Biomedical Instrumentation

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Amplifiers and Signal Processing

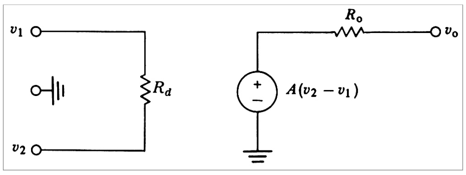
Applications of Operational Amplifier In Biological Signals and Systems

- The three major operations done on biological signals using Op-Amp:
  - Amplifications and Attenuations
  - DC offsetting:
    - add or subtract a DC
  - Filtering:
    - Shape signal's frequency content

Ideal Op-Amp

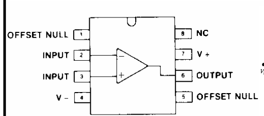
- Most bioelectric signals are small and require amplifications

Op-amp equivalent circuit:

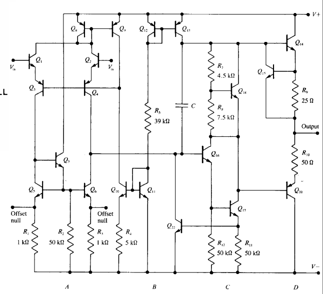


The two inputs are v_1 and v_2. A differential voltage between them causes current flow through the differential resistance R_d. The differential voltage is multiplied by A, the gain of the op amp, to generate the output-voltage source. Any current flowing to the output terminal v_o must pass through the output resistance R_o.

Inside the Op-Amp (IC-chip)

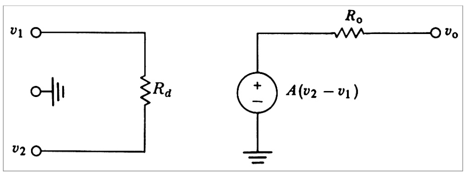


741 op amp



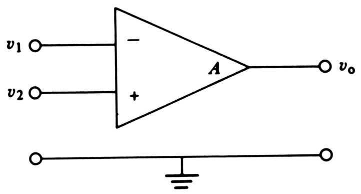
20 transistors
11 resistors
1 capacitor

Ideal Characteristics



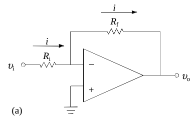
- $A = \infty$ (gain is infinity)
- $V_o = 0$, when $v_1 = v_2$ (no offset voltage)
- $R_d = \infty$ (input impedance is infinity)
- $R_o = 0$ (output impedance is zero)
- Bandwidth = ∞ (no frequency response limitations) and no phase shift

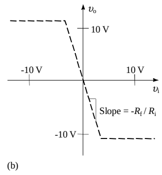
Two Basic Rules



- **Rule 1**
  - When the op-amp output is in its linear range, the two input terminals are at the same voltage.
- **Rule 2**
  - No current flows into or out of either input terminal of the op amp.

Inverting Amplifier



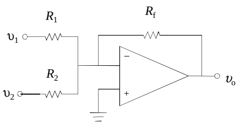


$$v_o = -\frac{R_f}{R_i} v_i \qquad G = \frac{v_o}{v_i} = -\frac{R_f}{R_i}$$

(a) An inverting amplified. Current flowing through the input resistor R_i also flows through the feedback resistor R_f.

(b) The input-output plot shows a slope of $-R_f / R_i$ in the central portion, but the output saturates at about ±13 V.

Summing Amplifier



$$v_o = -R_f\left(\frac{v_1}{R_1} + \frac{v_2}{R_2}\right)$$

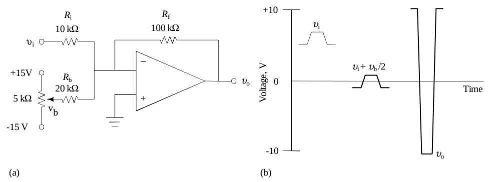
Example 3.1

- The output of a biopotential preamplifier that measures the electro-oculogram is an undesired dc voltage of ±5 V due to electrode half-cell potentials, with a desired signal of ±1 V superimposed. Design a circuit that will balance the dc voltage to zero and provide a gain of -10 for the desired signal without saturating the op amp.

Answer 3.1

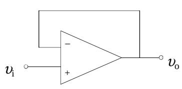
- We assume that v_b, the balancing voltage at v_i=5 V. For v_o=0, the current through R_f is zero. Therefore the sum of the currents through R_i and R_b, is zero.

$$\frac{v_o}{R_i} + \frac{v_b}{R_b} = 0 \quad \Rightarrow \quad R_b = \frac{-R_i v_b}{v_i} = \frac{-10^4(-10)}{5} = 2\times10^4\Omega$$



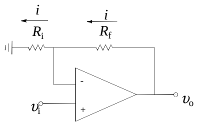
Follower (buffer)

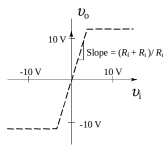
- Used as a buffer, to prevent a high source resistance from being loaded down by a low-resistance load. In another word it prevents drawing current from the source.



$$v_o = v_i \qquad G = 1$$

Noninverting Amplifier





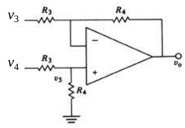
$$v_o = \frac{R_f + R_i}{R_i} v_i \qquad G = \frac{R_f + R_i}{R_i} = \left(1 + \frac{R_f}{R_i}\right)$$

Differential Amplifiers

- **Differential Gain G_d**

$$G_d = \frac{v_o}{v_4 - v_3} = \frac{R_4}{R_3}$$

- **Common Mode Gain G_c**
  - For ideal op amp if the inputs are equal then the output = 0, and the $G_c = 0$.
  - No differential amplifier perfectly rejects the common-mode voltage.



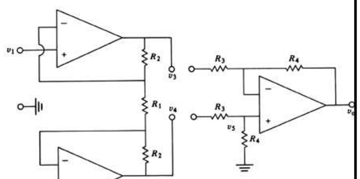
$$v_o = \frac{R_4}{R_3}(v_4 - v_3)$$

- **Common-mode rejection ratio *CMMR***
  - Typical values range from 100 to 10,000

$$CMRR = \frac{G_d}{G_c}$$

- Disadvantage of one-op-amp differential amplifier is its low input resistance

Instrumentation Amplifiers



Differential Mode Gain

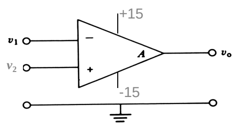
$$v_3 - v_4 = i(R_2 + R_1 + R_2)$$

$$v_1 - v_2 = iR_1$$

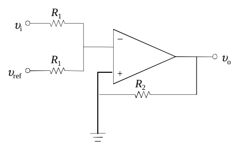
$$G_d = \frac{v_3 - v_4}{v_1 - v_2} = \frac{2R_2 + R_1}{R_1}$$

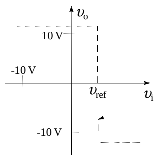
Advantages: High input impedance, High CMRR, Variable gain

Comparator – No Hysteresis



v_1* > *v_2*, *v_o = -13 V
v_1* < *v_2*, *v_o = +13 V

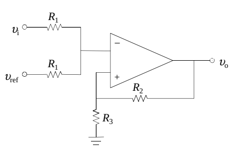


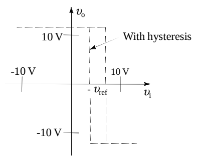


If $(v_i + v_{ref}) > 0$ then v_o = -13 V else v_o = +13 V
R_1 will prevent overdriving the op-amp

Comparator – With Hysteresis

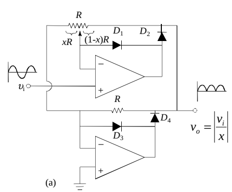
- Reduces multiple transitions due to mV noise levels by moving the threshold value after each transition.

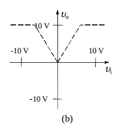




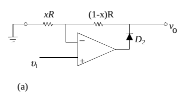
Width of the Hysteresis $= 4V_{R3}$

Rectifier

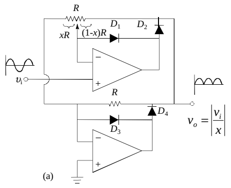


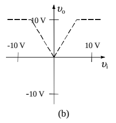


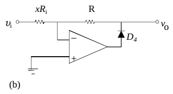
- Full-wave precision rectifier:
  - For $v_i > 0$, D_2 and D_3 conduct, whereas D_1 and D_4 are reverse-biased. Noninverting amplifier at the top is active



Rectifier







- Full-wave precision rectifier:
  - For $\upsilon_i < 0$,
    D_1 and D_4 conduct, whereas D_2 and D_3 are reverse-biased.
    Inverting amplifier at the bottom is active

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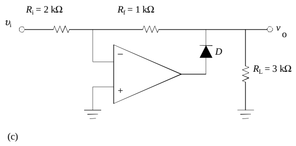
One-Op-Amp Full Wave Rectifier



- For $\upsilon_i < 0$, the circuit behaves like the inverting amplifier rectifier with a gain of +0.5. For $\upsilon_i > 0$, the op amp disconnects and the passive resistor chain yields a gain of +0.5.

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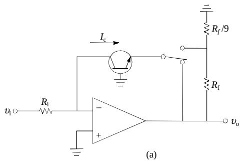
Logarithmic Amplifiers

- **Uses of Log Amplifier**
  - Multiply and divide variables
  - Raise variable to a power
  - Compress large dynamic range into small ones
  - Linearize the output of devices



$$V_{BE} = 0.06\log\left(\frac{I_C}{I_S}\right)$$

$$v_o = 0.06\log\left(\frac{v_i}{R_i \cdot 10^{-13}}\right)$$

(a) A logarithmic amplifier makes use of the fact that a transistor's V_{BE} is related to the logarithm of its collector current.
For range of I_c equal 10^{-7} to 10^{-2} and the range of υ_o is -.36 to -0.66 V.

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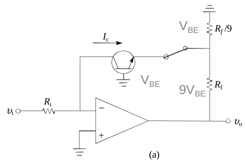
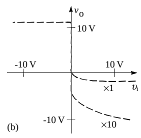
Logarithmic Amplifiers





(a) With the switch thrown in the alternate position, the circuit gain is increased by 10. (b) Input-output characteristics show that the logarithmic relation is obtained for only one polarity; ×1 and ×10 gains are indicated.

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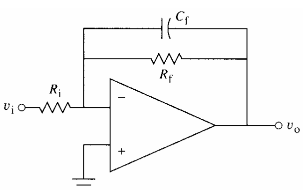
Integrators

$$v_o = -\frac{1}{R_i C_f}\int_0^{t_1} v_i\,dt + v_{ic}$$

$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{Z_f}{Z_i}$$

$$\frac{V_o(j\omega)}{V_i(j\omega)} = \frac{-R_f}{R_i + j\omega R_f R_i C}$$

$$\frac{V_o(j\omega)}{V_i(j\omega)} = \frac{-1}{\frac{R_i}{R_f} + j\omega R_i C}$$



$$\frac{v_o}{v_i} = \frac{-R_f}{R_i} \quad \text{for } f < f_c$$

$$f_c = \frac{1}{2\pi R_f C_f}$$

A large resistor R_f is used to prevent saturation

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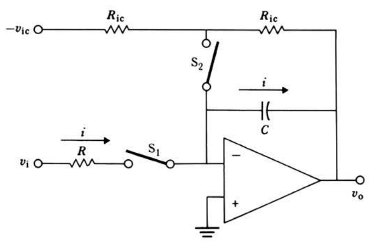

- **A three-mode integrator**
  With S_1 open and S_2 closed, the dc circuit behaves as an inverting amplifier. Thus $\upsilon_o = \upsilon_{ic}$ and υ_o can be set to any desired initial conduction. With S_1 closed and S_2 open, the circuit integrates. With both switches open, the circuit holds υ_o constant, making possible a leisurely readout.

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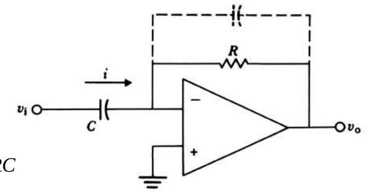
Differentiators

- **A differentiator**
  - The dashed lines indicate that a small capacitor must usually be added across the feedback resistor to prevent oscillation.

$$v_o = -RC\frac{dv_i}{dt}$$

$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{Z_f}{Z_i}$$

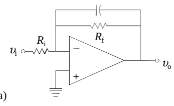
$$\frac{V_o(j\omega)}{V_i(j\omega)} = -j\omega RC$$

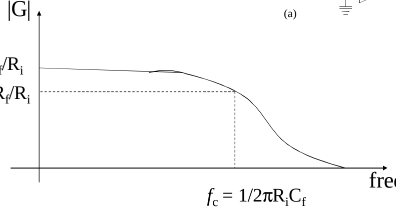


Active Filters- Low-Pass Filter

- A low-pass filter attenuates high frequencies

$$\text{Gain} = G = \frac{V_o(j\omega)}{V_i(j\omega)} = \frac{-R_f}{R_i}\frac{1}{1+j\omega R_f C_f}$$

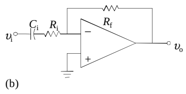


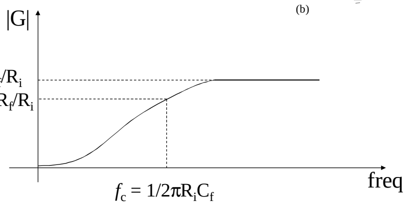


Active Filters (High-Pass Filter)

- A high-pass filter attenuates low frequencies and blocks dc.

$$\text{Gain} = G = \frac{V_o(j\omega)}{V_i(j\omega)} = \frac{-R_f}{R_i}\frac{j\omega R_i C_i}{1+j\omega R_i C_i}$$

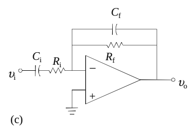


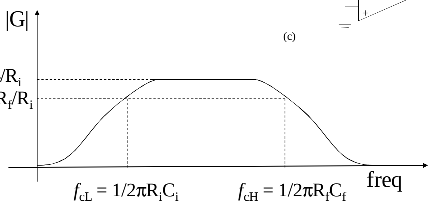


Active Filters (Band-Pass Filter)

- A bandpass filter attenuates both low and high frequencies.

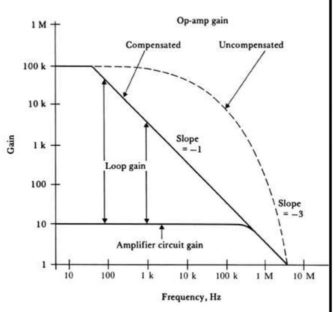
$$\frac{V_o(j\omega)}{V_i(j\omega)} = \frac{-j\omega R_f C_i}{(1+j\omega R_f C_f)(1+j\omega R_i C_i)}$$



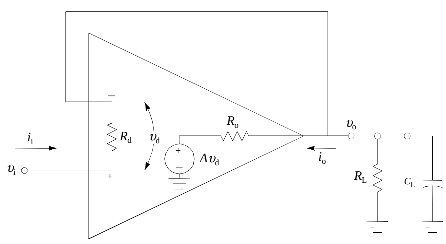


Frequency Response of op-amp and Amplifier

- Open-Loop Gain
- Compensation
- Closed-Loop Gain
- Loop Gain
- Gain Bandwidth Product
- Slew Rate



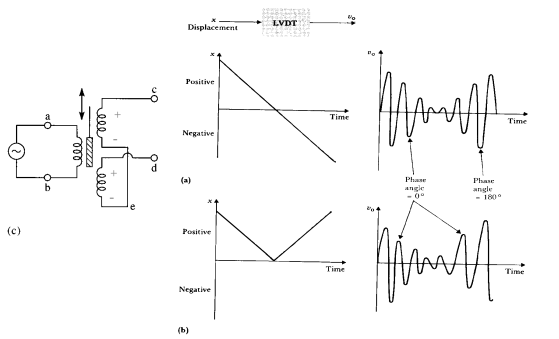
Input and Output Resistance



$$R_{ai} = \frac{\Delta v_i}{\Delta i_i} = (A+1)R_d \qquad R_{ao} = \frac{\Delta v_o}{\Delta i_o} = \frac{R_o}{A+1}$$

Typical value of R_d = 2 to 20 MΩ Typical value of R_o = 40 Ω

Phase Modulator for Linear variable differential transformer LVDT



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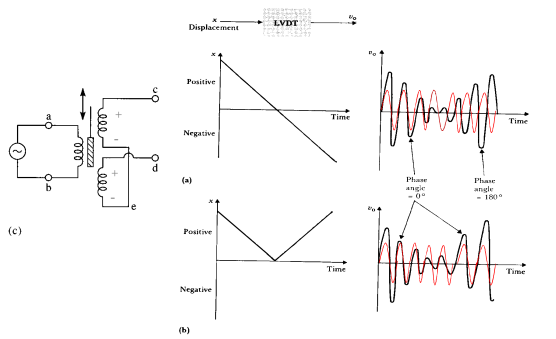
Phase Modulator for Linear variable differential transformer LVDT



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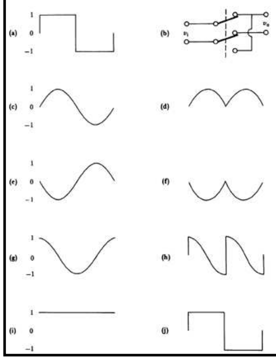
Phase-Sensitive Demodulator



Used in many medical instruments for signal detection, averaging, and Noise rejection

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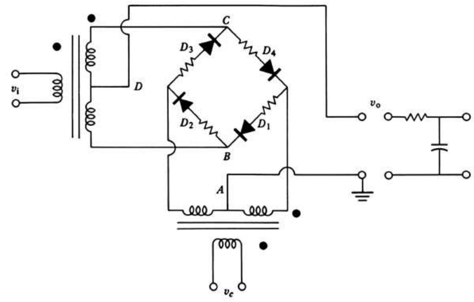
The Ring Demodulator

- If v_c is positive then D_1 and D_2 are forward-biased and $v_A = v_B$. So $v_o = v_{DB}$
- If v_c is negative then D_3 and D_4 are forward-biased and $v_A = v_c$. So $v_o = v_{DC}$



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