ECE 113- Basic Electronics

Lecture week 11: Op-Amp

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Op-Amps

Presentation Outline

- What is an Op-Amp?
- Characteristics of Ideal and Real Op-Amps
- Common Op-Amp Circuits
- Applications of Op-Amps
- References

Operational Amplifiers (Op amp)

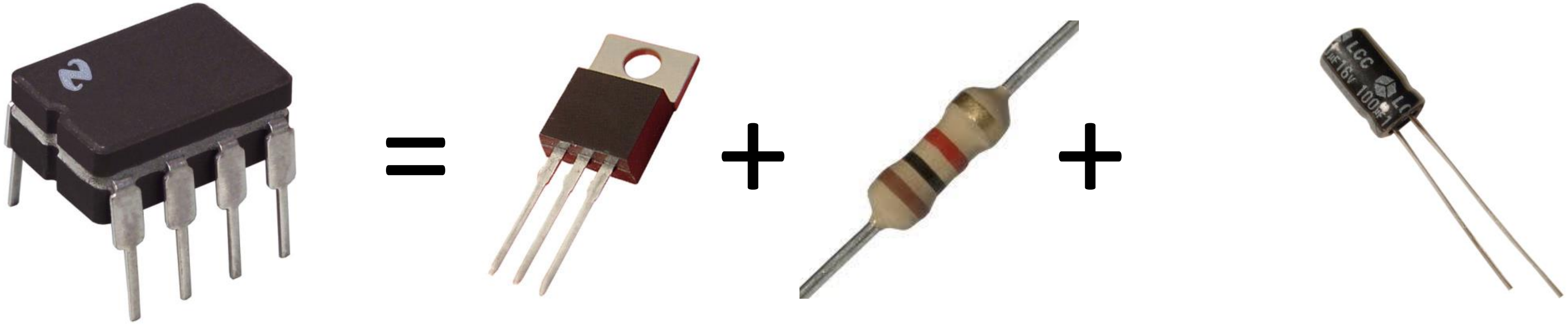
- Analog integrated circuit (IC)
- Developed to perform mathematical operations
- Earlier op-amps were vacuum tube based
- Enabled construction of analog computers

Applications:

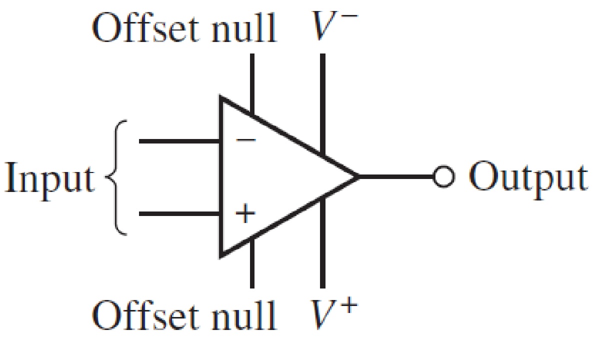
✓Amplifier
✓Analog computation – comparator, sum, integration, differentiation
✓Analog Filter
✓Instrumentation amplifier
✓Oscillator
✓Controller

What is an Op-Amp?

- An *Operational Amplifier* (known as an “Op-Amp”) is a device that is used to amplify a signal using an external power source
- Op-Amps are generally composed of:
  - Transistors, Resistors, Capacitors



Op-amp



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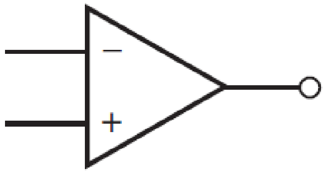

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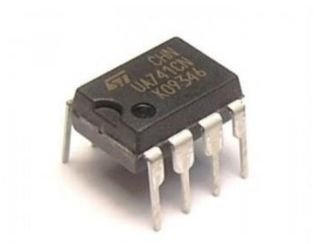

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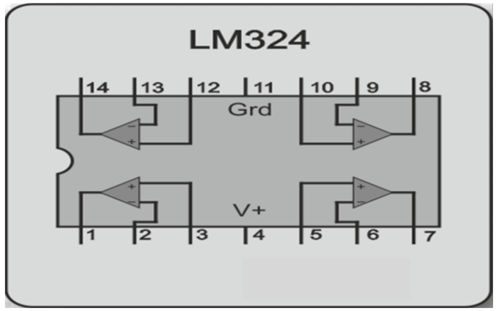

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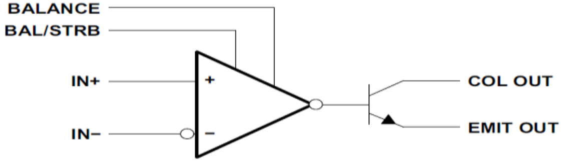

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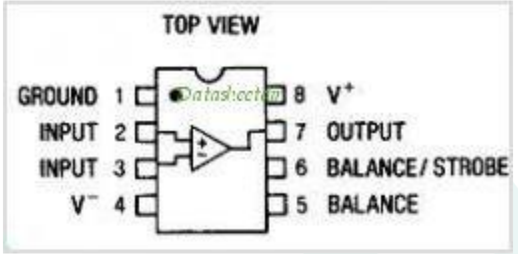

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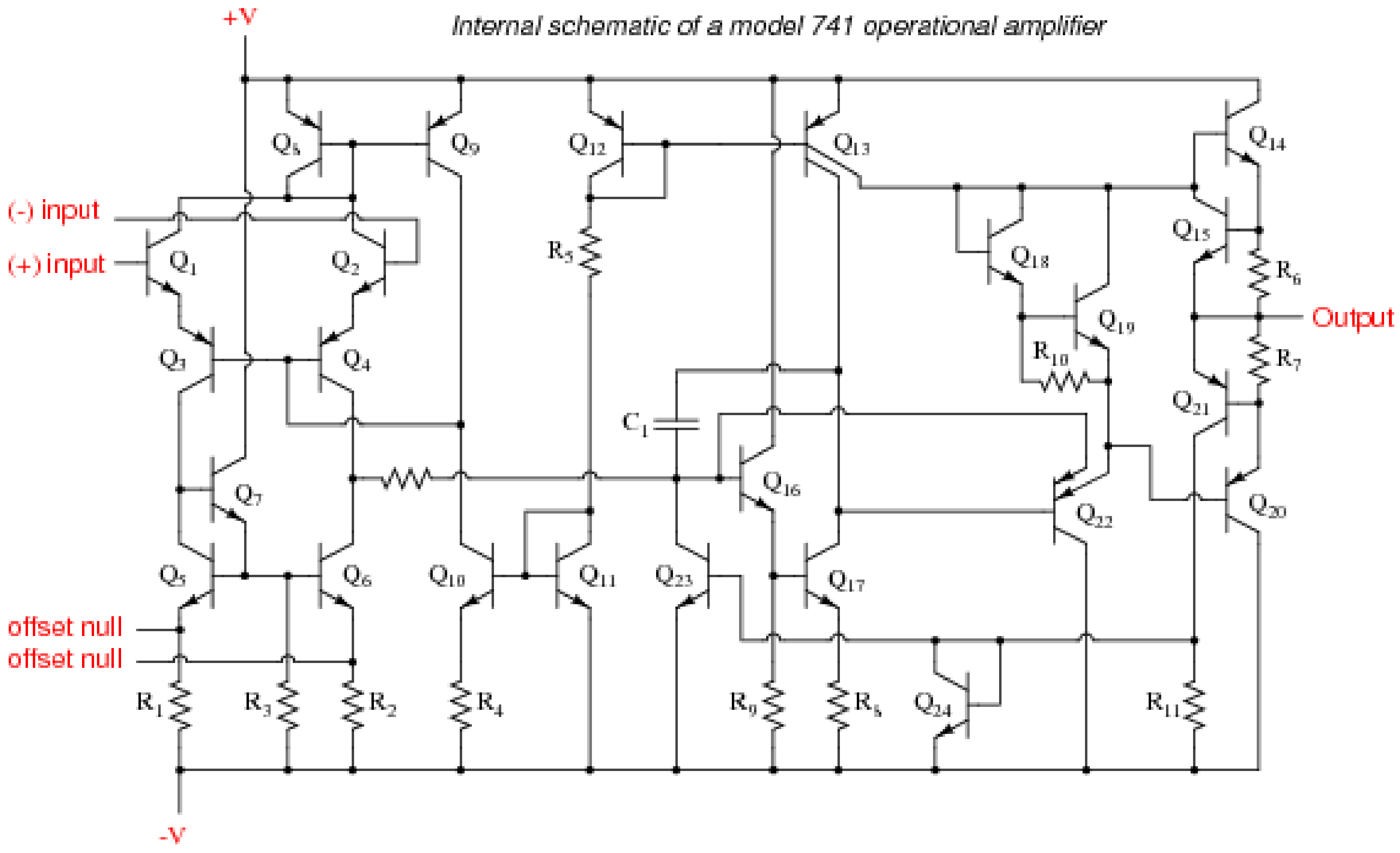
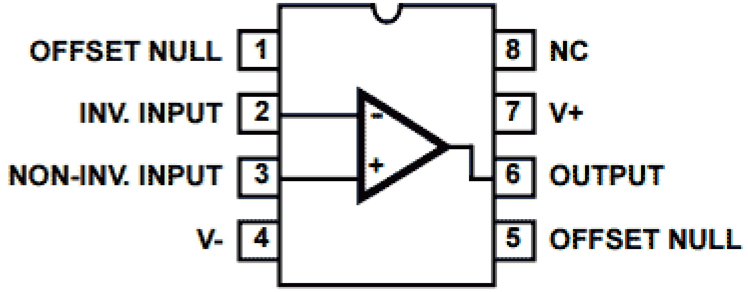
LM741 op amp

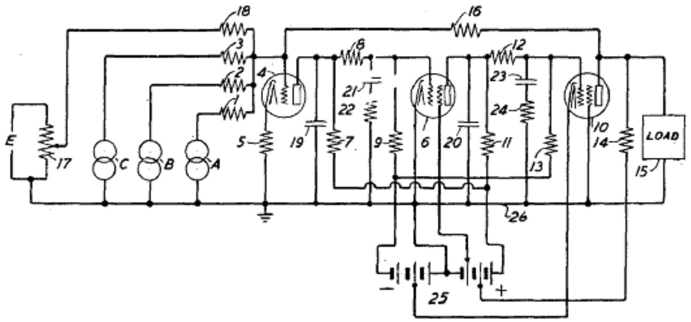
Internal schematic of a model 741 operational amplifier



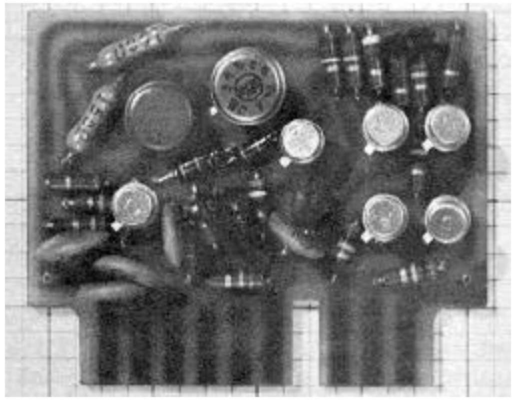


Brief History

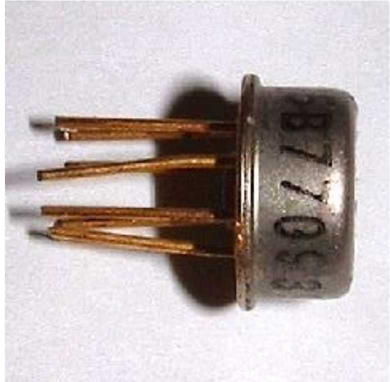
- First patent for Vacuum Tube Op-Amp (1946)



- First Commercial Op-Amp available (1953)



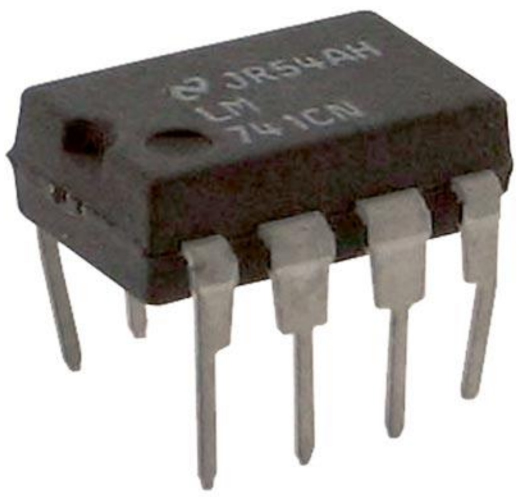
- First discreteTransistor Op-Amps (1961)



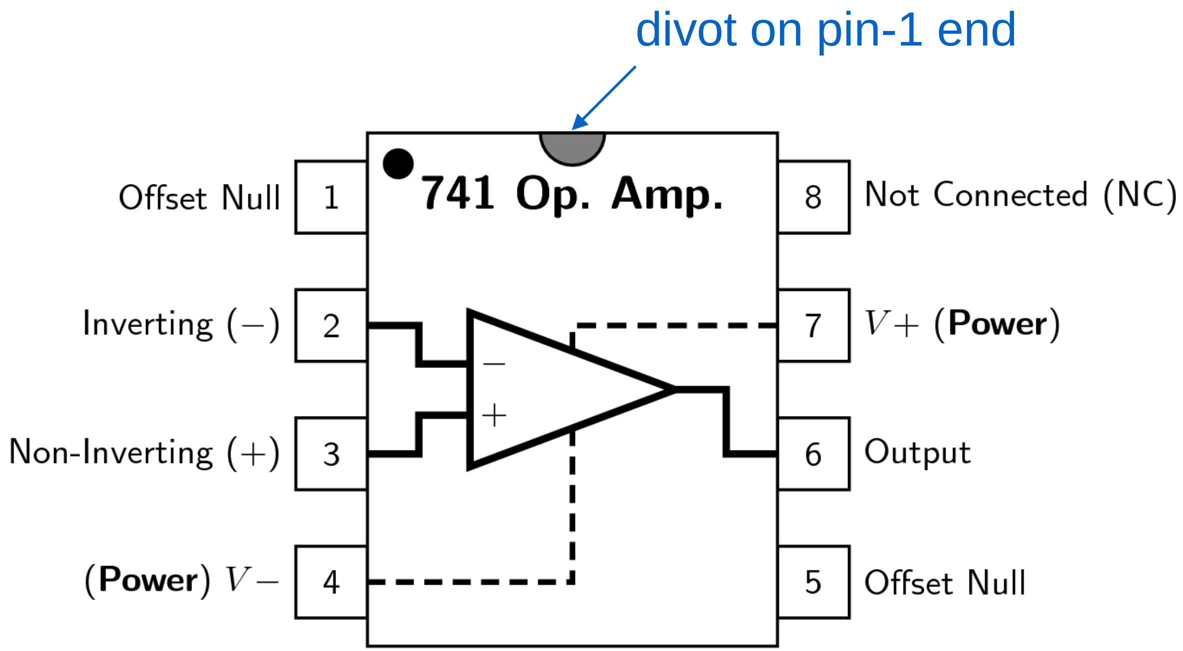
- First commercially successful Monolithic Op-Amps (1965)

History Continued…

- Leading to the advent of the modern IC which is still used even today (1967 – present)



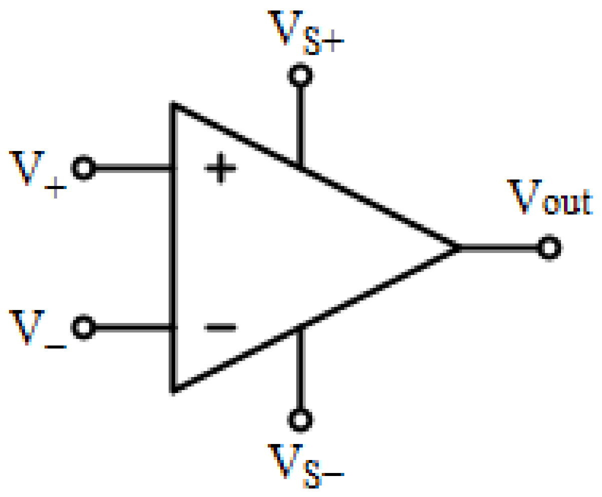
Fairchild µA741



Pin Diagram of µA741

Op-Amps Characteristics

A traditional Op-Amp:



V_+ : non-inverting input
V_- : inverting input
V_{out} : output
V_{s+} : positive power supply
V_{s-} : negative power supply

$$V_{out} = K\,(V_+ - V_-)$$

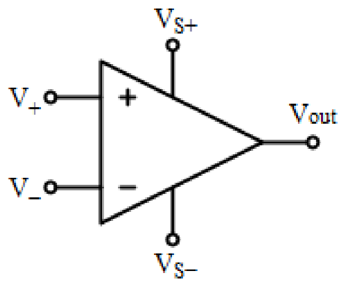
- The difference between the two inputs voltages (V_+ and V_-) multiplied by the gain (K, “amplification factor”) of the Op-Amp gives you the output voltage

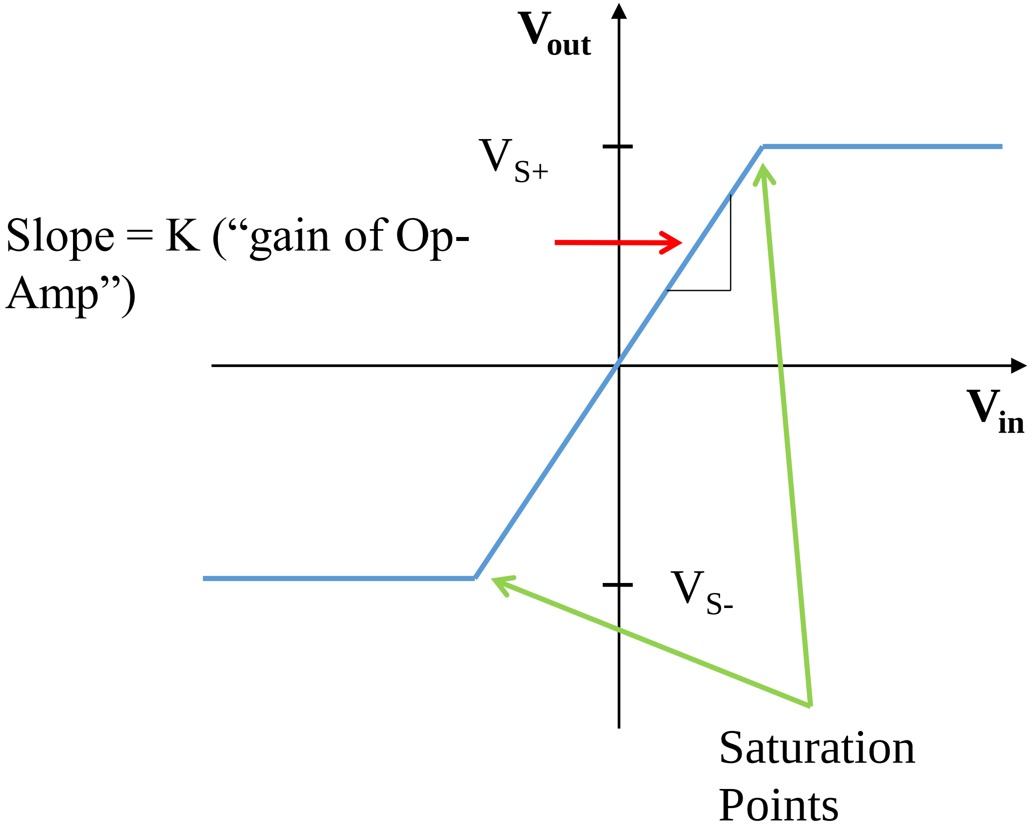
- The output voltage can only be as high as the difference between the power supply (V_{s+} / V_{s-}) and ground (0 Volts)

A traditional Op-Amp is basically a differential amplifier

Saturation

Saturation is caused by increasing/decreasing the input voltage to cause the output voltage to equal the power supply's voltage*





The slope is normally much steeper than it is shown here. Potentially just a few milli-volts (mV) of change in the difference between V_+ and V_- could cause the op-amp to reach the saturation level

* Note that saturation level of traditional Op-Amp is 80% of supply voltage with exception of CMOS op-amp which has a saturation at the power supply's voltage

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An Ideal Op-Amp

- Infinite voltage gain (K)
- Infinite input impedance
- Zero output impedance
- Infinite bandwidth
- Zero input offset voltage (i.e., exactly zero out if zero in).

voltage gain is infinite

→ This means the voltage between the inverting and non-inverting terminal (i.e. differential input voltage) is essentially zero for finite output voltage.

Infinite input impedance

→ Input impedance is the ratio of input voltage to input current and is assumed to be infinite to prevent any current flowing from the source supply into the amplifiers input circuitry ($I_{IN} = 0$).

Zero output impedance

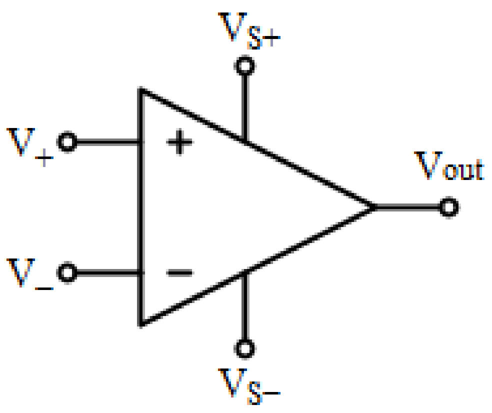
→ This means that regardless of the amount of current drawn by an external load, the output voltage of the op amp remains unaffected.

Infinite bandwidth

→ An ideal operational amplifier has an infinite frequency response and can amplify any frequency signal from DC to the highest AC frequencies so it is therefore assumed to have an infinite bandwidth.

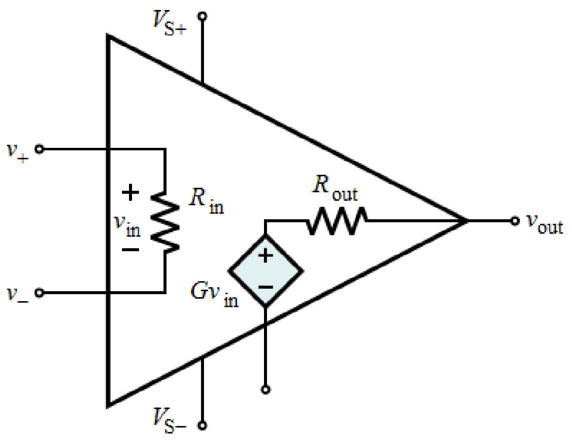
Ideal versus Real Op-Amps

Parameter	Ideal Op-Amp	Real Op-Amp
Differential Voltage Gain	∞	10^5 - 10^9
Gain Bandwidth Product (Hz)	∞	1-20 MHz
Input Resistance (R)	∞	10^6 - 10^{12} Ω
Output Resistance (R)	0	100 - 1000 Ω



Ideal

Real



Op-Amp offset voltage and current

- An ideal op-amp is perfectly balanced. i.e. the output $v_0 = 0$ when two inputs are equal (i.e. $v_1 = v_2$). This assumes perfect symmetry between two halves of the differential amplifier used as the input stage of an op-amp.

- In practical op-amp, an unbalanced is caused by the mismatch of inputs transistors. This mismatch causes the flow of unequal bias current through the input terminals and results in a non-zero output voltage without any input voltage. This can be balanced by applying a small d.c. voltage between the input terminals. This voltage is called **input offset voltage**.

- The input offset voltage is usually very small and hence can be neglected in many applications with relatively large input voltages. But there are certain cases, it cannot be neglected and various null adjustments are used.

- The **input offset current** is the difference between the two bias currents entering into the input terminals of a balanced amplifier. The input bias current is defined as the average of two separate currents entering the input terminals of a balanced amplifier.

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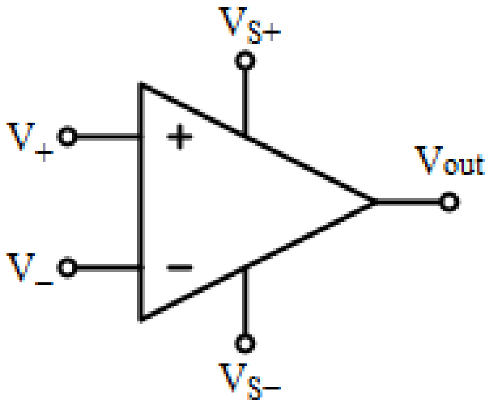
Basics of an Op-Amp Circuit

- An op-amp amplifies the difference of the inputs V_+ and V_- (known as the differential input voltage)
- This is the equation for an *open loop* gain amplifier:



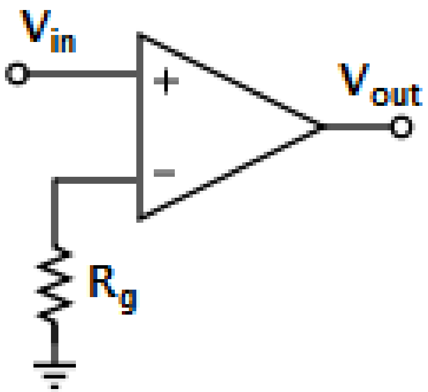
$$\boxed{V_{out} = K\,(V_+ - V_-)}$$

- K is typically very large – at around 10,000 or more for IC Op-Amps
- This equation is the basis for all the types of amps we will be discussing

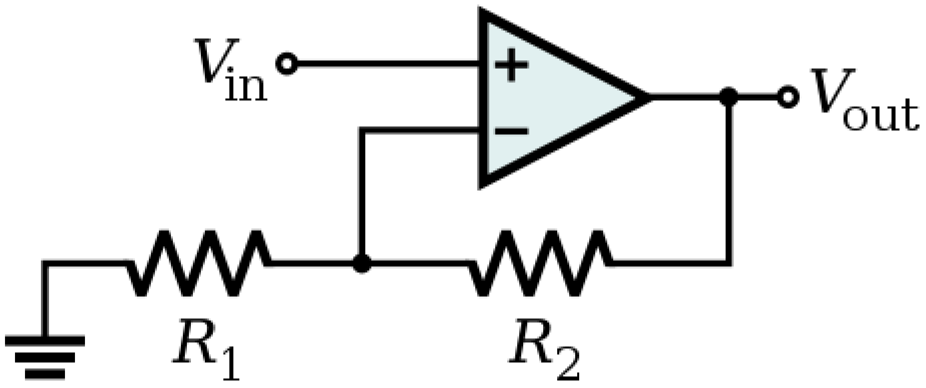
So if V_+ is greater than V_-, the output goes positive
If V_- is greater than V_+, the output goes negative

Open Loop vs Closed Loop

- A closed loop op-amp has feedback from the output to the input, an open loop op-amp does not have feedback.



Open Loop

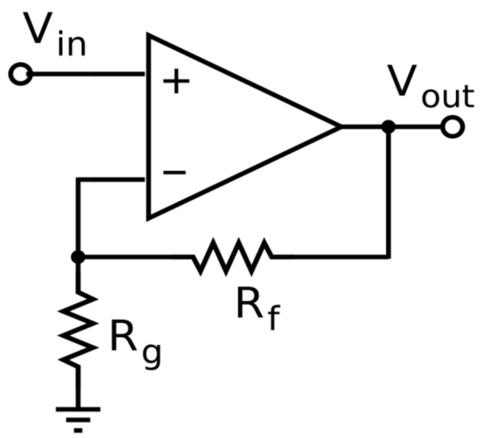


Closed Loop

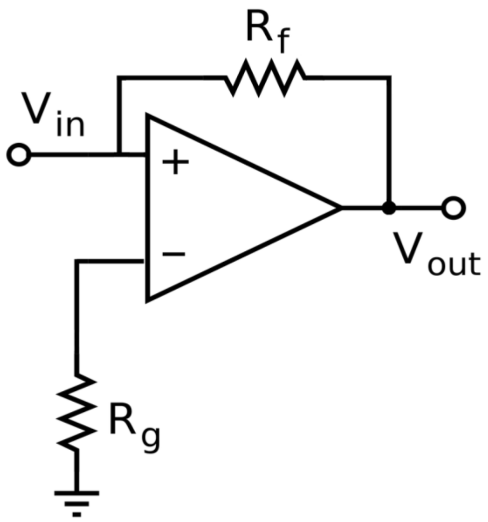
- ➢ Without feedback the operational amplifier has an open-loop operation. This open-loop operation is practical only when the operational amplifier is used as a comparator (a circuit which compares two input signals or compares an input signal to some fixed level of voltage).
- ➢ As an amplifier, the open-loop operation is not practical because the very high gain of the operational amplifier creates poor stability. (Noise and other unwanted signals are amplified so much in open-loop operation that the operational amplifier is usually not used in this way.) Therefore, most operational amplifiers are used with feedback (closed-loop operation)

Negative vs. Positive Feedback

- Negative feedback connects the output to the inverting input (-), whereas positive feedback connects the output to the non-inverting input (+).



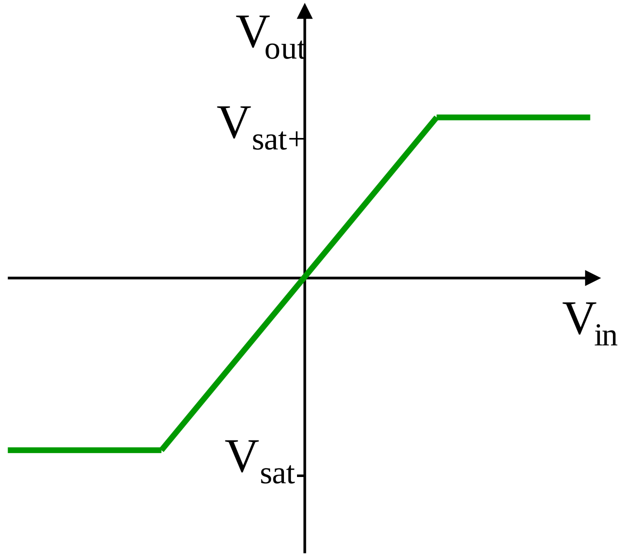
Negative Feedback



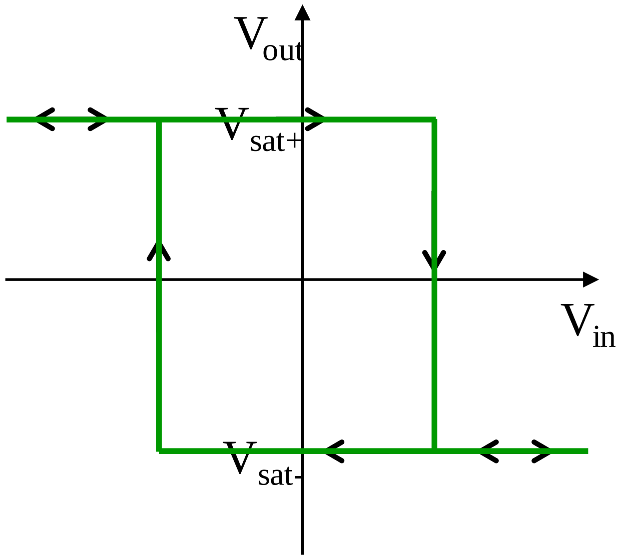
Positive Feedback

Negative vs. Positive: Output

- Negative feedback op-amps can produce any voltage in the supply power range.
- Positive feedback op-amps can only produce the maximum and minimum voltages of the range.



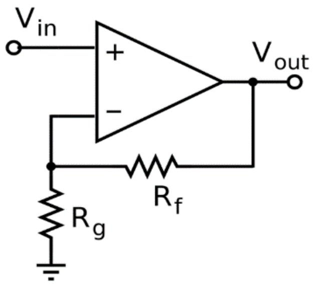
Negative Feedback



Positive Feedback

negative feedback

- negative feedback makes it self-correcting
- in this case, the op-amp drives (or pulls, if V_{in} is negative) a current through the load until the output equals V_{in}
- so what we have here is a buffer: can apply V_{in} to a load without burdening the source of V_{in} with *any* current!



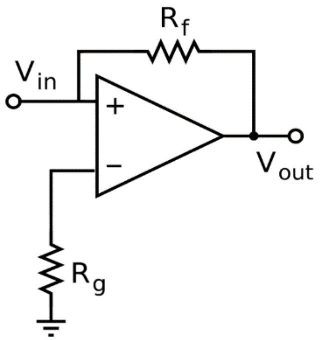
positve feedback

if the + input is even a smidge higher than V_{in}, the output goes way positive

This makes the + terminal even *more* positive than V_{in}, making the situation worse

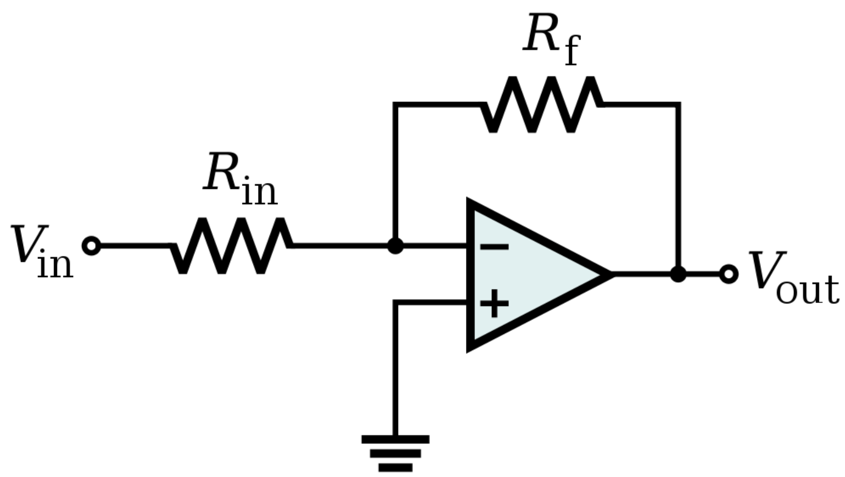
This system will immediately “rail” at the supply voltage

could rail either direction, depending on initial offset



Inverting Op-Amp

- Voltage input is connected to inverting input
- Closed loop op-amp
- Voltage output is connected to inverting input through a feedback resistor
- Non-inverting input is grounded
- Amplifies and inverts the input voltage
- Non-inverting input is determined by *both* voltage input and output
- The polarity of the output voltage is opposite to that of the input voltage

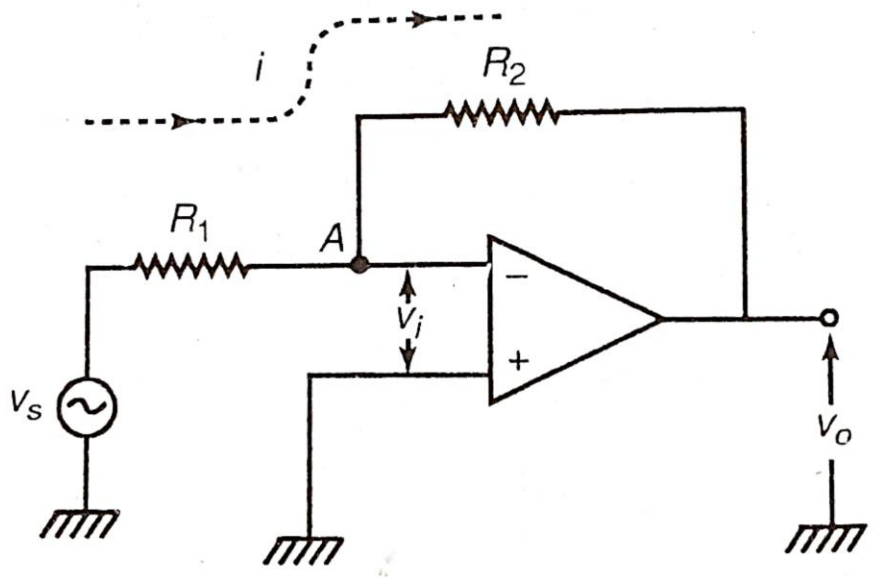


Concept of virtual ground of an inverting op-amp

- The attached Fig. shows the basic circuit of an inverting op-amp which employs negative feedback voltage through R_2. The negative feedback voltage through R_2 tends to cancel the input signal at the point A and tries to keep the point A at the ground potential.

- If vi be the potential at A then output $v_0 = A_V.v_i$ (AV is the gain). Since the open loop gain $|A_V| \rightarrow \infty$, for a finite v_0, we must have $v_i \rightarrow 0$. Further, since the input impedance $R_i \rightarrow \infty$, practically no current enters into the op-amp input terminals.

- Therefore, there is a "**virtual ground**" at the point A. The word virtual is used to imply that the point A is effectively connected to the ground, no current actually flows into this short. Obviously, it is not the actual ground. However, this concept of virtual ground makes the analysis and understanding of many op-amp circuits very simple.



Inverting Op-Amp

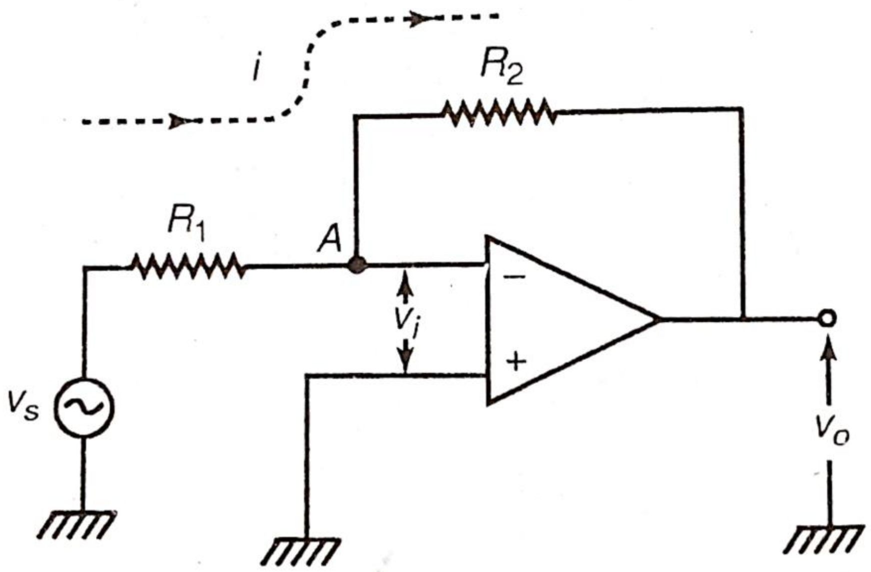
Functionality: to amplify the input voltage to output voltage with a negative gain.

Since input resistance of ideal op amp is ideally infinite, no current will flow in op amp input terminals. Gain K is also infinite.

The junction of R_1 and R_2 will be at virtual ground.

Therefore, the current *i* through R_1 is also the current through R_2

$$\therefore i = \frac{v_s - v_i}{R_1} = \frac{v_i - v_o}{R_2}$$



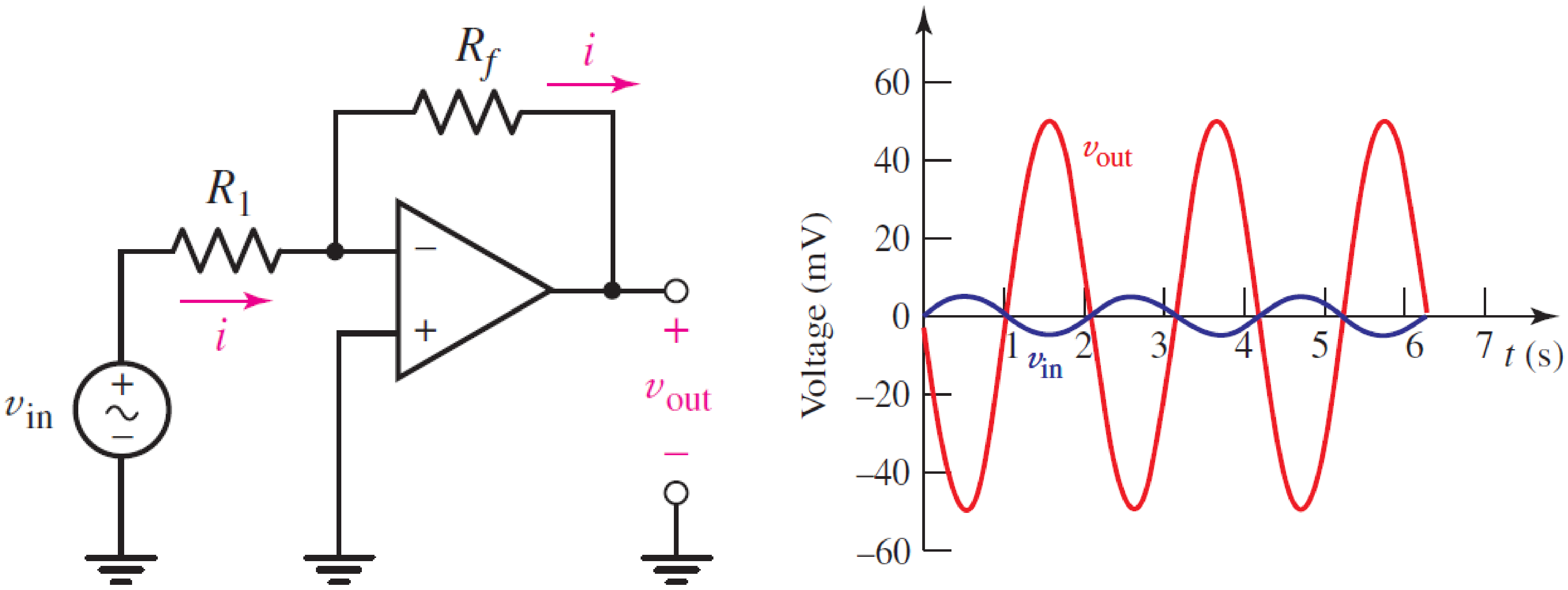
Using the concept of virtual ground,

$$i = \frac{v_s - 0}{R_1} = \frac{0 - v_0}{R_2}$$

So, the closed-loop gain of the inverting op-amp is $\dfrac{v_0}{v_s} = -\dfrac{R_2}{R_1}$

The '–ve' sign indicates the output is 180° out of phase with the input. The gain depends on the ratio of the two resistors R_1 and R_2 and is independent of the op-amp parameters.

Inverting Op-Amp

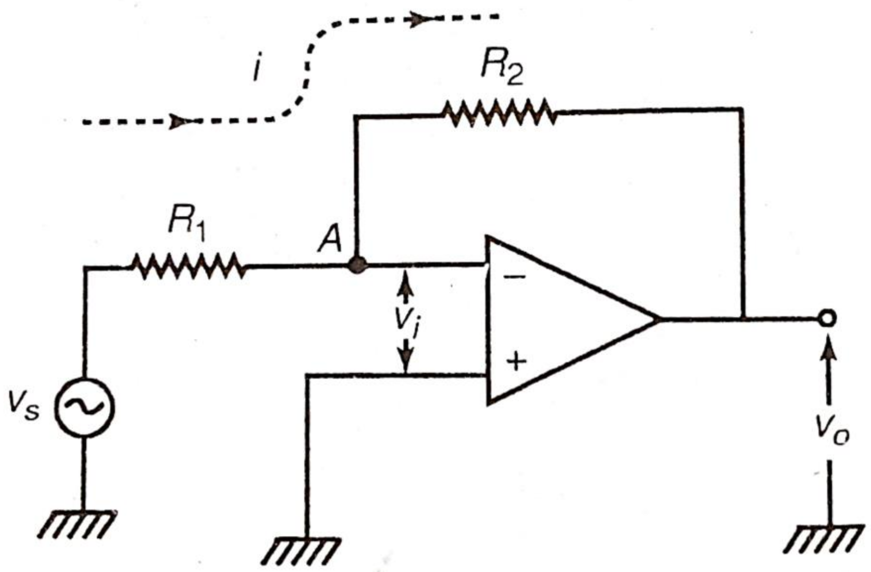


Scale changer

If R_1 and R_2 are two accurately known resistors, then the output

$$v_0 = -\frac{R_2}{R_1} v_s = -K v_s$$

where $K = R_2/R_1$ is an accurately known constant. Thus the circuit multiplies the input by –K, called the scale factor.



Phase shifter

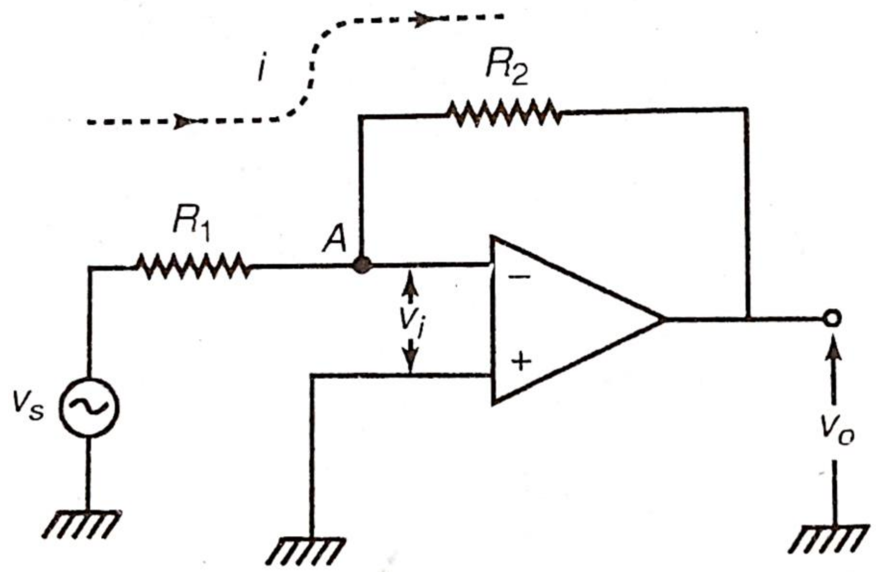
If R_1 and R_2 are replaced by impedances Z_1 and Z_2, then like before

$$\frac{v_0}{v_s} = -\frac{Z_2}{Z_1}$$

If Z_1 and Z_2 are chosen to have equal magnitude but different phases, then we can write

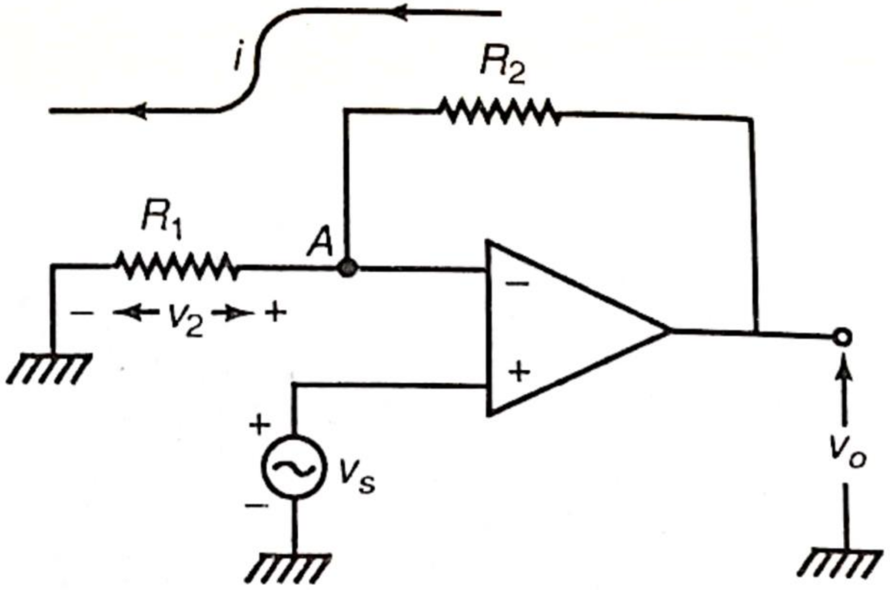
$$\frac{v_0}{v_s} = -\frac{|Z_2|e^{j\varphi 2}}{|Z_1|e^{j\varphi 1}} = e^{j(\pi+\varphi 2-\varphi 1)}$$

where φ1 and φ2 are the phase angles. Thus op-amp can shift the phase of input voltage v_s by the angle (π+ φ2- φ1) which can have any value between 0 to 360°, while at the same time the amplitude of the input remains unchanged.



Non-Inverting Op-Amp

Functionality: to amplify the input voltage to output voltage with a positive gain. Here, the signal is applied to the non-inverting terminal.



- If, v_2 is the potential at point A, then the differential input is (v_s-v_2). So, the output voltage is $v_0 = A_V(v_s-v_2)$.
- For a finite v_0, we must have $v_2 = v_s$. Thus there is a "**virtual short**" at the input terminals of the op-amp.
- Since, the input impedance of op-amp tends to infinite, practically no current enters into the op-amp. So same current passes through R_1 and R_2. Thus

$$\frac{v_0 - v_2}{R_2} = \frac{v_2 - 0}{R_1}$$

$$\frac{v_0}{v_s} = \frac{v_0}{v_2} = 1 + \frac{R_2}{R_1}$$

The output v_0 is in phase with input v_s. This circuit acts as non-inverting amplifier with gain **$(1 + R_2/R_1)$.**

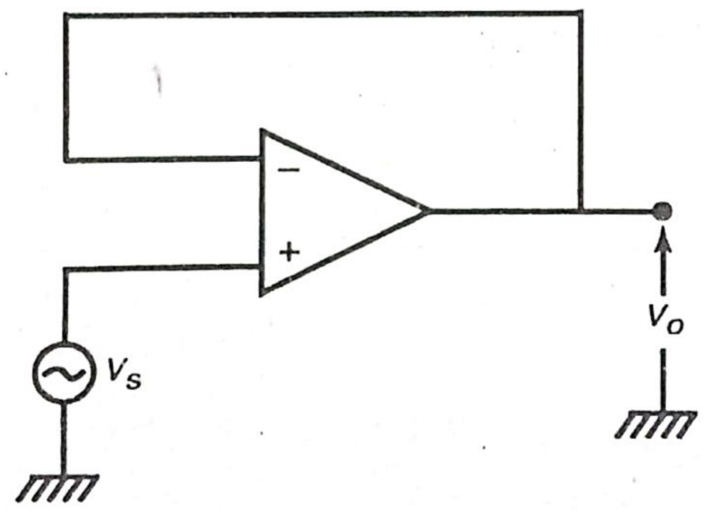
Unity gain follower or voltage follower

In non-inverting amplifier in previous slide, if we choose $R_1 = \infty$ and/or $R_2 = 0$, then closed loop gain $v_0/v_2 = 1$.

The amplifier then acts as a voltage follower i.e. a non-inverting amplifier with unity gain.

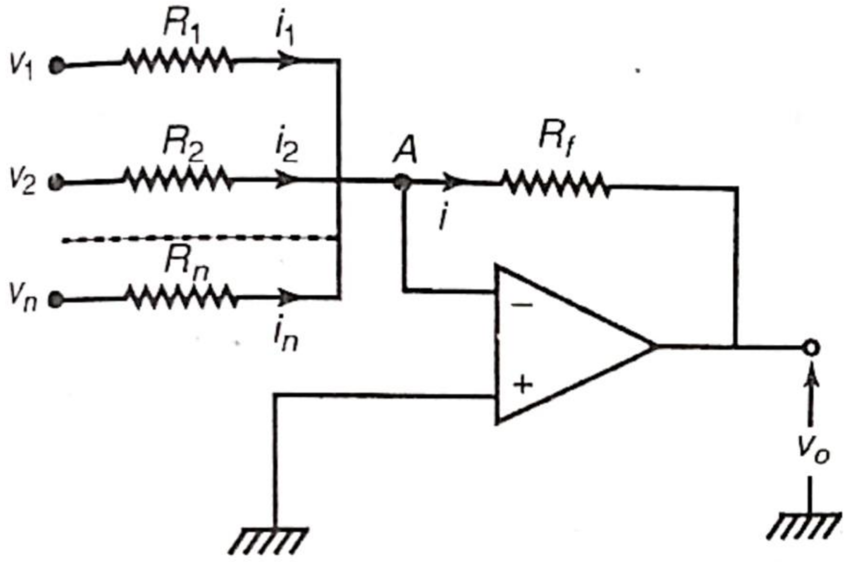
It has practically infinite input resistance and zero output resistance. So, the circuit can be used as buffer of isolation amplifier. It allows the input voltage to be transferred to the output without any change and at the same time avoids the loading of the source.

In other words, it can be used as an impedance marching device between a high impedance source and a low impedance load



Adder or summing amplifier

This circuit shows an op-amp adder which provides a mean of algebraically adding a number of voltages, each multiplies by a constant gain factor. Since the point A may be treated as virtual ground, we can write



$$i_1 + i_2 \cdots + I_n = i$$

$$\text{or} \quad \frac{v_1}{R_1} + \frac{v_2}{R_2} + \cdots + \frac{v_n}{R_n} = -\frac{v_0}{R_f}$$

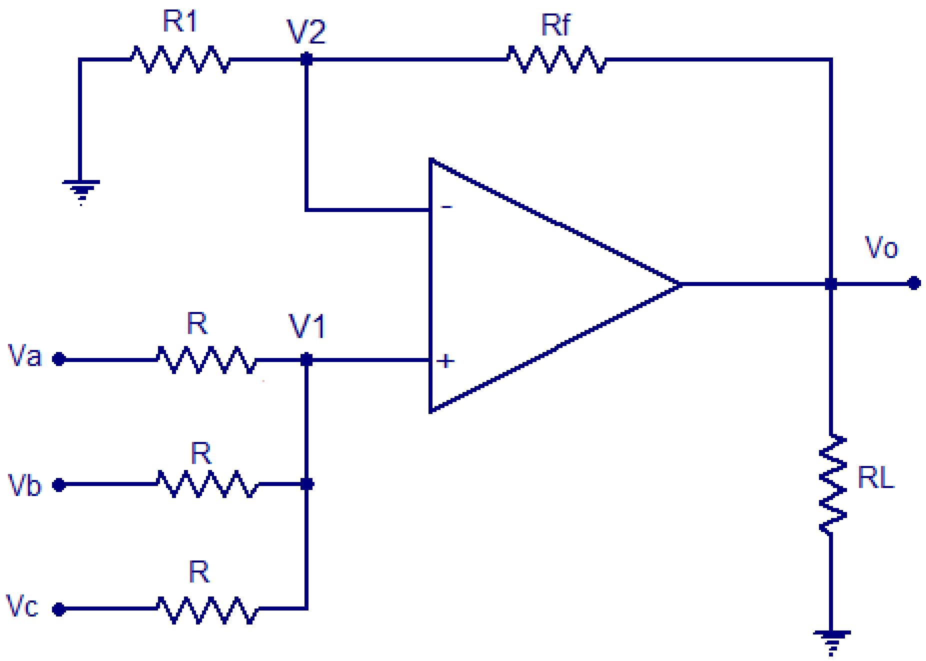
$$\therefore \quad v_0 = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \cdots + \frac{R_f}{R_n}v_n\right)$$

If $R_1 = R_2 = \cdots = R_n$ then

$$v_0 = -\frac{R_f}{R_1}(v_1 + v_2 + \cdots + v_n)$$

Thus, the output is proportional to the algebraic sum of the inputs.

Summing amplifier – Non-inverting configuration



Summing amplifier non inverting configuration

Differential amplifier

This is circuit of and differential amplifier which amplifies the difference between the input signals v_1 and v_2. Since the open loop gain and input impedance are infinite, there exists a virtual short circuit at the input terminals of the op-amp.

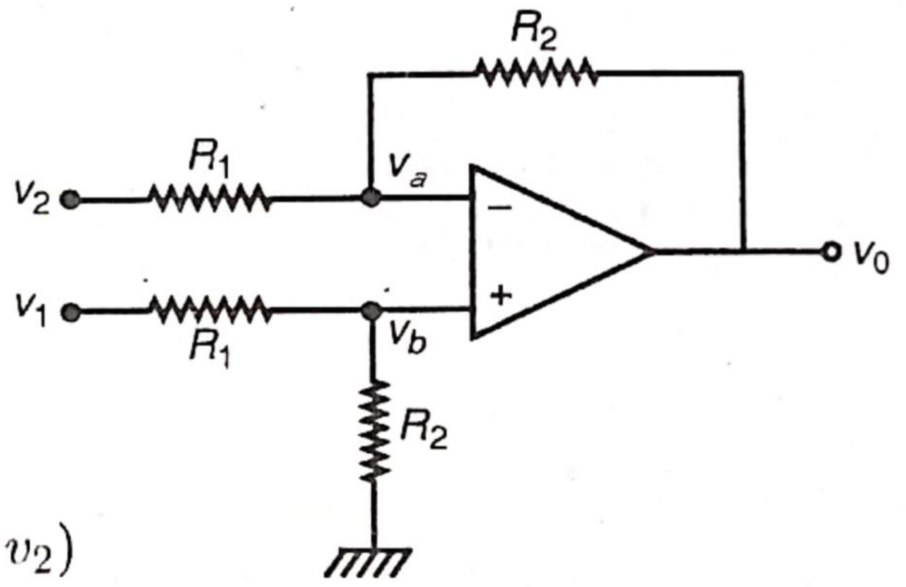
So the potentials v_a and v_b are equal as shown in the circuit.

Also, same current flows through R_1 and R_2.

Therefore,

$$\frac{v_2 - v_a}{R_1} = \frac{v_a - v_0}{R_2} \qquad (1)$$

$$\frac{v_1 - v_b}{R_1} = \frac{v_b - 0}{R_2} \qquad (2)$$



Putting $v_a = v_b$, and subtracting eq. (2) from (1), we get, $v_0 = \frac{R_2}{R_1}(v_1 - v_2)$

Thus, the circuit amplifies the difference of two input signals.

Subtractor: If we choose $R_1 = R_2$, then we get $v_0 = (v_1\text{-}v_2)$, then the circuit acts as a subtractor

Integrator

The output of this circuit is proportional to the integration of input signal.
Here A is a virtual ground, so same current flows through R and C.
Therefore,

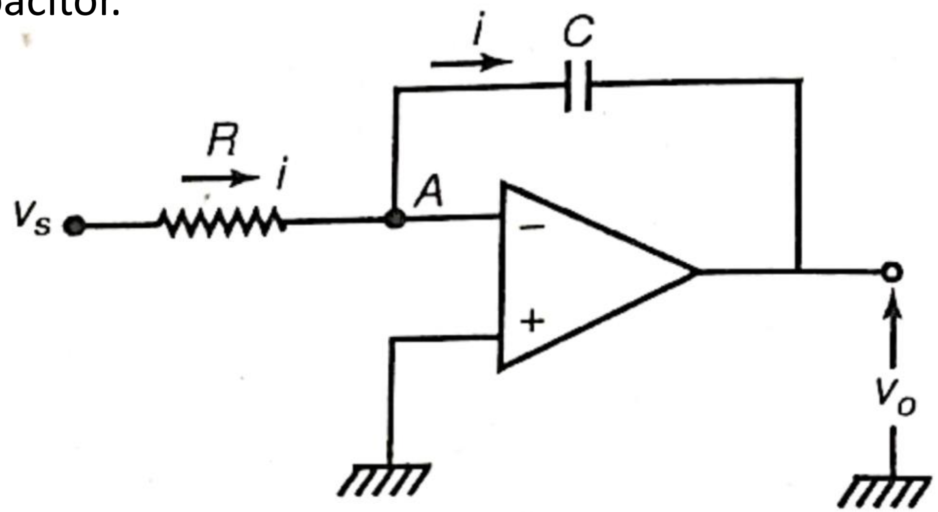
$$i = \frac{v_s - 0}{R} = \frac{dq}{dt} = -\frac{d}{dt}(Cv_0)$$

where, we take $\boldsymbol{q = C(0-v_0)}$ as the instantaneous charge on the capacitor.

So, the output voltage is,

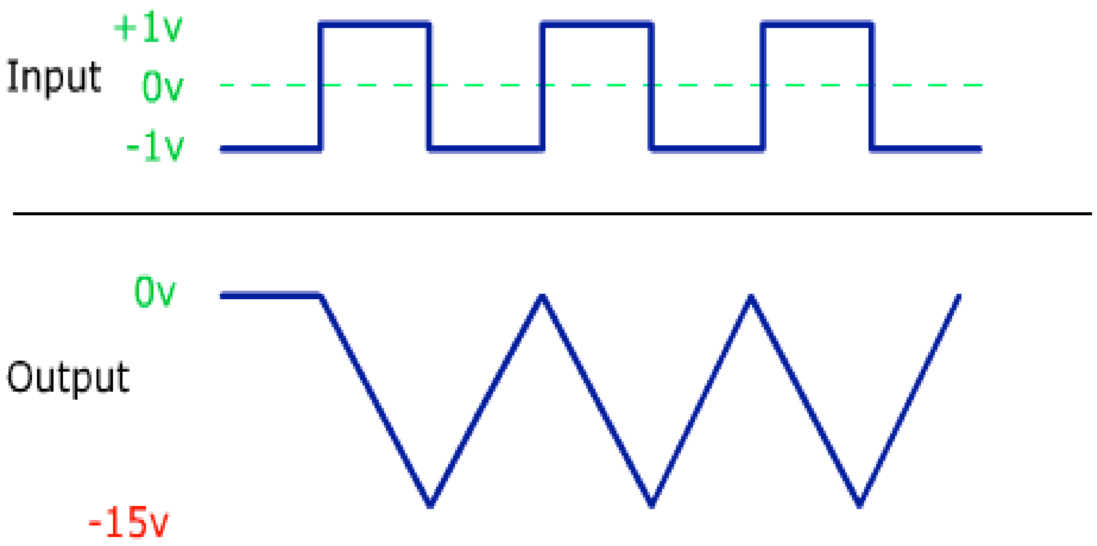
$$v_o = -\frac{1}{CR}\int v_s dt$$

The output is the integration of the input signal



Op-Amp Integrator

- An integrating op-amp circuit can create a sawtooth signal if a square wave is applied at V_{in}



Differentiator

Output is proportional to the time derivative of the input.

Since, A can be treated as virtual ground and practically same current flows through C and R, so

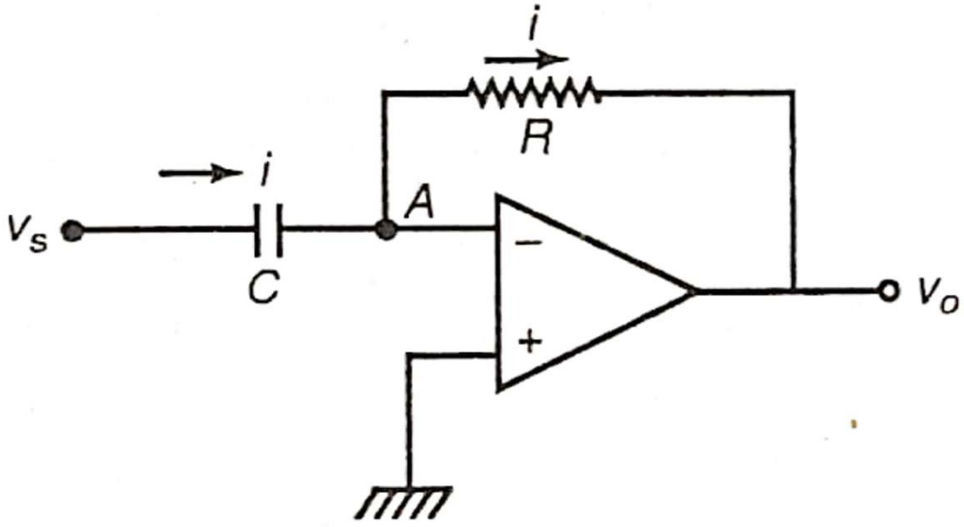
$$i = \frac{dq}{dt} = \frac{d}{dt}(Cv_s) = \frac{0 - v_0}{R}$$

Where q = Cv_s is the instantaneous charge on the capacitor.

Therefore,

$$v_o = -CR\frac{dv_s}{dt}$$

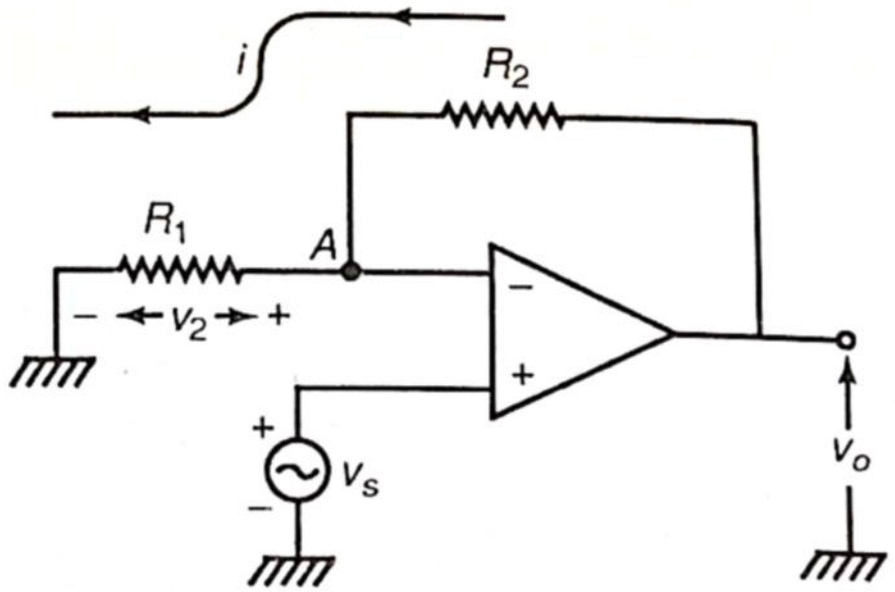
The output is the time derivative of the input signal



Voltage to current converter

Very often, it is necessary to convert a voltage signal to a proportional output current. A non-inverting amplifier can be used for this purpose.
Since the potential at the point A tends to the input voltage vs, the current through R_1 is $i = v_s/R_1$
Almost the same current flows through R_2 and thus the current R_2 is independent of R_2 and is proportional to the input voltage v_s.
This circuit can be used as a voltage to current converter.

Such a circuit is used in driving the deflection coil in a television tube



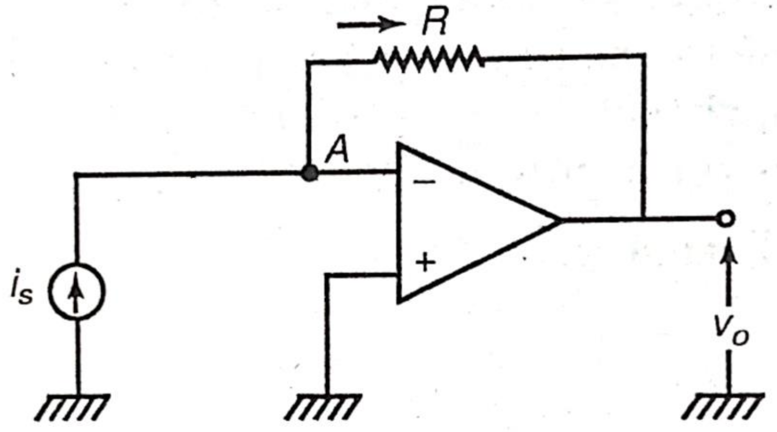
Current to voltage converter

This is a current to voltage converter circuit in which the output is proportional to the input current.

Since, A is virtual ground, whole input signal i_s passes through the feedback resistor R. Thus,

$$v_0 = -i_s R$$

Obviously, the output voltage is proportional to the input current

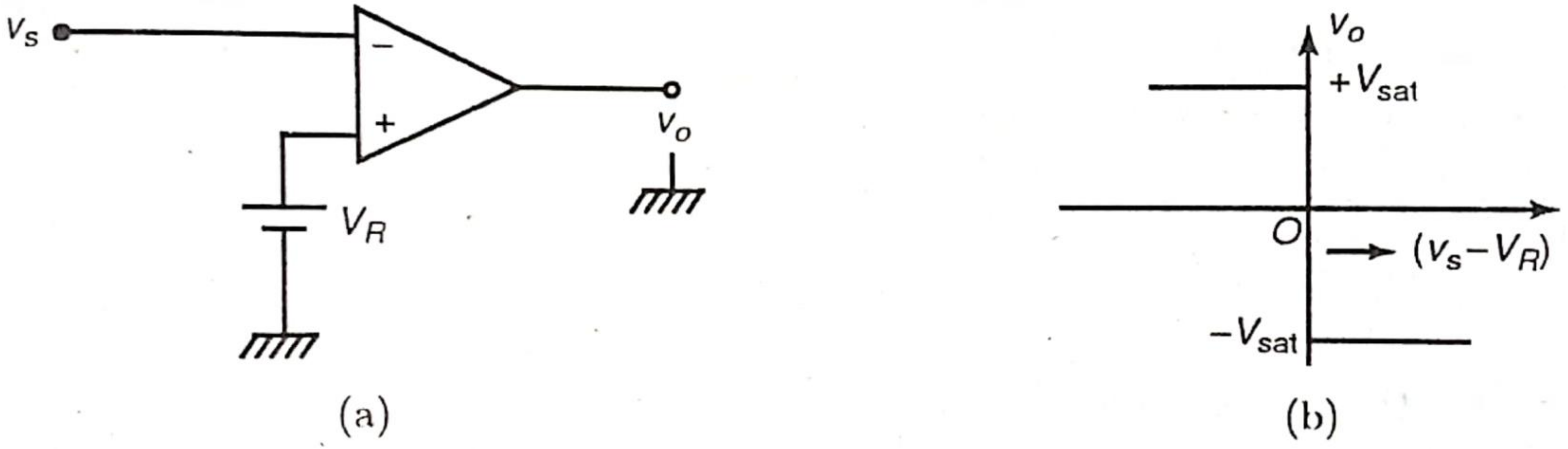


Voltage comparator and square wave generator

Comparator is a circuit which can compare two voltages. In this circuit, input signal v_s can be compared with a reference voltage V_R. When $v_s < V_R$, the output goes to maximum positive saturation value ($+V_{sat}$).

When v_s crosses V_R towards the region $v_s > V_R$, the op-amp output switches to the negative saturation value ($-V_{sat}$).
Thus by looking at the output voltage we can instantly identify whether vs is greater or less than V_R

The comparator circuit can be used to generate a symmetric square wave from sine wave by just taking $V_R = 0$ and choosing v_s as the sinusoidal wave.



Voltage comparator (a) circuit (b) output

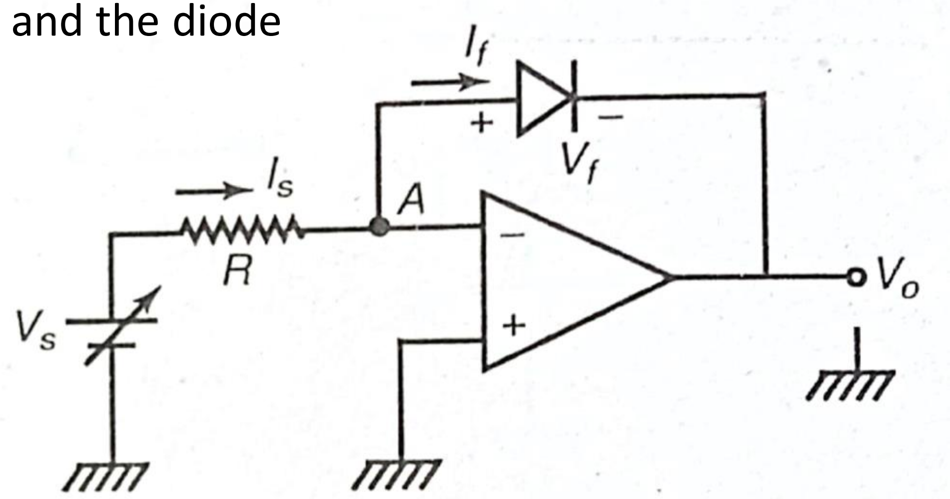
Logarithmic and exponential amplifier

Since, there is a virtual ground at A, and almost same current passes through R and the diode

$$I_s = I_f \quad \text{or,} \quad \frac{V_s - 0}{R} = I_0\left(e^{\frac{eV_f}{\eta KT}} - 1\right)$$

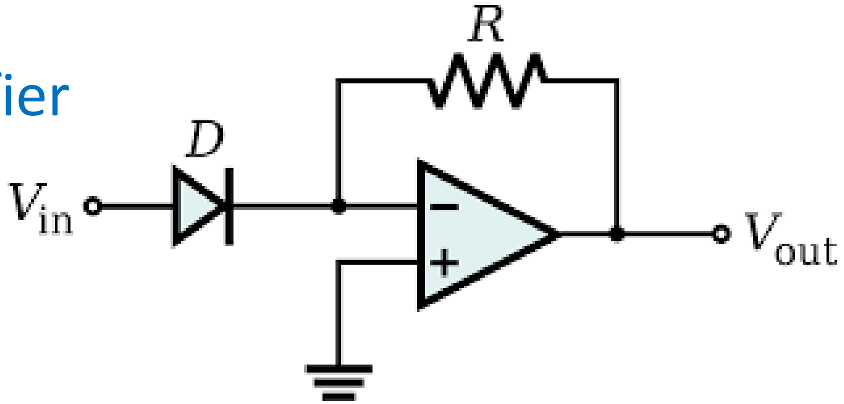
$$\approx I_0 e^{\frac{eV_f}{\eta KT}}$$

$$V_0 = -V_f = -\frac{\eta KT}{e}\ln\frac{V_s}{I_0 R}$$

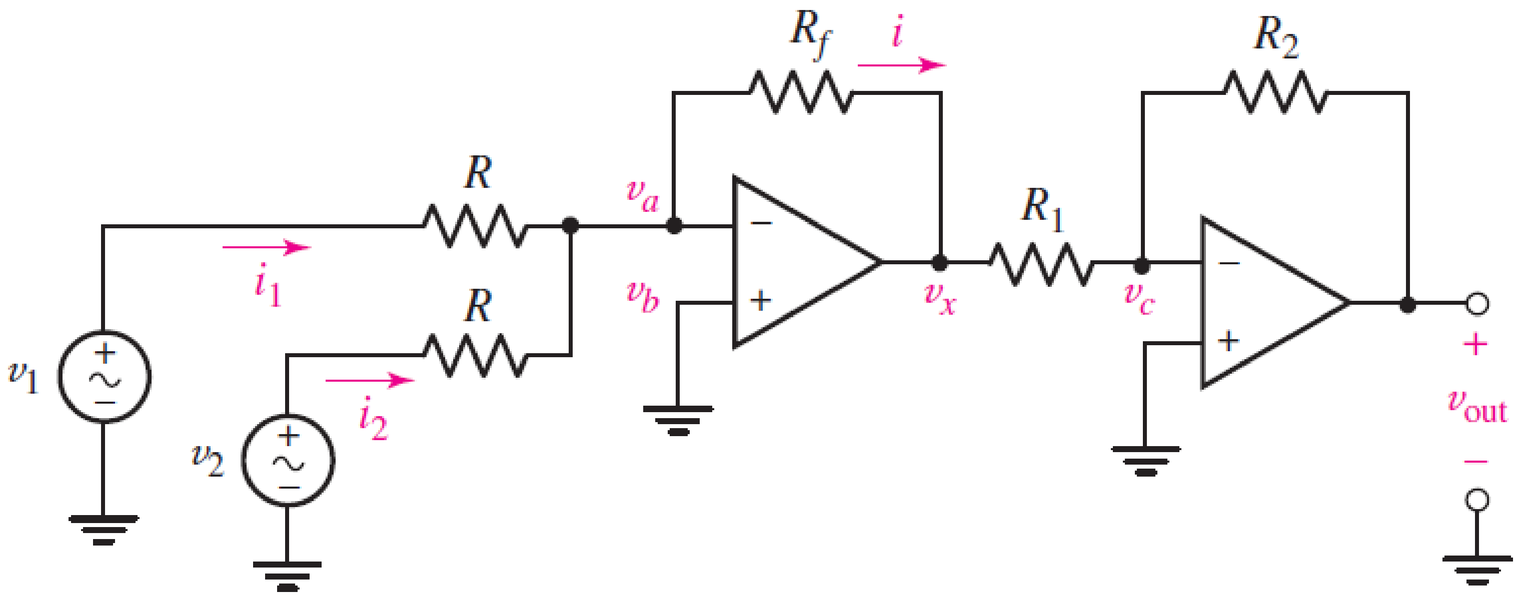


where I_0 is the reverse saturation current and η = 1 for Ge and approximately 2 for Si-made diode. Thus the output is proportional to the logarithm of the input voltage.

Exponential amplifier



Cascaded stages



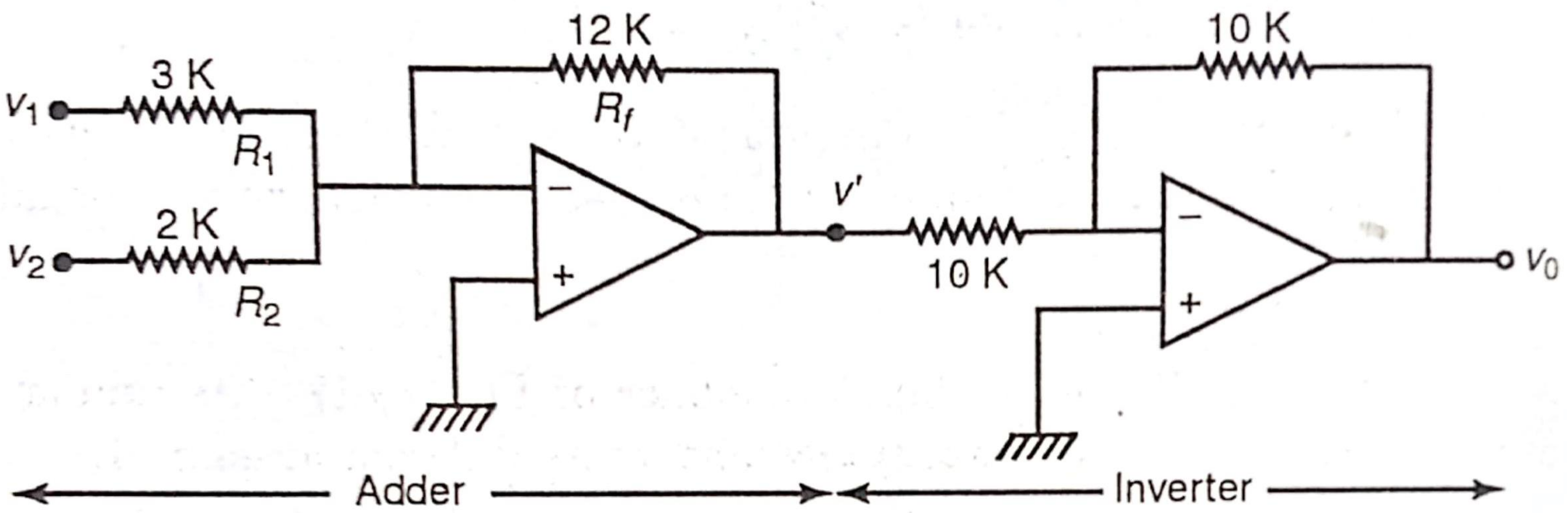
$$v_x = -\frac{R_f}{R}(v_1+v_2)$$

$$v_{out} = -\frac{R_2}{R_1} v_x$$

$$= \frac{R_2}{R_1}\frac{R_f}{R}(v_1+v_2)$$

Exercise

Draw a circuit using one or more op-amp whose output v_0 is given as $v_0 = 4v_1 + 6v_2$, where v_1 and v_2 are the input signals

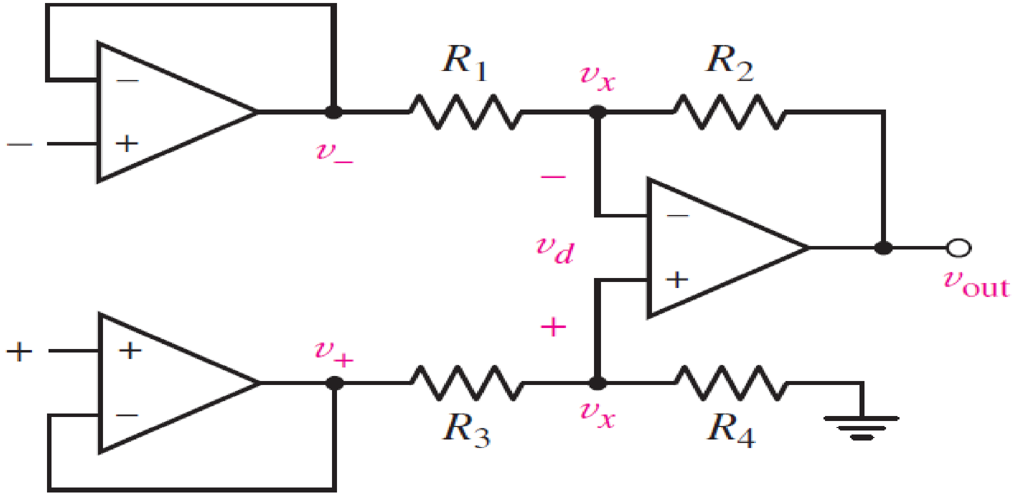


$$v' = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2\right) = -(4v_1 + 6v_2)$$

Now the inverter output $v_0 = -v' = 4v_1 + 6v_2$

Instrumentation amplifier using op-amp

Instrumentation amplifier is a kind of differential amplifier with additional input buffer stages. The addition of input buffer stages makes it easy to match (impedance matching) the amplifier with the preceding stage.



$$\frac{v_x - v_-}{R_1} + \frac{v_x - v_{out}}{R_2} = 0 \quad -(I)$$

$$\frac{v_x - v_+}{R_3} + \frac{v_x}{R_4} = 0 \quad -(II)$$

$$v_x = \frac{v_+}{1 + \frac{R_3}{R_4}}$$

$$v_{out} = \frac{R_4}{R_3}\left(\frac{1 + R_2/R_1}{1 + R_4/R_3}\right) v_+ - \frac{R_2}{R_1} v_-$$

$$\frac{R_4}{R_3} = \frac{R_2}{R_1} = K$$

$$v_{out} = K(v_+ - v_-)$$

Presentation Outline

- What is an Op-Amp?
- Characteristics of Ideal and Real Op-Amps
- Common Op-Amp Circuits
- **Applications of Op-Amps**
- References

Applications

- Active filters
  - Signal processing
  - Digital Image processing
- Strain gauges
- Control circuits
  - PID controllers (proportional–integral–derivative controller)
  - PI controllers for temperature, flow, pressure, speed, etc. measurement circuitry
- And much more…

Applications - Filters

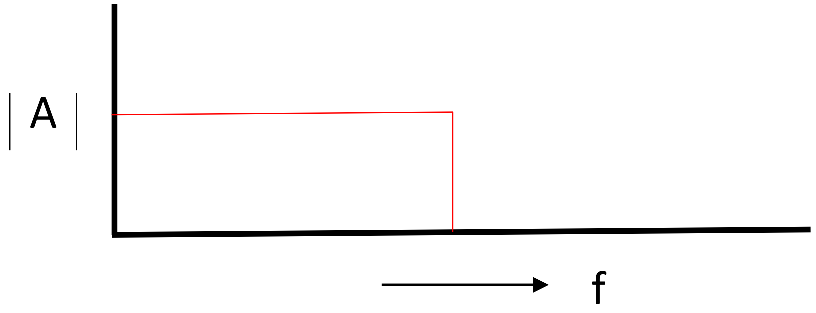
<u>Types:</u>

•Low pass filter

•High pass filter

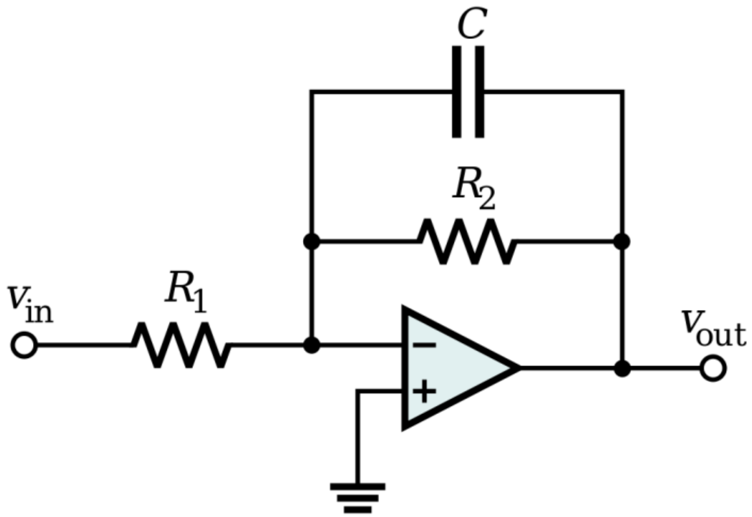
•Band pass filter

•Band stop filter

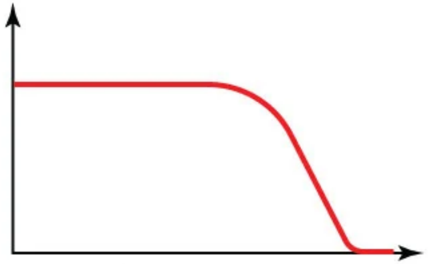


Low-Pass Filter

low pass filter only allows low frequency signals



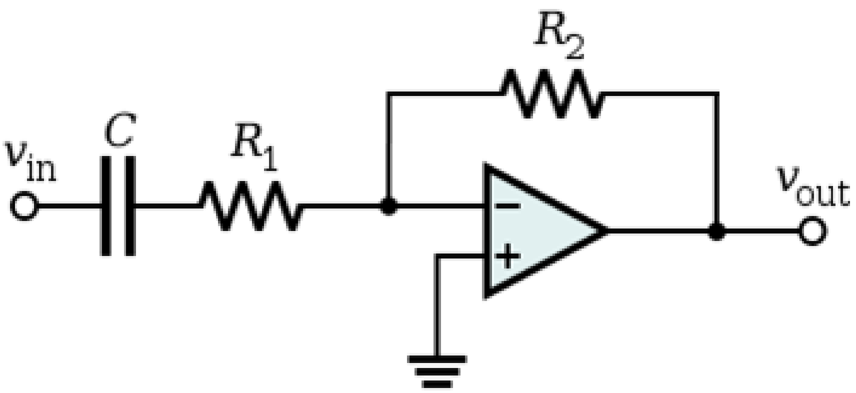
- Attenuates frequencies above the cutoff frequency.
- Cutoff frequency (Hz):
  - $f_c = \dfrac{1}{2\pi R_2 C}$
- Gain in the passband:
  - $G = -\dfrac{R_2}{R_1}$



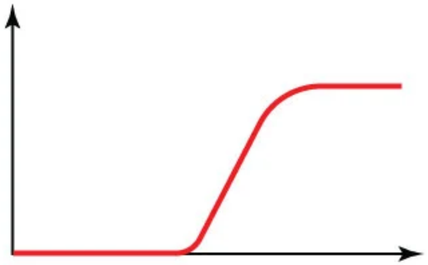
Low-pass

High-Pass Filter

attenuates low frequencies and passes high frequency signals



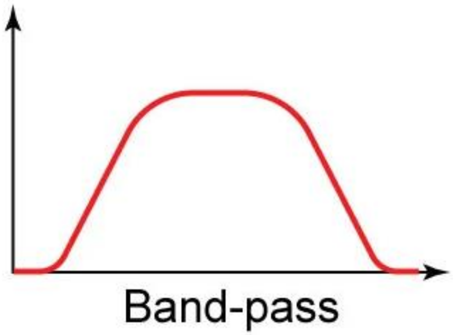
- Attenuates frequencies below the cutoff frequency.
- Cutoff frequency (Hz):
  - $f_c = \dfrac{1}{2\pi R_1 C}$
- Gain in the passband:
  - $G = -\dfrac{R_2}{R_1}$

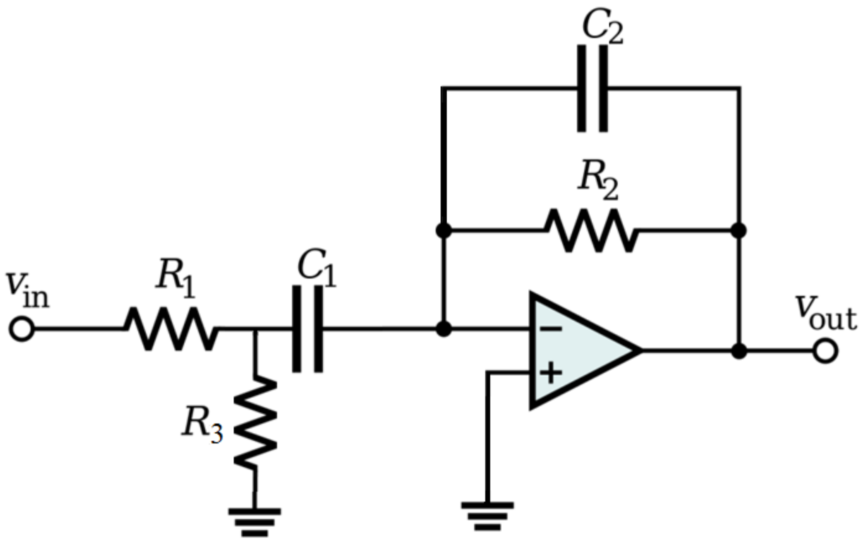


High-pass

Bandpass Filter

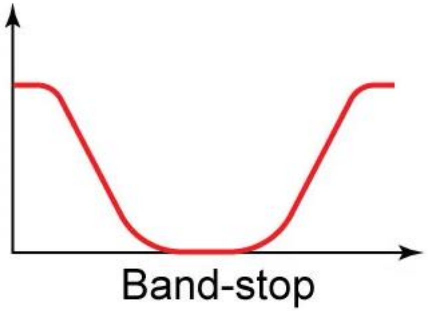
A band pass filter is a frequency selector. It allows one to select or pass only one particular band of frequencies from all other frequencies that may be present in the circuit.

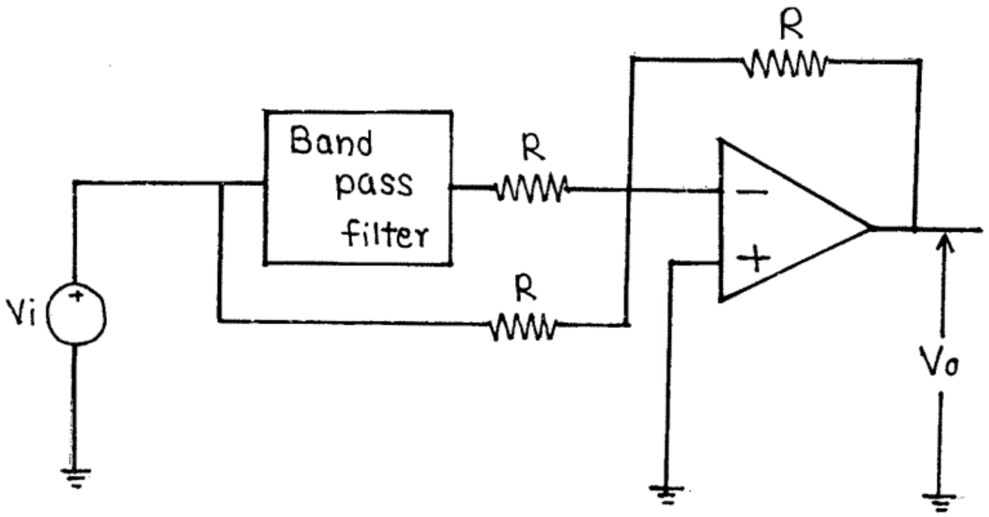




Band Stop (Notch) Filter

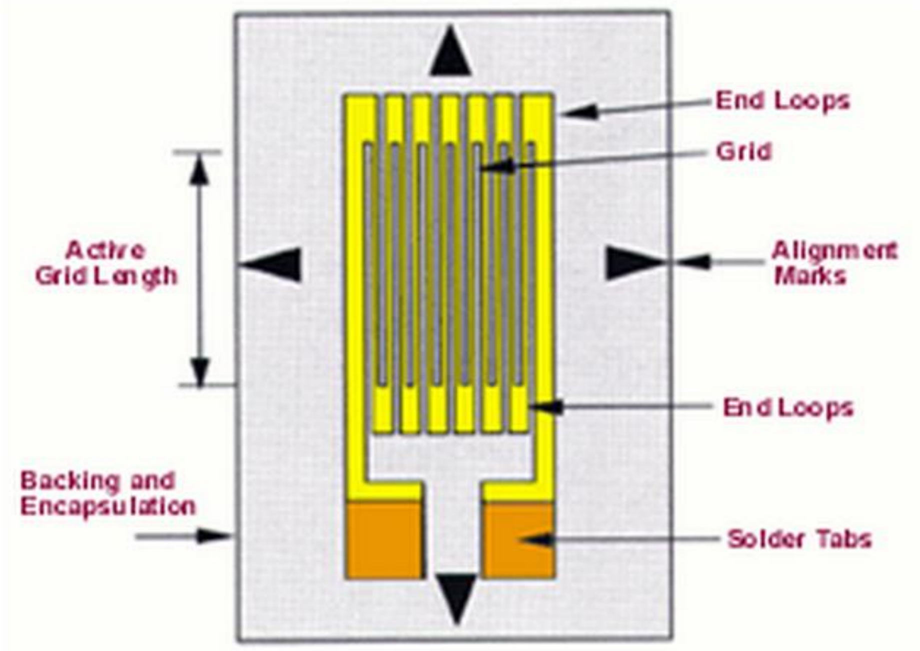
A band reject filter or notch filter is one which passes all frequencies except a single band





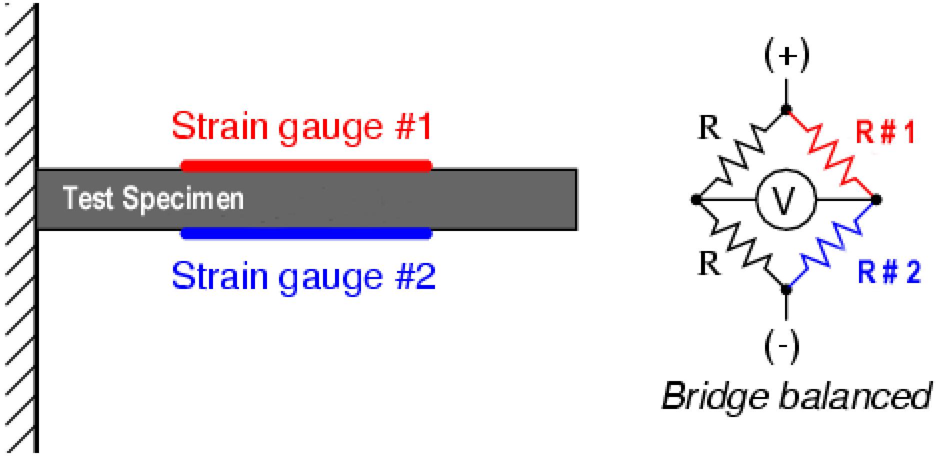
Notch filter using band pass filter and summing amplifier

Strain Gauge

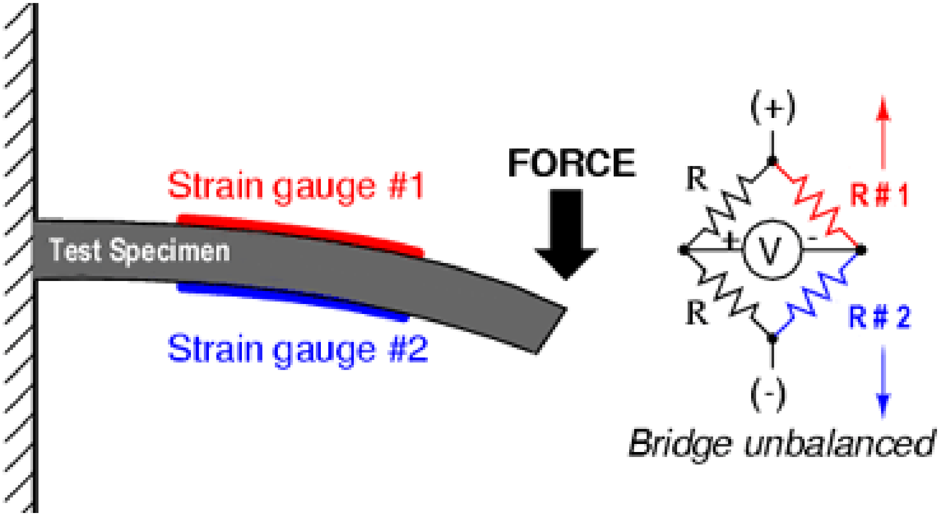


- Strain gauges consist of a pattern of resistive foil mounted on a backing material.
- As the foil is subjected to stress, the resistance of the foil changes in a defined way.
- This results in an output signal directly related to the stress value, typically a few millivolts.
- Op-Amps are utilized to amplify the output signal level to 5~10 V, a suitable level for application to data collection systems.

Strain Gauge Applications



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

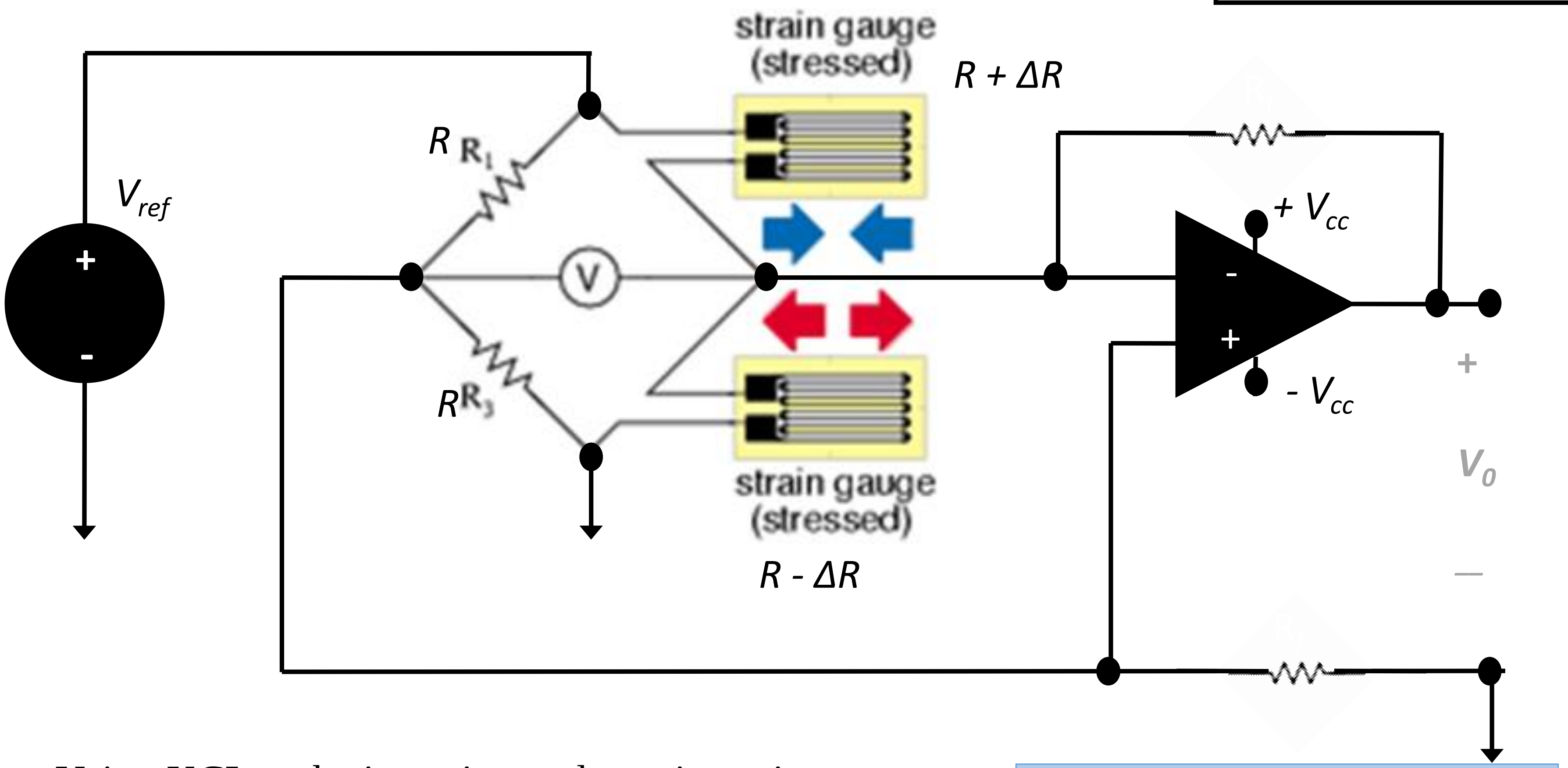
(Strain) Unbalanced Bridge

R #1 ≠ R #2

Strain Gauge Applications

Half-Bridge Arrangement

Op amp used to amplify output from strain gauge



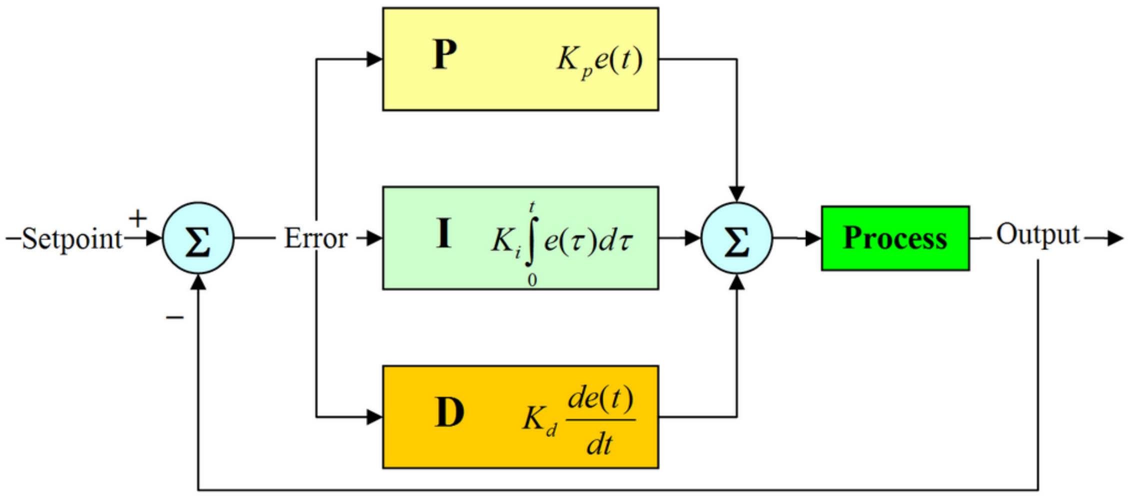
Using KCL at the inverting and non-inverting terminals of the op amp we find that ➔

$\varepsilon \sim V_o = 2\Delta R(R_f/R^2)$

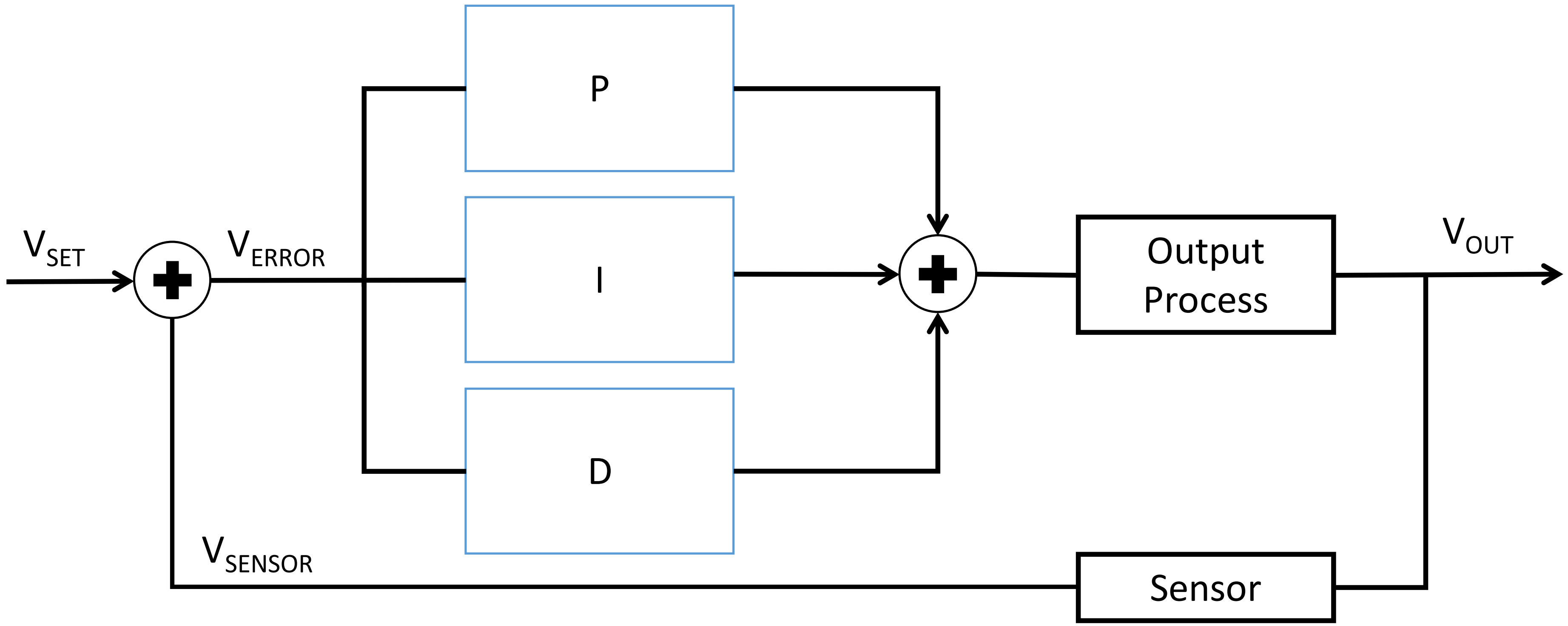
PID Controller

- A proportional-integral-derivative (PID) controller is a generic feedback mechanism widely used in industrial control systems.
- It calculates an “error” value as the difference between a measured process variable and a desired setpoint.
- Using this error, it calculates a control input using tuning parameters K_p, K_d, and K_i to drive the error to zero.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt} e(t)$$



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 $\sim V_{SET}$

PID Controller

- So where do op-amps come in?
  - The error is calculated using a Summing Op-Amp.
  - Using this error voltage:
    - The derivative of the error is calculated using a Derivative Op-Amp.
    - The integral of the error is calculated using an Inverting Op-Amp.
  - The tuning parameters K_p, K_d, and K_i can be selected by appropriate selection of resistors and capacitors.

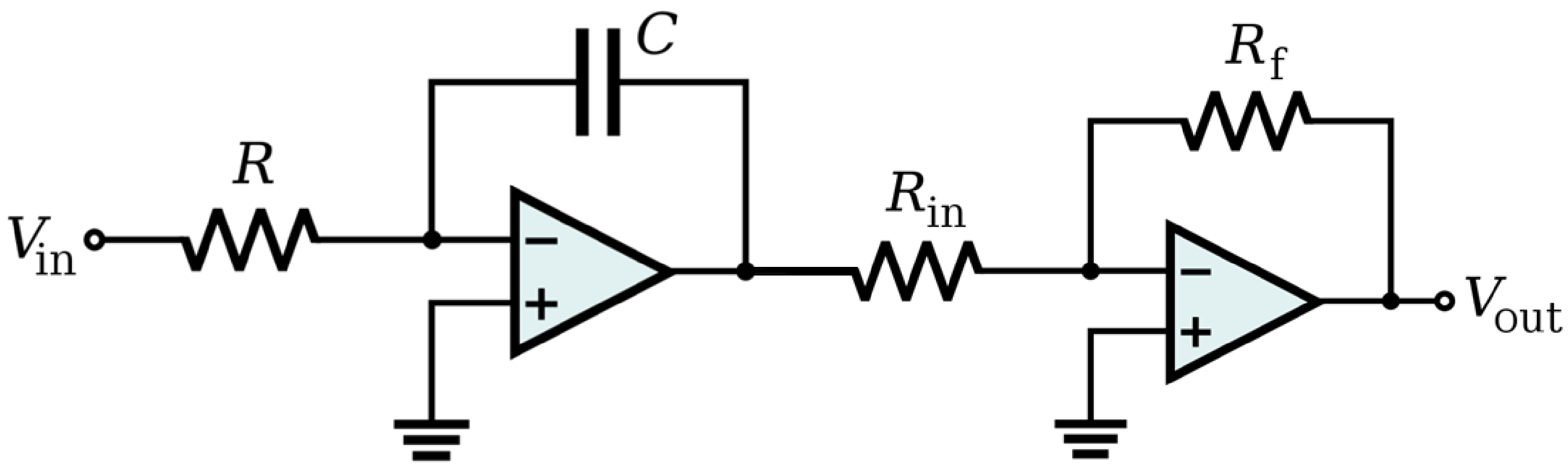
And much more…

- Comparators
- Detectors
    - Threshold detector
    - Zero-level detector
- Oscillators
    - Wien bridge oscillator
    - Relaxation oscillator
- Level shifters

Outline Presentation

- Introduction
- Characteristics of Ideal and Real Op-Amps
- Basic Circuits of Op-Amps
- Applications
- Exercise

Exercise



- Consider the circuit above running for 5 seconds. Find $V_{out}(5)$ when:
  - $V_{out}(0) = 0$
  - $V_{in}(\mathrm{t}) = 3\mathrm{t}$
  - $R = 5M\Omega$, $C = 5\mu$, $R_{in} = 10k\Omega$, $R_f = 20k\Omega$

Exercise

1. Design circuits to obtain following outputs:

   - $.v_0 = -\, v_1 \; - 10\, v_2 \; - 5\, v_3$
   - $v_0 = \; v_1 \; - 10\, v_2 \; - 5\, v_3$
   - $v_0 = -10\, v_1 + 10\, v_2$
   - $v_0 = -5 \int v_1 \, dt$ $\quad$ v_1 *is a pulse input with amplitude* $1\, V$ *and pulse width* $1\, s$.
   - $v_0 = -10 \, \frac{dv_1}{dt} + v_1 \; - 10\, v_2 \; - 5\, v_3$ $\quad$ v_1 *is cosine function with frequency 100 Hz and peak amplitude of 1 V*

2. How can I get square wave from a sinusoidal input using op amp?

3. How do I get triangular waveform from a square waveform?