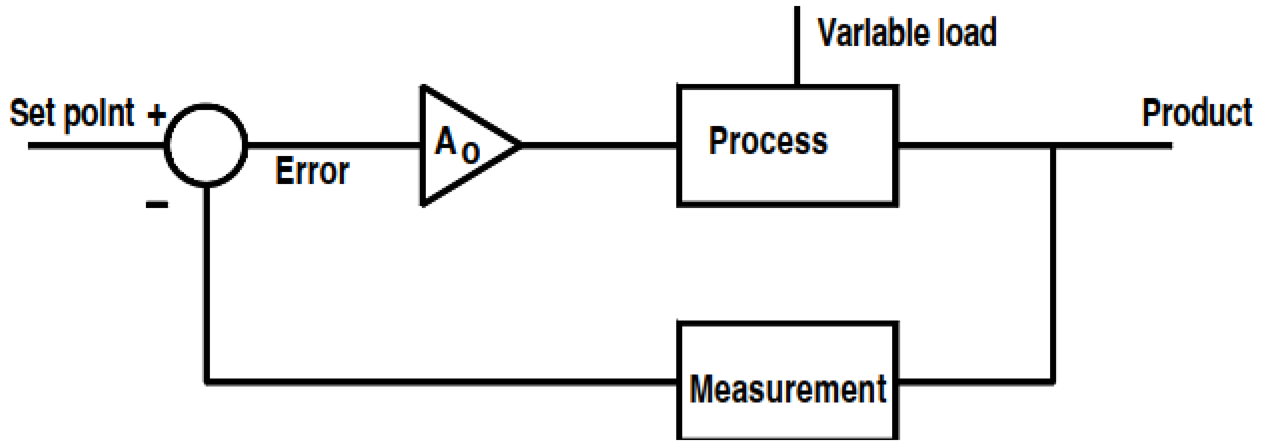
$$A_v \approx \frac{1}{\beta}$$

$$V_o = E \times A_o = (V_{in} - \beta V_{out}) \times A_o$$

Control Loops

- One characteristic of control systems is the control loop between a fixed point and some error.

- Negative feedback can be used to maintain a set operating point (temp/pressure)



Application	Set point	Measurement	Control method	Load
DC power supply	Voltage	Voltmeter	Transistor	Current drawn
Hot water heater	Temperature	Thermometer	Heater	Water flow
Traffic	Speed limit	Speedometer	Accelerator	Road incline
Economy	Growth	Inflation	Interest rates	Rest of world

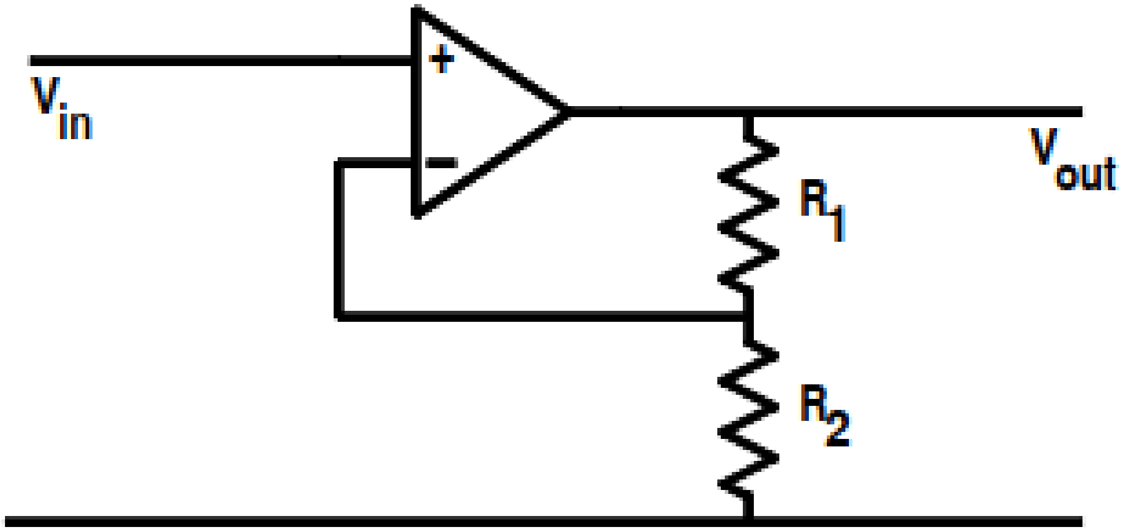
Non-inverting op amp

- The fraction of the output voltage can be determined using a potential divider at the op amp output

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

- Or simplified:

$$A_c = \frac{V_{out}}{V_{in}} = \frac{R_1 + R_2}{R_2} = 1 + \frac{R_1}{R_2}$$



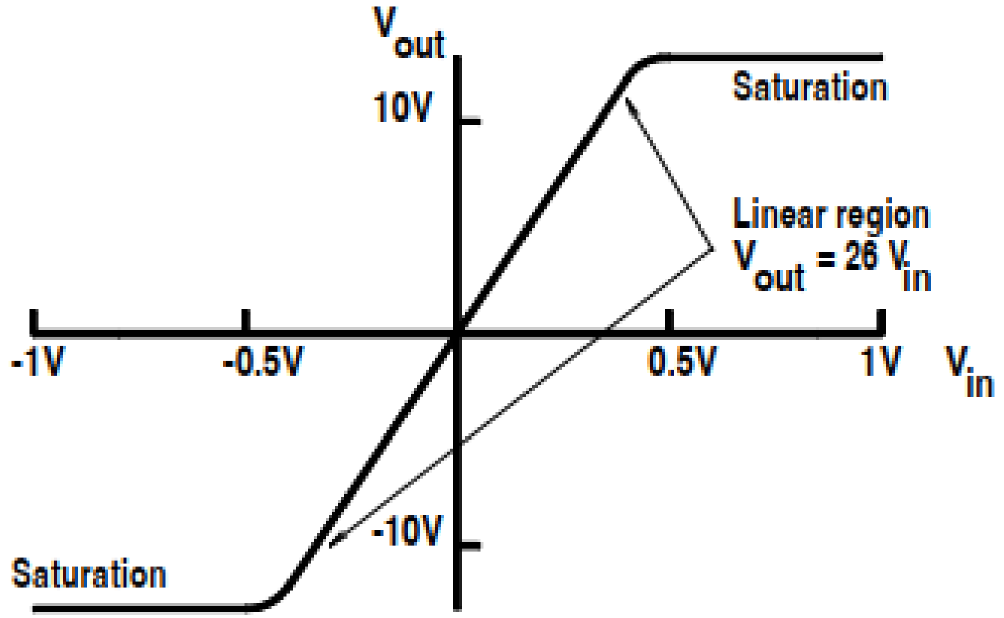
Non-inverting op amp

- Closed-loop Gain:

$$A_c = \frac{R_1 + R_2}{R_2}$$

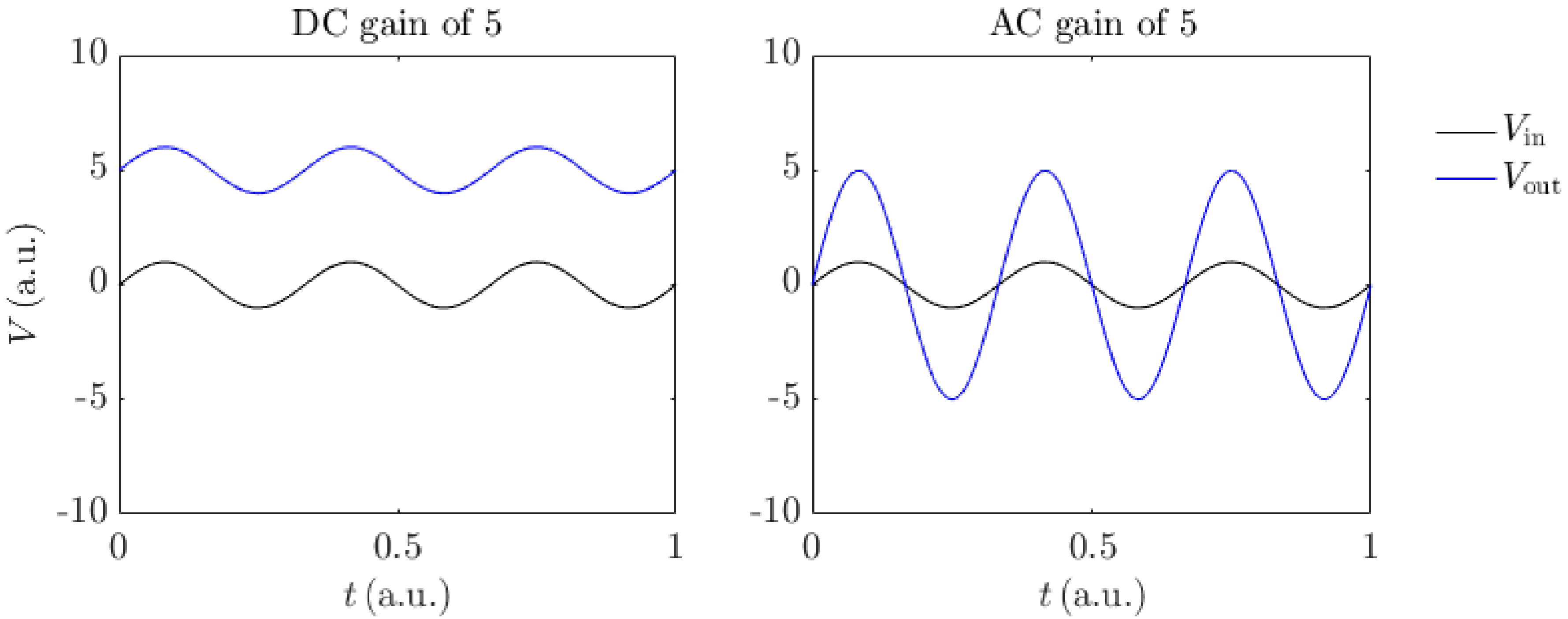
- Feedback Fraction:

$$\beta = \frac{R_2}{R_1 + R_2} \approx \frac{1}{A_c}$$



DC versus AC

- For DC signals, amplifiers raise the voltage rate according to the gain of the circuit
- For AC, we have to consider what is being amplified



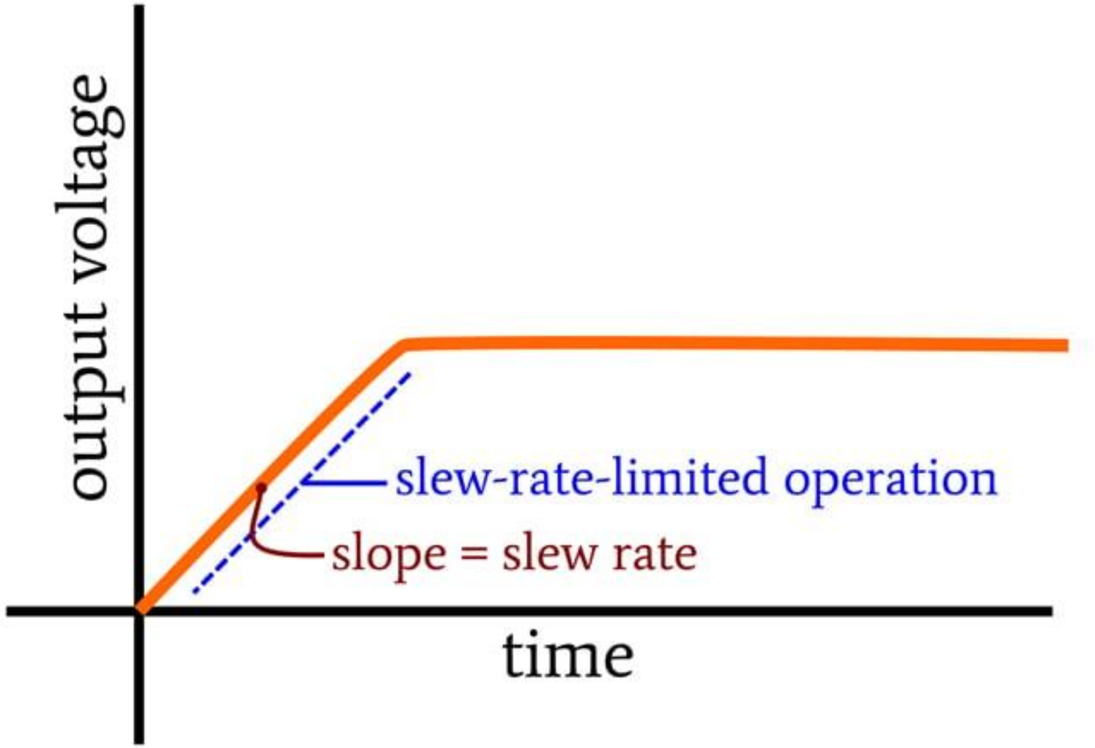
Frequency Response

- Op amps cannot respond instantaneously to a change in input
- Certain op amp components have a frequency response (capacitors, transistors) limiting their maximum frequency usage
- When large voltage differentials are applied to a negatively feedbacked op amp, there may be a delay in the voltage appearing
- As frequency increases, the ability of the op amp to amplify the signal begins to reduce

Slew Rate

- The Slew Rate is defined as the maximum rate of voltage change that can be generated by the op amp circuitry

- It is a measured as a voltage relative to time typically around $0.7\ \mathrm{V} \cdot \mu\mathrm{s}^{-1}$ for a 741 op amp



Gain Bandwidth Product

- Op amps have a fixed gain/bandwidth relationship with the gain being a function of frequency for smaller signals (i.e. the output isn't limited by the slew rate).

$$\text{gain} \times \text{bandwidth} = \text{constant}$$

- The 741 has a GBW around 1 MHz (not listed in this datasheet) meaning that with a 1 MHz input the max gain is one (the gain drops off as frequency increases).

- For the 741: $\text{gain} \times \text{bandwidth} = 10^6$

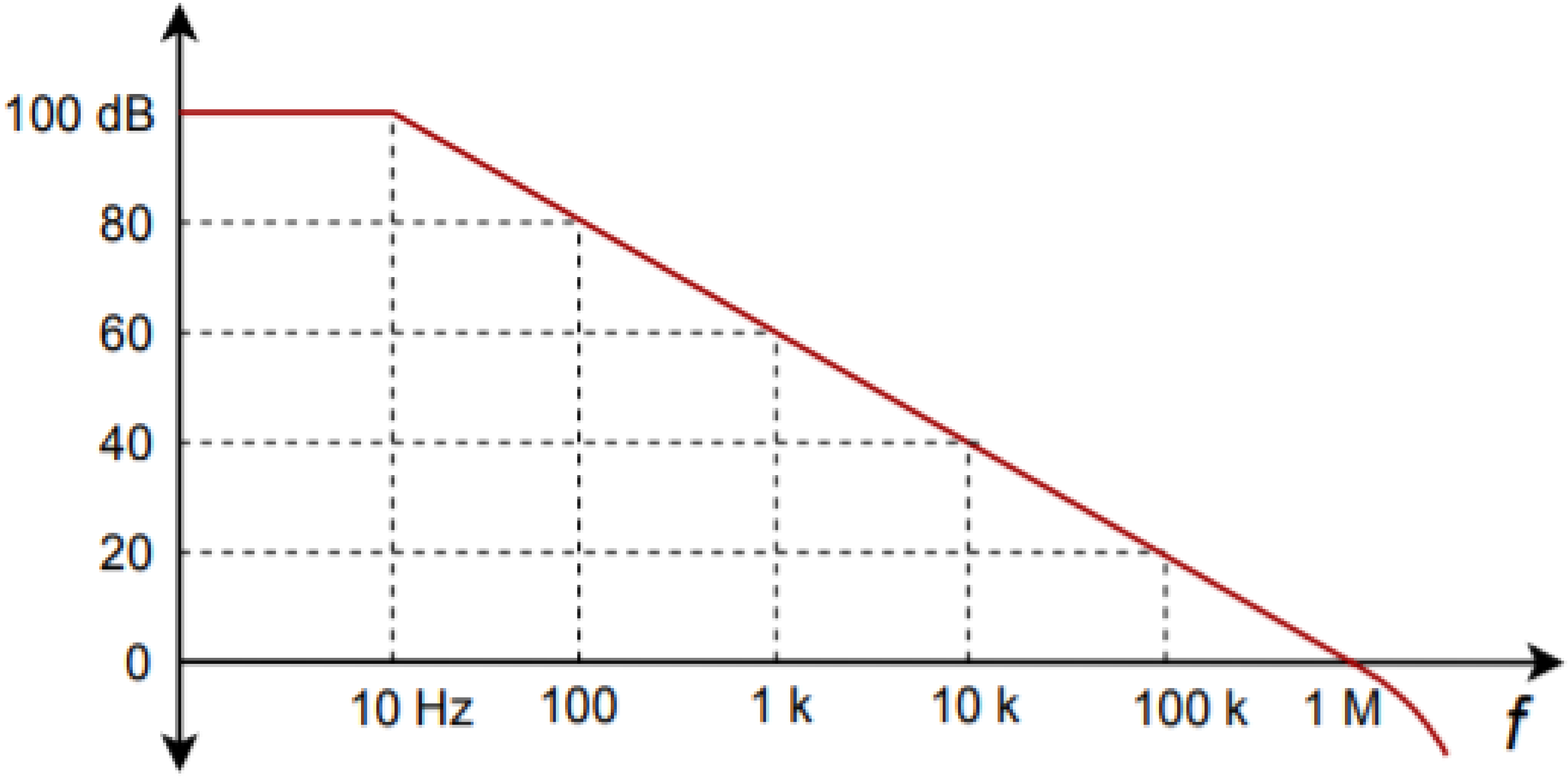
Gain Bandwidth Product

- In actuality, the gain is less than one because GBW is defined as the 3 dB point.

- If the input signal was 100 kHz the max gain would be 10, with a 10 kHz input the max gain would be 100, and so on.

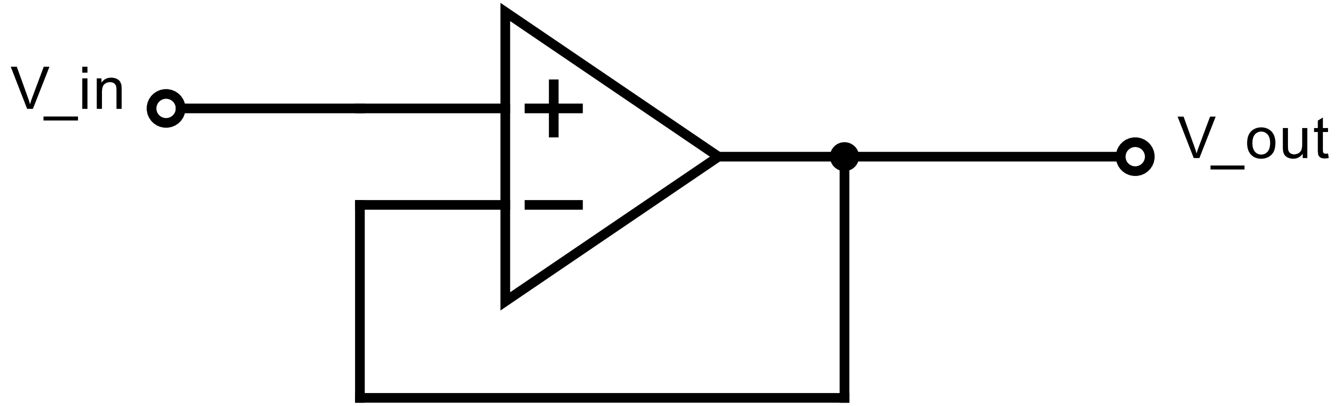
- The 741 is considered a slow op-amp. There are op-amps available with a GBW over 1 GHz

Gain Bandwidth Product



Voltage follower

– Consider this case. What is the output voltage?



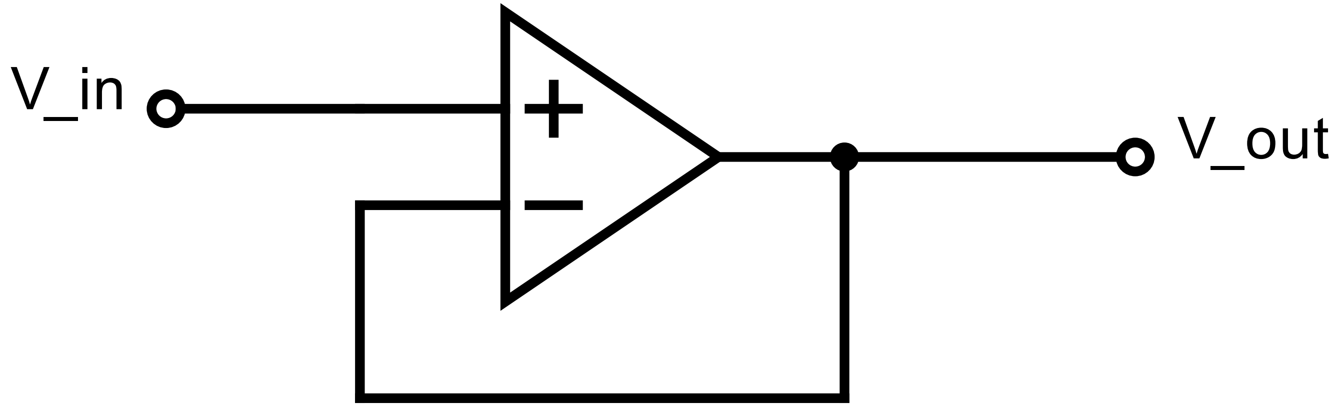
Voltage follower

- From our general op amp equation:

$$V_{out} = A_o(V_+ - V_-) = A_o(V_{in} - V_{out})$$

$$A_o V_{in} - A_o V_{out}$$

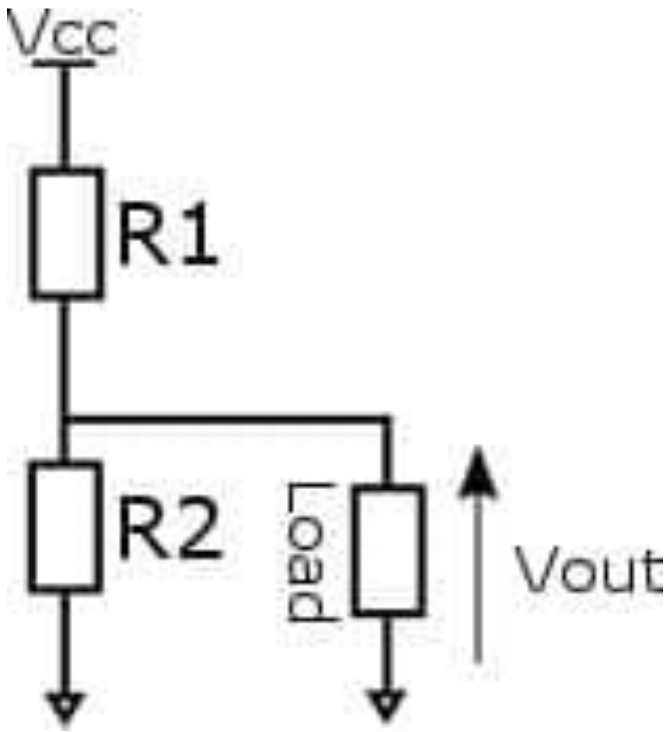
- Op amp impedance: $Z_{in} = 10\ \mathrm{M\Omega}$ and $Z_{out} = 100\ \Omega$
- $V = IZ$

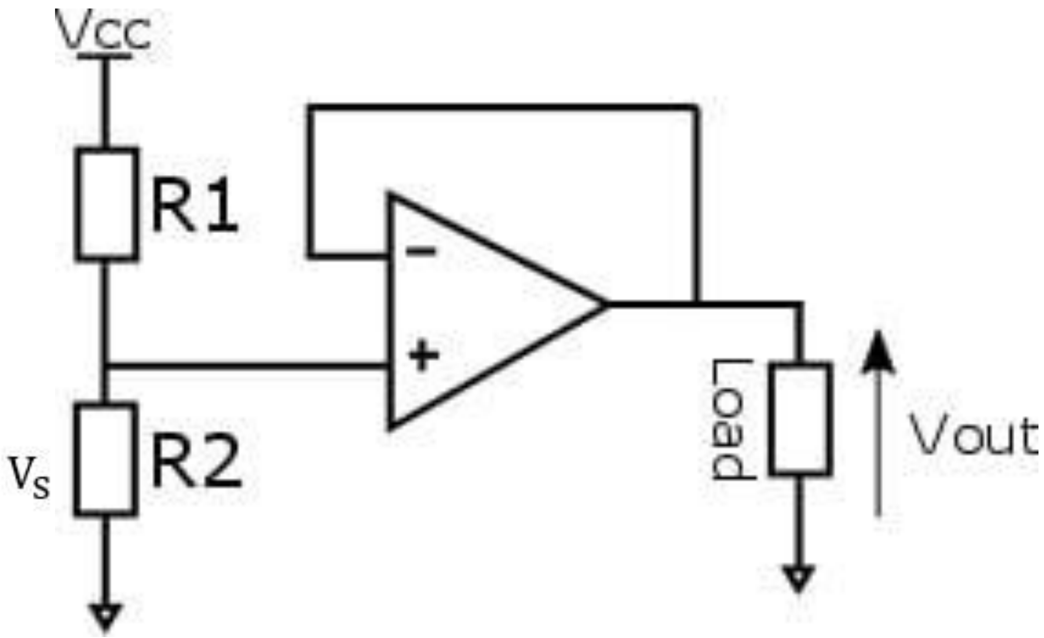


$$V_S = V_e$$

Voltage follower

- Consider the two following circuits



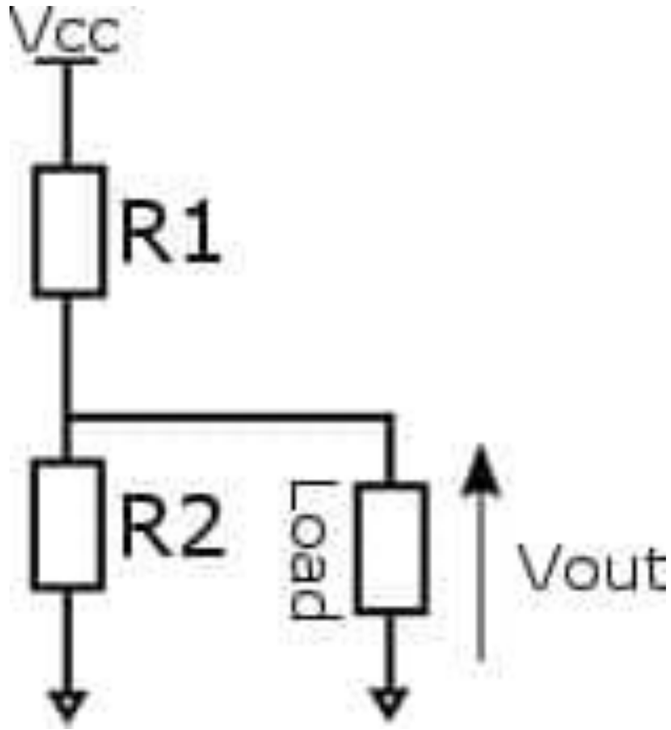


Voltage follower

- This circuit is based on a voltage divider, and the circuit cannot function.

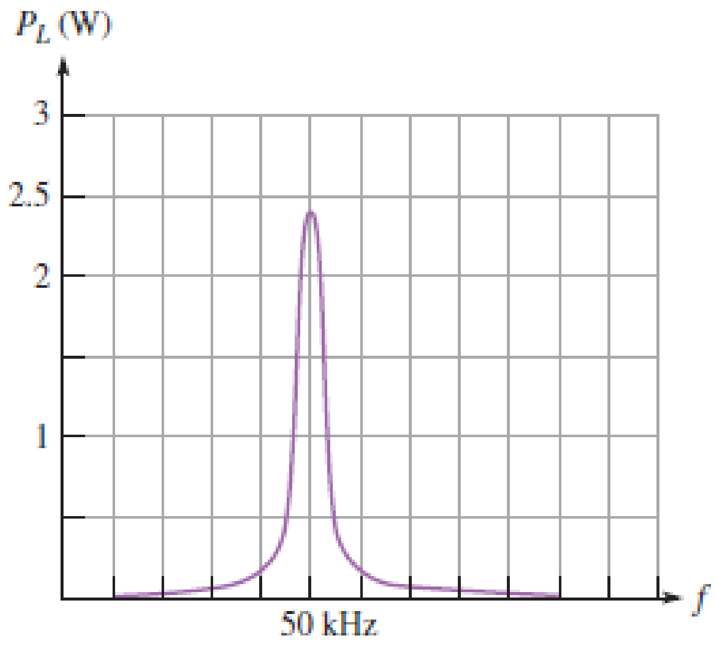
- Z_{Load} may have large variations, so V_{out} can change dramatically, when R_2 is of the same magnitude as Z_{Load}

$$P = I^2 Z_{Load} = \frac{Z_{Load}}{V_{out}^2}$$



Maximum Power Transfer

- Maximum Power Transfer in DC circuits occurs when $R_{total} = R_{load}$
- In AC circuits, it occurs when $Z_{total} = Z_{load}$

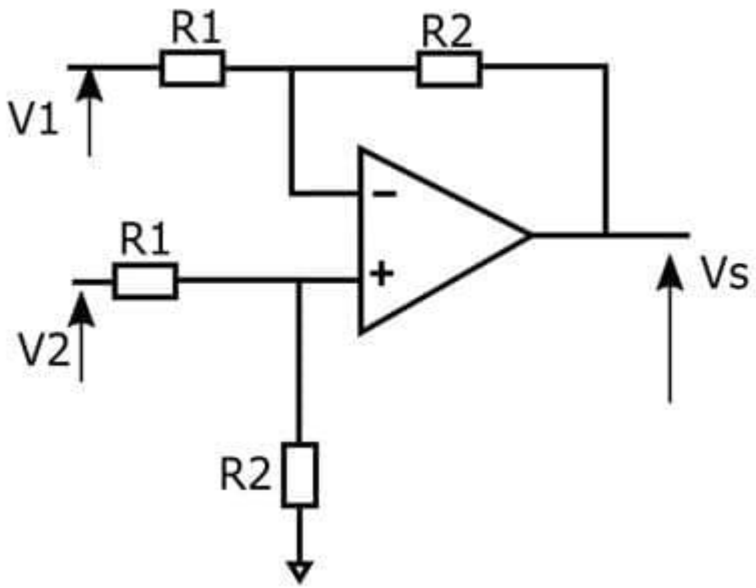


Differential Amplifiers

- An inverting op amp amplified a voltage that was applied on the inverting pin, and the output voltage was out of phase.

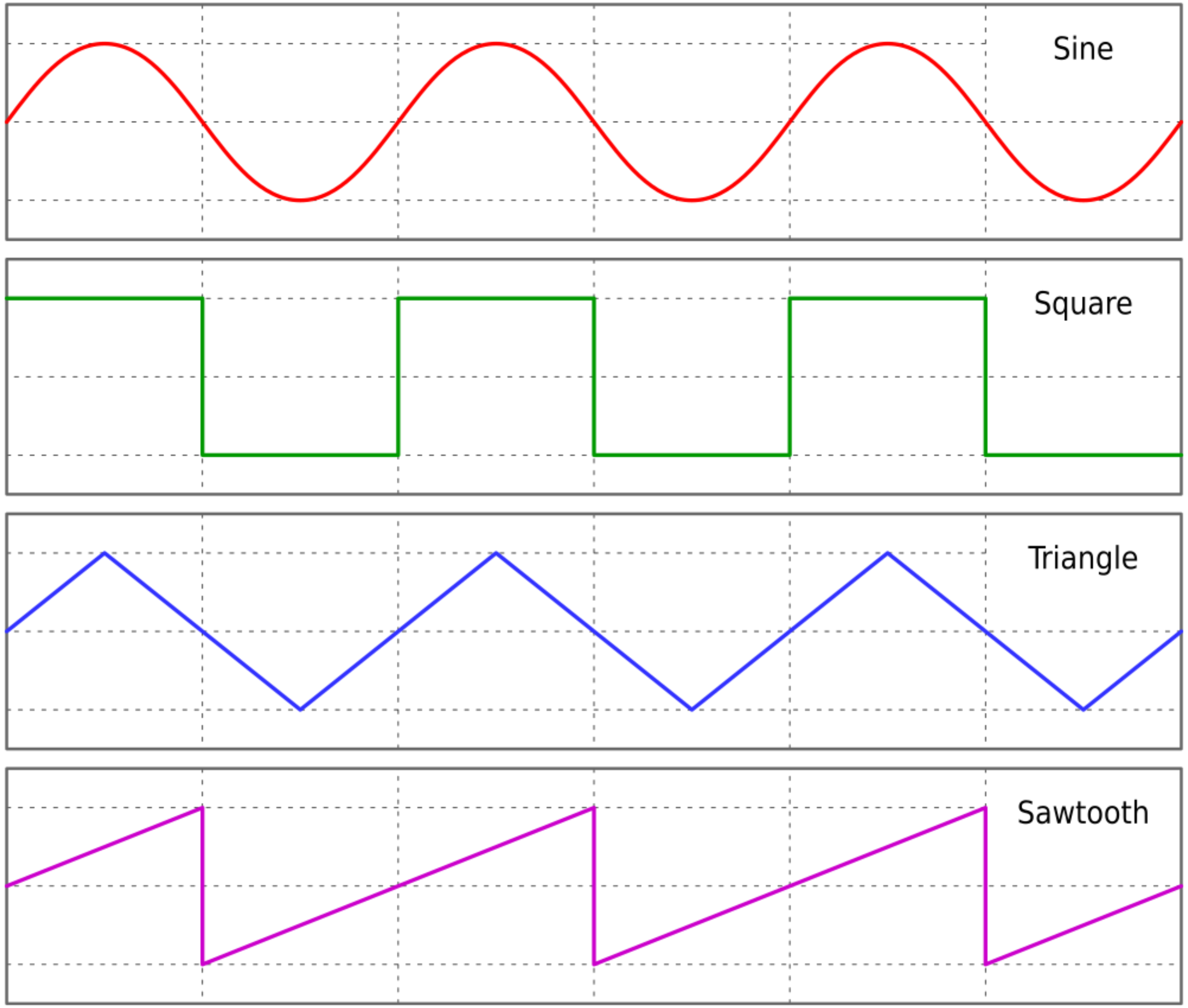
- The non-inverting pin is connected to ground with this configuration.

- If the circuit is modified by applying a voltage through a voltage divider on the non-inverting, we end up with a differential amplifier as shown below.



$$V_S = \frac{R_2}{R_1}(V_2 - V_1)$$

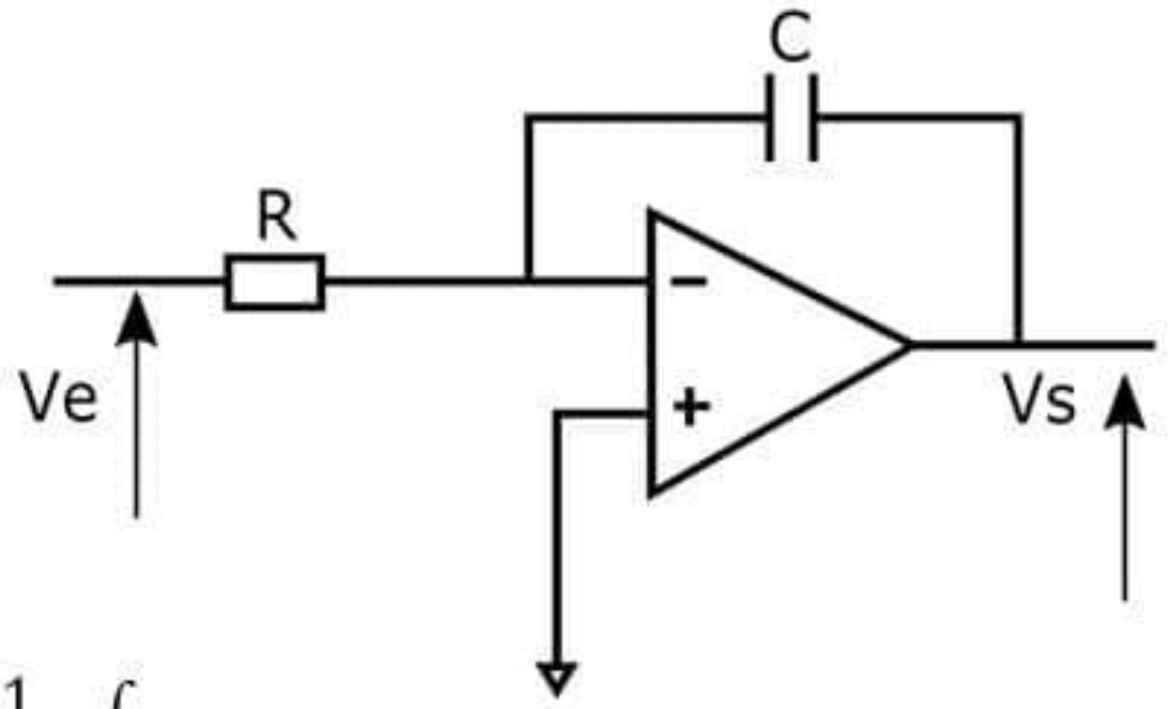
Waveform Manipulation



Integrators

- If a circuit needs a triangle waveform, we can integrate square wave signal.

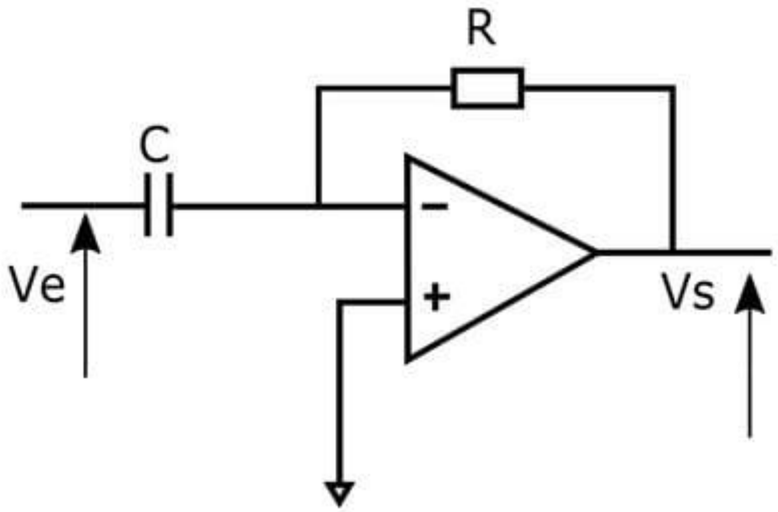
- With an operation amplifier, a capacitor on the inverting feedback path, and a resistor on the input inverting pin as shown below, the input signal is integrated.



$$V_S = -\frac{1}{RC}\int V_e\,dt$$

Differentiators

- Alternatively, if we swap the resistor and capacitor we get a differentiator



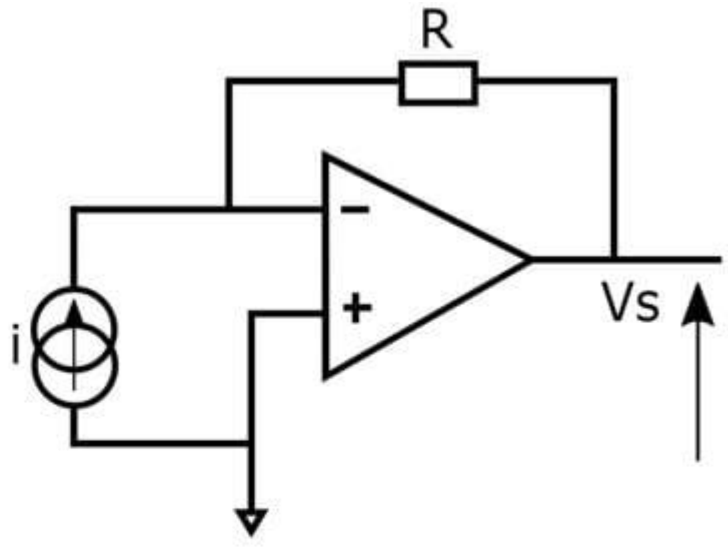
$$V_s = -RC\,\frac{dV_e}{dt}$$

Current/Voltage Convertor

- A photodetector converts light into current.

- To convert the current into voltage, a circuit with an operational amplifier, a feedback loop through a resistor on the non-inverting, and the diode connected between the two input pins

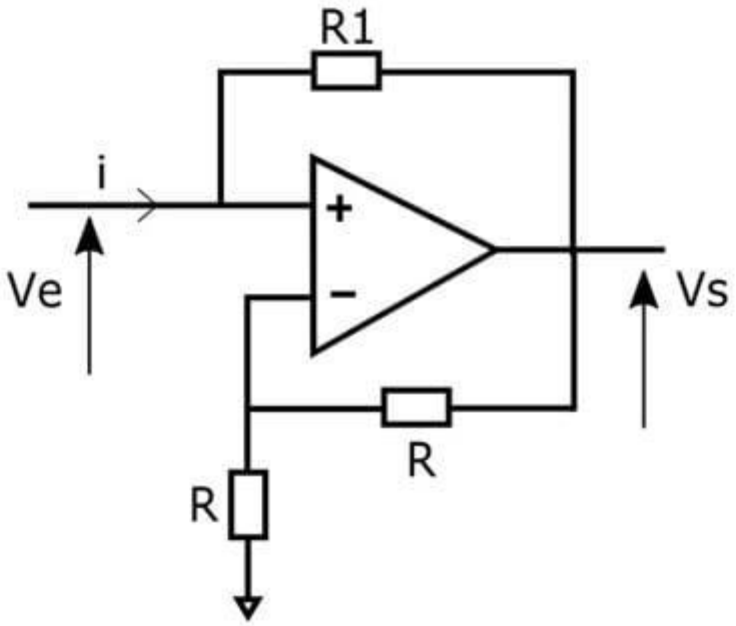
- This gets an output voltage proportional to current generated by the photodiode



$$V_s = R\,I$$

Negative Resistance

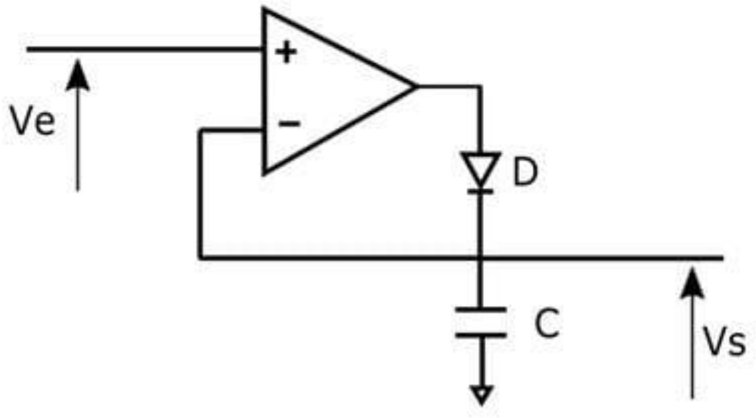
- A feedback on the inverting pin forces the output voltage to be the double of the input voltage.
- As the output voltage is always higher than the input voltage
- The positive feedback through the R1 resistor on the non-inverting pin simulates a negative resistance.



$$V_e = -R_1 I$$

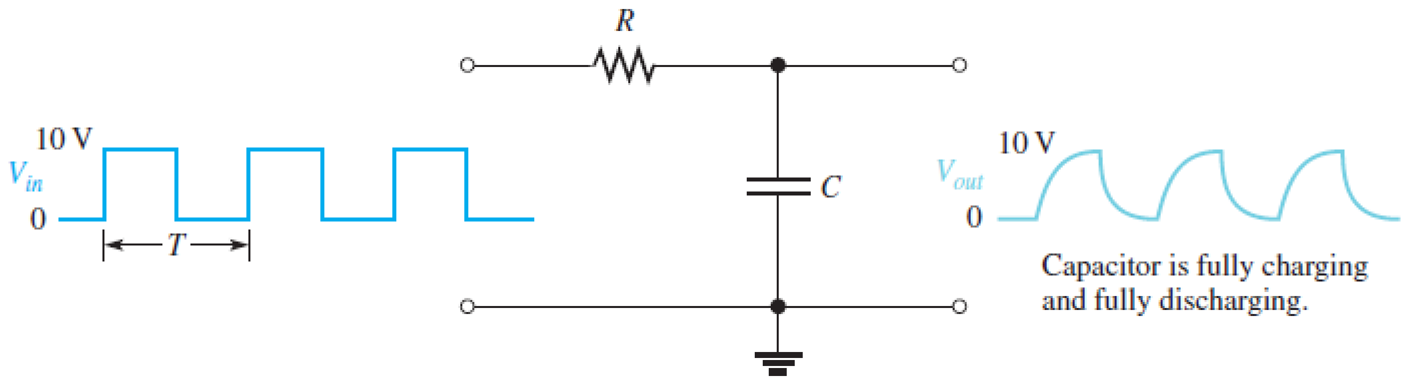
Peak Detector

- The capacitor is used as a memory.
- When the input voltage on the non-inverting input is higher than the voltage on the inverting input that is also the voltage across the capacitor, the amplifier enters in saturation and the diode is forward and charges the capacitor.
- Assuming the capacitor does not have a quick self discharge, when the input voltage V_e is lower than voltage across the capacitor, the diode is blocked.
- Hence, the peak voltage is recorded thanks to the capacitor.

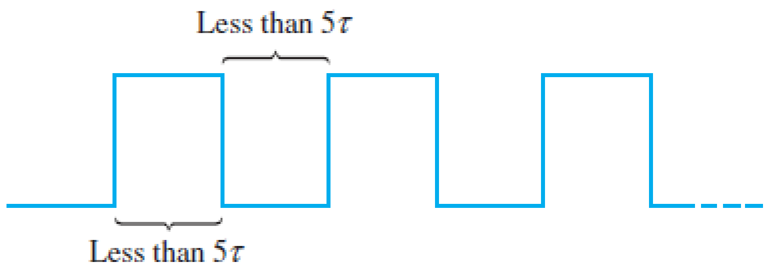


Time Reactive Circuits

- RL and RC circuits are responsive to incoming AC signals



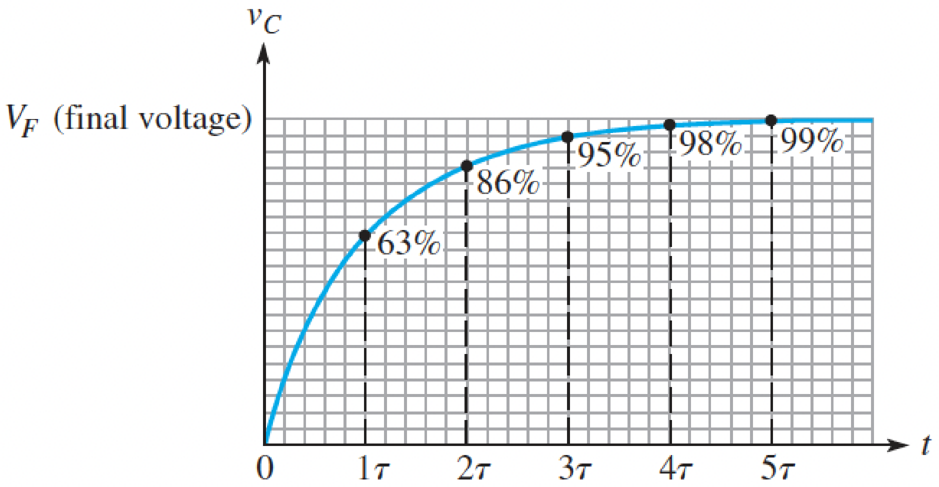
- The input signal may not allow the capacitor to fully charge fully if the time constant is less than 5



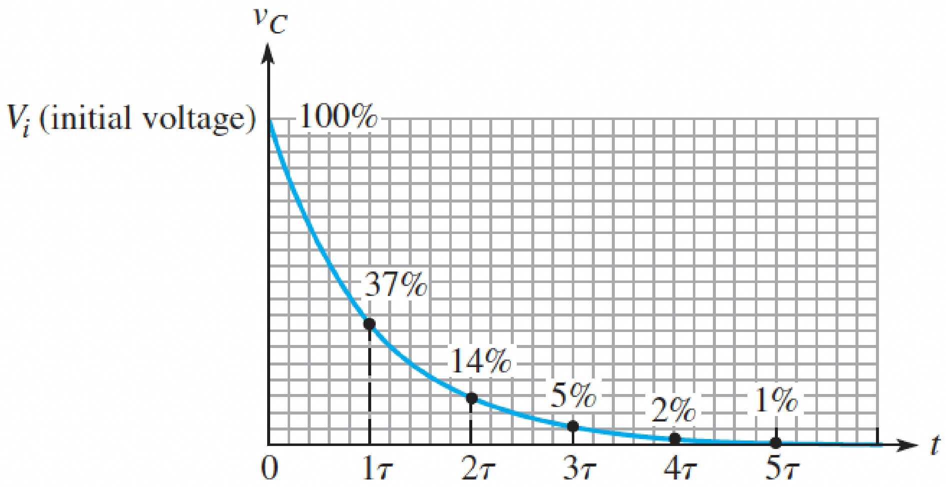
Analog Computation

- In a Resistor-Capacitor circuit, the resistance will alter the capacitor charging time
- The Time Constant (τ) is equal to the resistance times the capacitance

$$\tau = RC$$

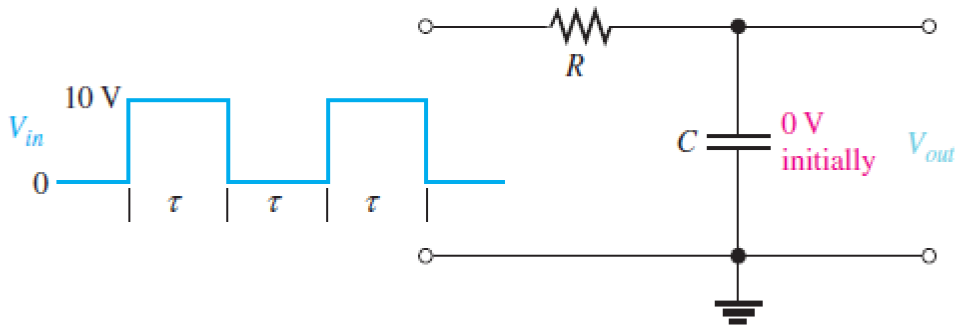


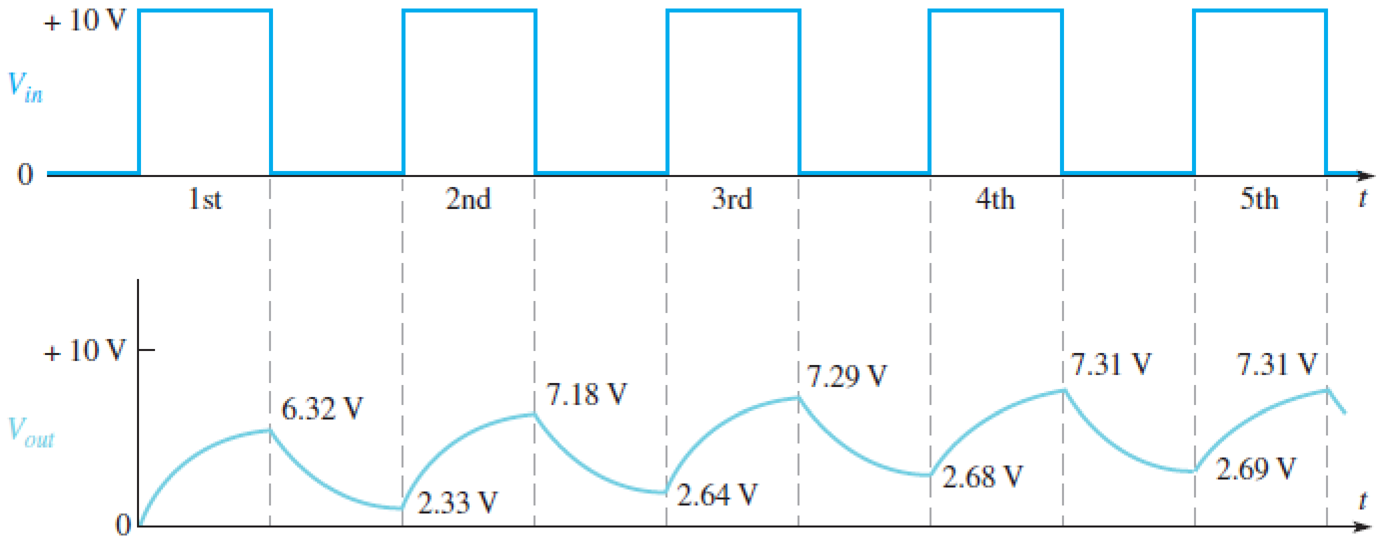
(a) Charging curve with percentages of the final voltage



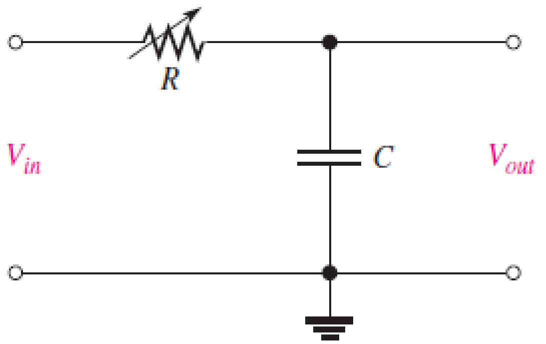
(b) Discharging curve with percentages of the initial voltage

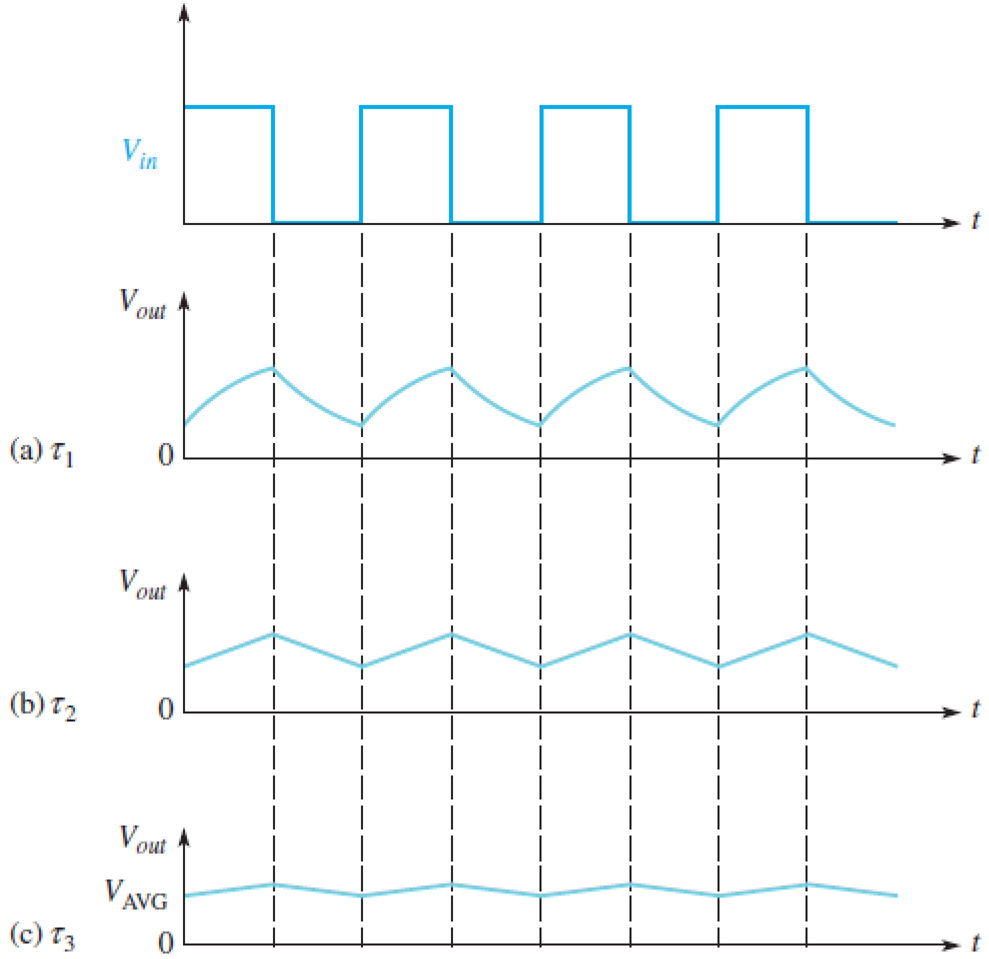
RC Integration circuit





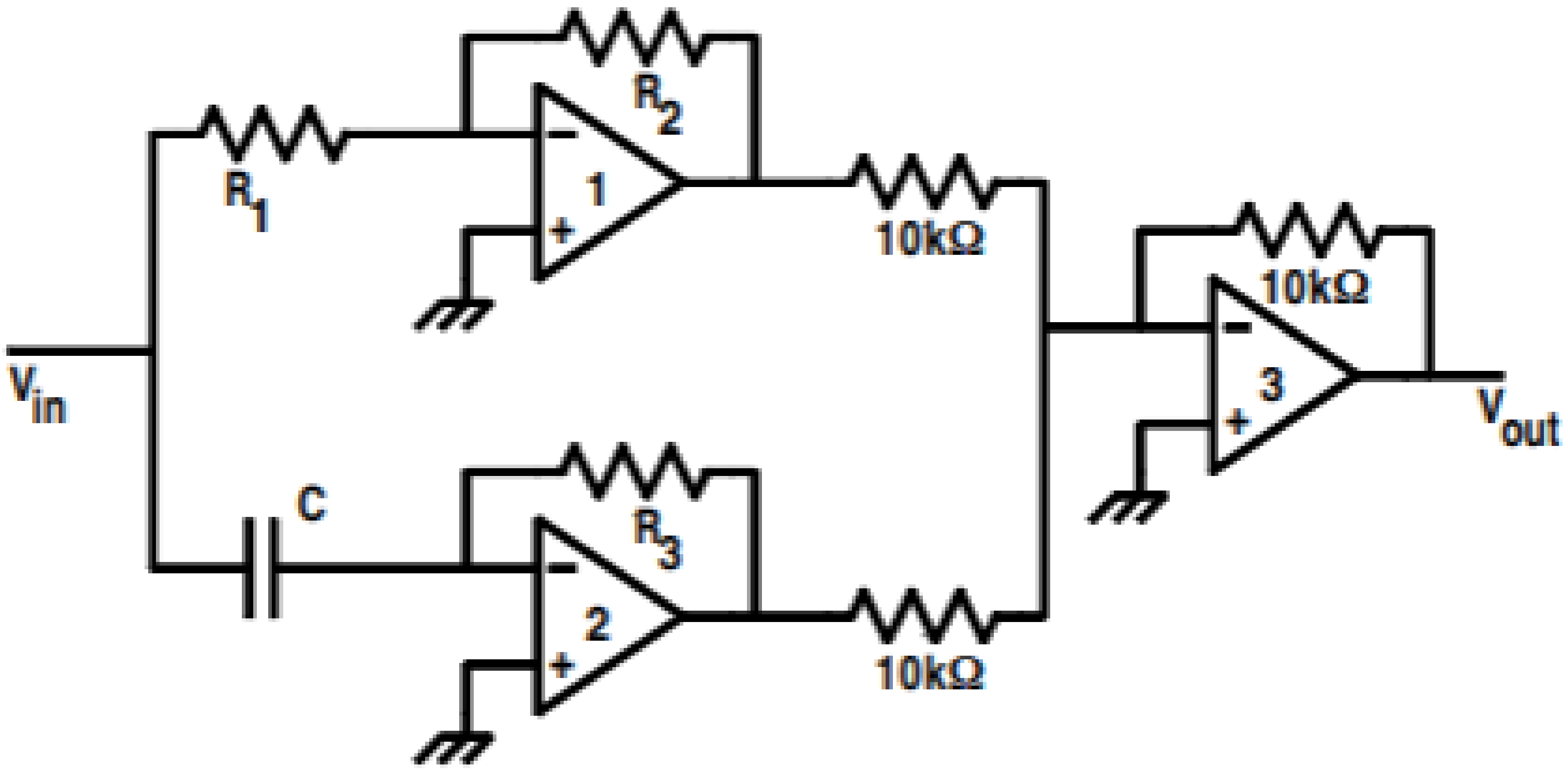
RC Integration circuit





Analog Computers

– Solve the following equation: $V_{out} = 3.3V_{in} + 2.2\frac{dV_{in}}{dt}$



Analog Computers

- Circuit has a gain of 3.3 and a derivative of $2.2\frac{dV_{in}}{dt}$

- Op amp 1: Gain of 3.3 so ${R_2}/{R_1} = 3.3$. If we say $R_1 = 10\ k\Omega$ then $\mathrm{R}_2 = 33\ k\Omega$

- Op amp 2 is the derivative :

  $$R_3C = 2.2$$
  $$C = 1\ \mu\mathrm{F}$$
  $$R3 = 2.2M\Omega$$

- Op amp 3 is an adder