CIS009-2, Mechatronics
Operational Amplifiers

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Outline

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Electrical Measurements

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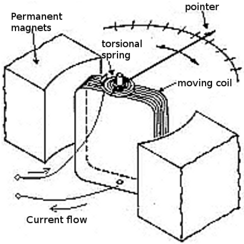
Electrical Measurements

Ammeter & Voltmeter

- Measurements of currents, potential differences, and resistances in electrical circuits require various specialised instruments.
- The first part of this lecture will be concerned with the instruments used for electrical measurements in DC (Direct Current).

Moving Coil Meters

- Most electrical measurements performed with **ammeters** and **voltmeters** - similar mechanisms:
  - sensitive small coil of wire suspended between poles of magnet; suffers deflection when current passes through it.



Electrical Measurements

Ammeter & Voltmeter

Ammeter Measures electric current flowing into its terminals

- **Low internal resistance** permits passage of whatever current enters its terminals without hindrance.
- *Must be connected in series* - low internal resistance will draw current from rest of circuit if connected in parallel.

Voltmeter Measures potential difference applied to its terminals

- **Large internal resistance** draws only an extremely small current, even when a potential difference applied to its terminals is large.
- *Must be connected in parallel* - large internal resistance will, in effect, stop flow of circuit current in series.

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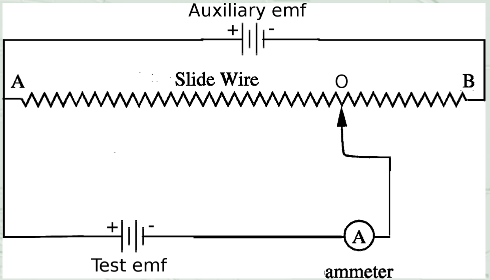
Voltmeter

Disadvatage of using a Voltmeter

- The Voltemeter does draw a small amount of current to measure a voltage.
- Sometimes this can be undesireable - when measuring the emf of a battery.
  - When a Voltmeter is conneted across the terminls of a battery, it draws a small amount of current.
  - The potential difference between the terminals will be reduced by the drop in the internal resistance of the battery.
    - *The electrolyte in a battery always has some resistance, causing the current to suffer a voltage drop before it leaves the terminals of the battery - the labels on batteries refer to the potential difference when no current is flowing (open circuit voltage)*

Potentiometer
An electrical balance

- Compares an unknown emf with a known reference emf.
- Comparison is made indirectly, in two steps, by means of a third auxiliary emf.



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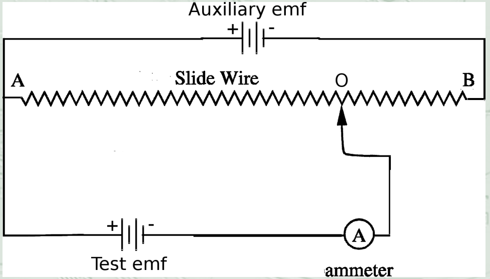
Potentiometer

An electrical balance

- Auxiliary emf connected to long wire of high resistance (AB).
- Potential along wire will be linearly decreasing function of the length of wire (AO)
- Experimenter moves contact (O) until ammeter reads zero.
- under these conditions the emf of the unknown source exactly matches the potential drop along the length (AO), and the potetniometer is said to be balanced.



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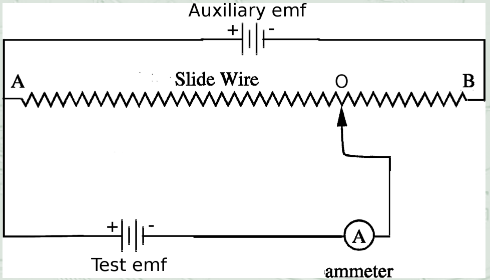
Potentiometer
An electrical balance

- Experimenter then repleces the unknown emf with a reference emf (known) and balances the potentiometer.
- The ratio of the old potential drop (AO) to the new potential drop (AO’) is equal to the ration of the unknown emf to the reference emf.
- From this the unknown emf can be directly calculated.
- This is a more reliable calibration of the potential than from a voltmeter.



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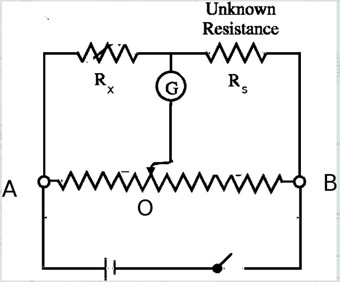
Wheatstone Bridge

To find unknown resistances

- Operation based on similar principles as the potentiometer.
- Precise comparisons of an unknown resistance with a known reference resistance.



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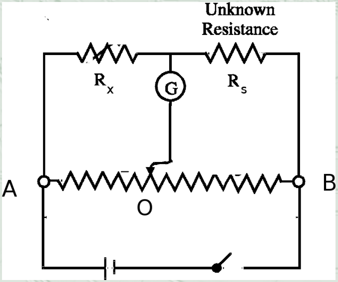
Wheatstone Bridge

To find unknown resistances

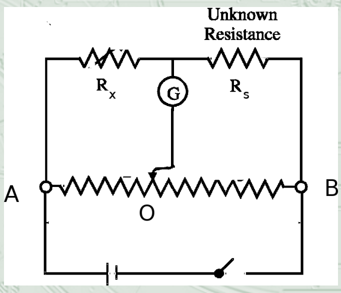
- One end of unknown resistance is connected to (A) and one end of a known resistance is connected to (B).
- Other ends are connected to an Ammeter (G)
- Experimenter balances the bridge (as in the case of the potentiometer) until the ammeter reads zero (so no current flows between (GO))



Wheatstone Bridge

To find unknown resistances

- Potential drop V_x must be equal to the potential drop (AO).
- Potential drop V_s must be equal to the potential drop (BO).
- Taking the ration of these proportionalities we find
$$\frac{R_x}{R_s} = \frac{AO}{BO}.$$
- This equation permits the direct calculation of the unknown resistance.

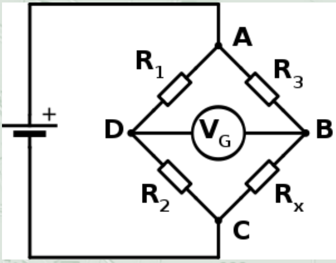


Wheatstone Bridge

The Conventianal circuit

- A Wheatstone bridge can be used to measure capacitance, inductance, impedance, as well as resistance.

$$R_x = \frac{R_2}{R_1} R_3$$



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Differential Amplifier

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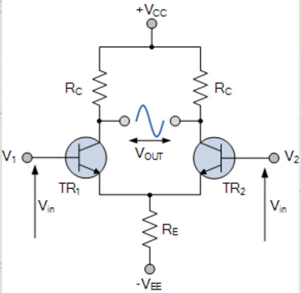
A Differential Amplifier

The Long-tailed Pair

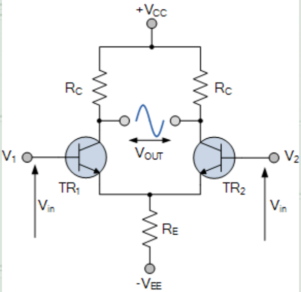
- Amplifies the difference between two voltages.
- Differential amplifiers often used to null out noise or bias-voltages that appear at both inputs.
- Supplies, $+V_{cc}$ and $-V_{ee}$, ensure a constant supply.
- Output, V_{out}, is the difference between the two input signals (two base inputs are in anti-phase)
  - As forward bias of TR_1 is increased, the forward bias of TR_2 is reduced.
  - Current flowing through the common emitter resistor R_e will remain constant.



A Differential Amplifier
The Long-tailed Pair

- Output signal is balanced; collector voltages either swing in opposite directions (anti-phase) or in the same direction (in-phase)
- Assuming a perfectly balanced circuit there is zero difference between the two collector voltages.
- Known as the *Common Mode of Operation* with the common mode gain (A_c) of the amplifier being the output gain when the input is zero.
- With the differential gain A_d:

$$V_{out} = A_d(V_1 - V_2) + A_c\left(\frac{V_1 + V_2}{2}\right)$$



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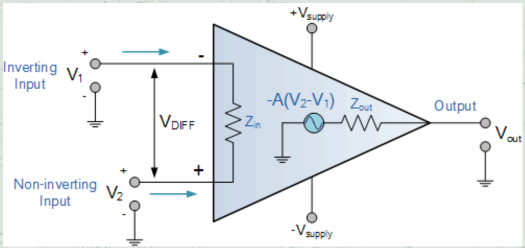
Operational Amplifier

The Ideal Operational Amplifier

An introduction to Op-Amps

- basic building blocks of Analogue Electronic Circuits.
- Operational amplifiers are used extensively in signal conditioning, filtering, add, subtract, integration and differentiation.
- An ideal Operational Amplifier is three-terminal device,
  - two high impedance inputs, one called the Inverting Input (-) and the other Non-inverting Input (+).
  - one output can sink and source either a voltage or a current.



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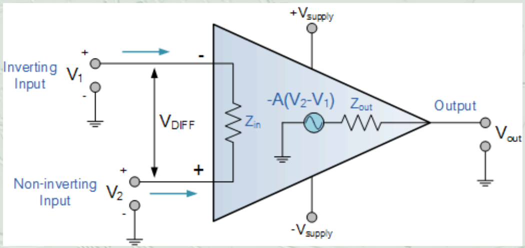
The Ideal Operational Amplifier

An introduction to Op-Amps

1. The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.
2. The inputs draw no current.

- Open-loop-gain, $A_{V0} = \infty$ (gain of op-amp without positive/negative feedback)
- Input impedance, $Z_{in} = \infty$ (ratio of input voltage to input current)
- Output impedance, $Z_{out} = 0$ (perfect internal voltage source; no internal R)
- Bandwidth, $BW = \infty$ (amplify any DC signal to highest AC frequencies)
- Offset Voltage, $V_{io} = 0$ (output zero when difference between inputs is zero)



The 741 Operational Amplifier
An introduction to Op-Amps

- Most commonly available and used of all operational amplifiers is the industry standard μA-741.

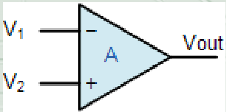


Figure : Op-Amp symbol

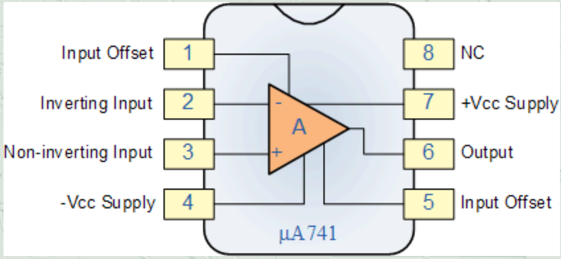


Figure : The 741 Op-Amp pin connection diagram (*orientation indicated by semi-circular notch*)

Negative Feedback

Stablising the Op-Amp

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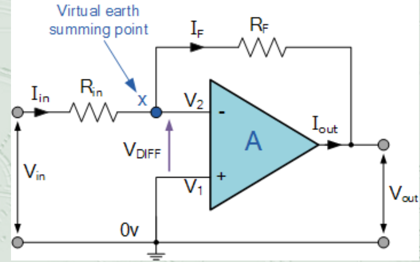
- As the open loop DC gain is extremely high
- can afford to lose some gain by connecting a suitable resistor from the output terminal back to the inverting input terminal using an external Feedback Resistor called R_f
- produces effect known as Negative Feedback, and gives a very stable Operational Amplifier system.
  - Negative Feedback is "feeding back" a fraction of output signal back to input,
  - feedback connection between output and inverting input forces the differential input voltage towards zero.
- produces a closed loop circuit resulting Closed-loop Gain.
- accurately control the overall gain of amplifier, but at a cost in reduction of amplifier bandwidth.
- inverting input will have a different signal than the actual input voltage
  - sum of the input voltage plus the negative feedback voltage.
  - must separate the real input signal from the inverting input by using an Input Resistor, R_{in}.

Inverting Amplifier Configuration

Closed loop operation of Op-Amp

- Inverting Amplifier circuit - operational amplifier connected with feedback to produce closed loop operation.
- For ideal op-amps, two rules about inverting amplifiers:
  1. no current flows into the input terminal
  2. $V_1 = V_2$



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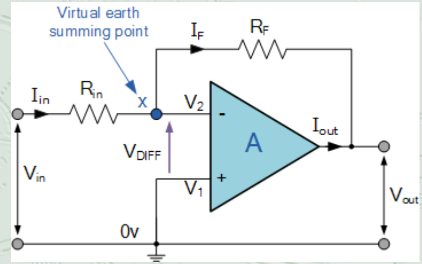
Inverting Amplifier Configuration

The Virtual Earth

- (X) at the same potential as positive (+) input which is 0V (ground); (X) is "Virtual Earth".
- input resistance of amplifier is equal to the value of the input resistor, R_{in}.
- closed loop gain set by the ratio of two external resistors.
- Differential Input Voltage is Zero as $V_1 = V_2 = 0$ (Virtual Earth).
- can derive the equation for calculating the closed-loop gain.



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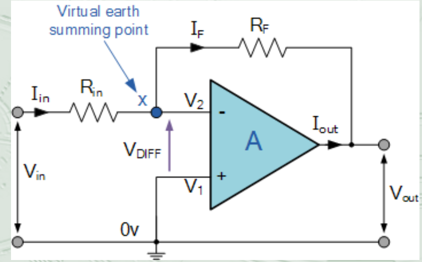
Inverting Amplifier Configuration

Closed-loop gain derivation

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

$$= \frac{V_{in} - V_2}{R_{in}} = \frac{V_2 - V_{out}}{R_f}$$

therefore, $$\frac{V_{in}}{R_{in}} = V_2\left(\frac{1}{R_{in}} + \frac{1}{R_f}\right) - \frac{V_{out}}{R_f}$$



Inverting Amplifier Configuration

Closed-loop gain derivation

$$
\begin{aligned}
i =& \frac{V_{in} - V_{out}}{R_{in} + R_f} \\
=& \frac{V_{in} - V_2}{R_{in}} = \frac{V_2 - V_{out}}{R_f} \\
\text{therefore, } \frac{V_{in}}{R_{in}} =& V_2 \left(\frac{1}{R_{in}} + \frac{1}{R_f} \right) - \frac{V_{out}}{R_f} \\
\text{since, } i =& \frac{V_{in} - 0}{R_{in}} = \frac{0 - V_{out}}{R_f} \text{ then } \frac{R_f}{R_{in}} = \frac{0 - V_{out}}{V_{in} - 0}
\end{aligned}
$$

- Which defines the **closed-loop gain** of an inverting amplifier (A_v):

$$A_v = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}} \quad (1)$$

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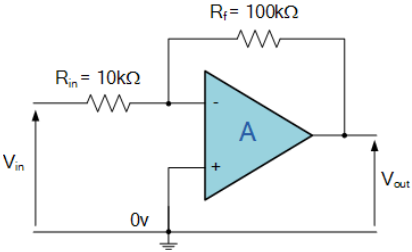
Example (closed loop gain calculation)

1. Find the closed loop gain of the following inverting amplifier circuit.
2. The gain of the original circuit is to be increased to 40, find the new values of the resistors required.

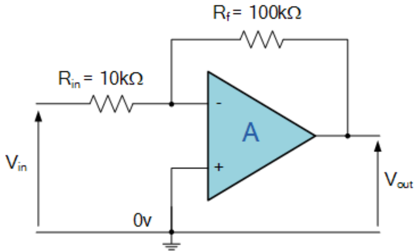


Inverting Amplifier Configuration

An Example

Example (closed loop gain calculation)

1. $A_v = 10$
2. $R_{in} = 10k\Omega$ and $R_f = 400k\Omega$



Inverting Buffer
The Unity Gain Inverter

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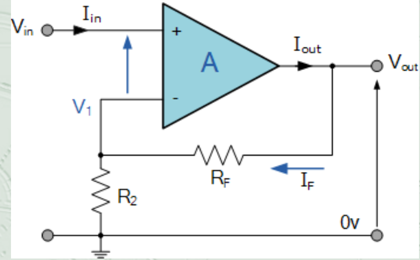
- We can imagine a special case for the Inverting Amplifier Configuration:
- If the two resistors are of equal value, $R_{in} = R_f$, then the gain of the amplifier will be -1 producing a complementary form of the input voltage at its output as $V_{out} = -V_{in}$.
- This type of inverting amplifier configuration is generally called a **Unity Gain Inverter** of simply an *Inverting Buffer*.

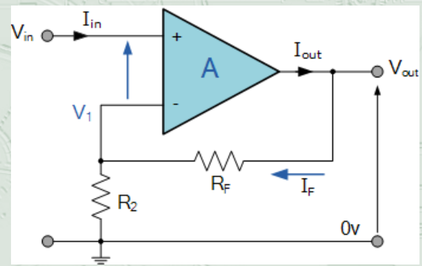
Non-Inverting Amplifier Configuration
Closed loop operation of Op-Amp

- V_{in} is applied directly to the non-inverting (+) input terminal
- Output gain of the amplifier becomes "Positive" in value in contrast to the Inverting Amplifier circuit whose output gain is negative in value.



Non-Inverting Amplifier Configuration
Feedback control

- Feedback control of non-inverting amplifier achieved by applying a small part of the output voltage back to the inverting (-) input via a $R_f - R_2$ voltage divider network (negative feedback).
  - R_{in} approaching ∞, as no current flows to positive input terminal
  - low output impedance, R_{out}



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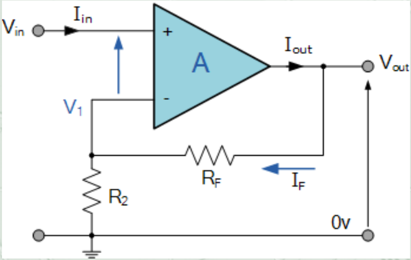
Non-Inverting Amplifier Configuration
Closed-loop gain derivation

$$V_1 = \left(\frac{R_2}{R_2 + R_f}\right) V_{out}$$

(ideal); $V_1 = V_{in}$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{R_2 + R_f}{R_2}$$



- giving the **closed loop gain** of a Non-inverting amplifier:

$$A_v = 1 + \frac{R_f}{R_2} \quad (2)$$

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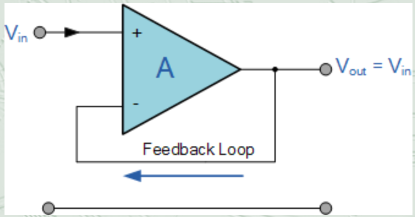
Voltage Follower

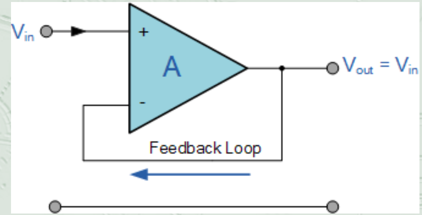
The Unity Gain Buffer

- We can imagine a special case for the Non-inverting Amplifier Configuration:
- If we made the feedback resistor $R_f = 0$ and $R_2 = \infty$, the circuit would have a fixed gain of $+1$ as all the output voltage would be present on the inverting input terminal (negative feedback).
- This would then produce a special type of the non-inverting amplifier circuit called a *Voltage Follower* also called a **unity gain buffer**.



Voltage Follower
The Unity Gain Buffer

- used in electronics to isolated circuits from each other.
- Also: voltage follower circuit with closed loop gain is Unity; voltage gain of an ideal operational amplifier with open loop gain (no feedback) is Infinite.
  - By carefully selecting the feedback components we can control the amount of gain produced by an operational amplifier anywhere from one to infinity.



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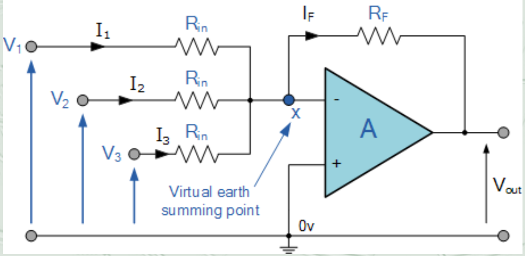
Summing Amplifier Configuration
Inverting Amplifier with multiple inputs

- The Summing Amplifier is a flexible circuit based on the Inverting Amplifier configuration that can be used for combining multiple inputs.
- If we add more input resistors to the input of the inverting amplifier, each equal in value to the original input resistor R_{in} we have a Summing Amplifier (also called *summing inverter* or *voltage adder* circuit).
- The output voltage V_{out} now becomes proportional to the sum of the input voltages, V_1, V_2, V_3.



Summing Amplifier Configuration

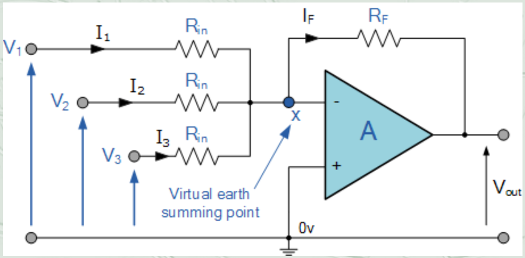
Inverting Amplifier with multiple inputs

$$I_F = I_1 + I_2 + I_3 = -\left(\frac{V_1}{R_{in}} + \frac{V_2}{R_{in}} + \frac{V_3}{R_{in}}\right)$$

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

- giving:

$$V_{out} = -\frac{R_F}{R_{in}}\left(V_1 + V_2 + V_3 + \dots\right) \tag{3}$$



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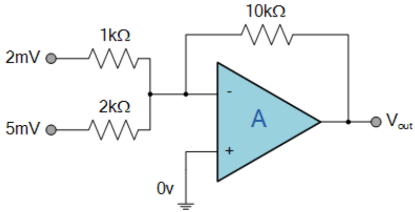
Scaling Summing Amplifier Configuration

Resistors with different values

- If the input resistors are of different values a “scaling summing amplifier” is produced which gives a weighted sum of the input signals.

Example (Scaling Summing Amplifier)

- What is V_{out} for the following circuit?



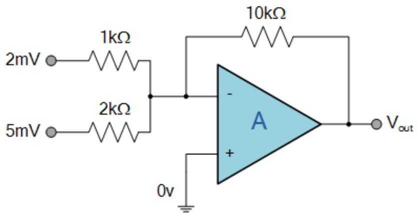
Scaling Summing Amplifier Configuration

Resistors with different values

- If the input resistors are of different values a "scaling summing amplifier" is produced which gives a weighted sum of the input signals.

Example (Scaling Summing Amplifier)

- $V_{out} = -45mV$



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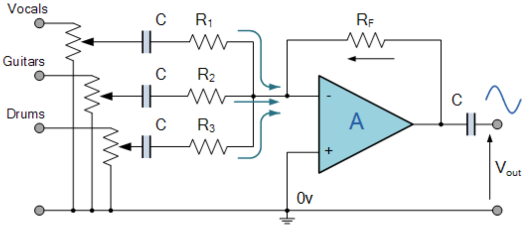
Scaling Summing Amplifier Configuration

An Application

Example (Audio Mixer)

- If the input resistances of a summing amplifier are connected to potentiometers the individual input signals can be mixed together by varying amounts. For example to produce an audio mixer for adding or mixing together individual waveforms (sounds) from different source channels (vocals, instruments, etc) before sending them combined to an audio amplifier.



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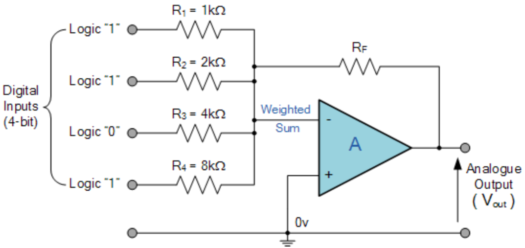
Scaling Summing Amplifier Configuration

An Application

Example (Digital to Analogue Converter)

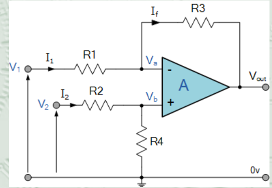
- Weighted sum digital-to-analogue converter - If input resistors R_{in} double in value for each input then a digital logical voltage, either a logic level "0" or a logic level "1" on these inputs will produce an output which is the weighted sum of the digital inputs.



Differential Amplifier Configuration

A subtractor

- Can connect signals to both of the inputs at the same time producing another common type of operational amplifier circuit called a Differential Amplifier.
- Connecting one voltage signal onto one input terminal and another voltage signal onto the other input terminal the resultant output voltage will be proportional to the "Difference" between the two input voltage signals of V_1 and V_2.
- differential amplifiers amplify the difference between two voltages making this type of operational amplifier circuit a *Subtractor*.

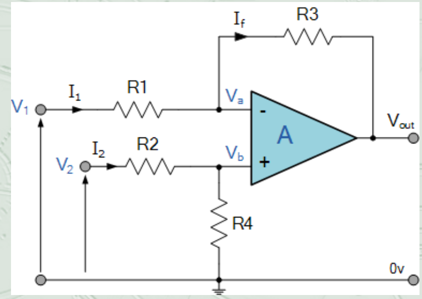


Differential Amplifier Configuration

A subtractor

$$I_1 = \frac{V_1 - V_a}{R_1}, \quad I_2 = \frac{V_2 - V_b}{R_2}, \quad I_f = \frac{V_f - (-V_{out})}{R_3}$$

$$V_a = V_b = V_2 \left(\frac{R_4}{R_2 + R_4} \right)$$



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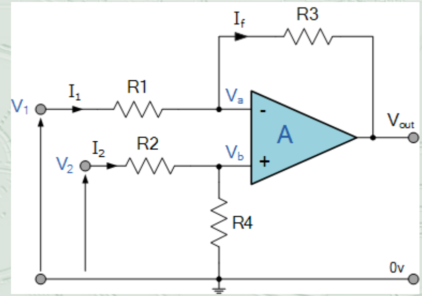
Differential Amplifier Configuration

A subtractor

If $V_b = 0$ then $V_{out(a)} = -V_1 \dfrac{R_3}{R_1}$

If $V_a = 0$ then $V_{out(b)} = V_2 \dfrac{R_4}{R_2 + R_4} \dfrac{R_1 + R_3}{R_1}$

$$V_{out} = -V_1 \frac{R_3}{R_1} + V_2 \frac{R_4}{R_2 + R_4} \frac{R_1 + R_3}{R_1}$$



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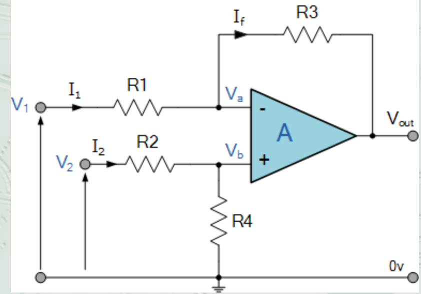
Differential Amplifier Configuration

A subtractor

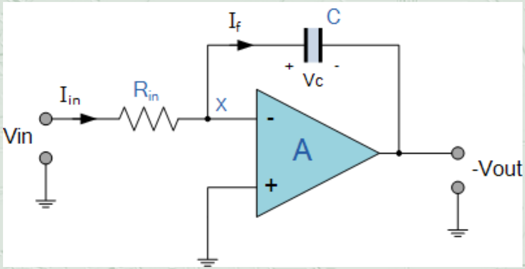
- When resistors $R_1 = R_2$ and $R_3 = R_4$ the above transfer function for the differential amplifier can be simplified to the following expression:

$$V_{out} = \frac{R_3}{R_1}(V_2 - V_1) \quad (4)$$



Other Common Configurations

The Integrator Amplifier



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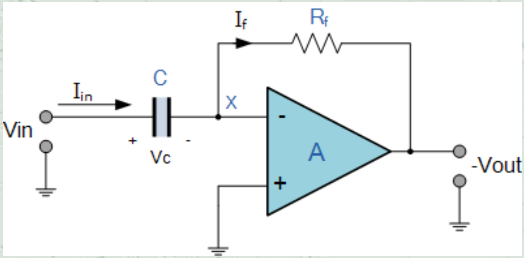
Other Common Configurations

The Differentiator Amplifier



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Resources

Resources

This lecture references the following sources of information

- H. Ohanian - Physics (2nd ed.)
- P. Horowitz, W. Hill - The Art of Electronics (2nd ed.)
- Wayne Storr - Basic Electronics Tutorials - http://www.electronics-tutorials.ws/opamp/

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