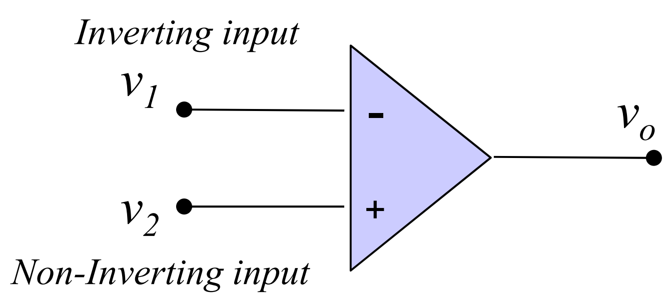
Operational Amplifiers

Lesson #5

Chapter 2

Operational Amplifiers

- An operational Amplifier is an ideal differential with the following characteristics:
  - Infinite input impedance
  - Infinite gain for the differential signal
  - Zero gain for the common-mode signal
  - Zero output impedance
  - Infinite Bandwidth



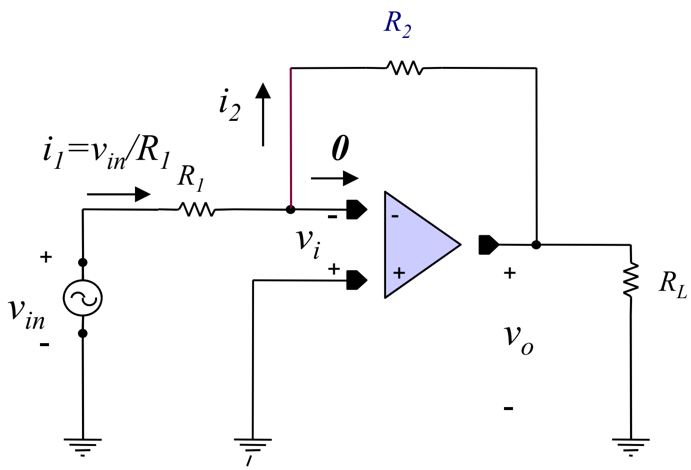
Operational Amplifier Feedback

- Operational Amplifiers are used with negative feedback
- Feedback is a way to return a portion of the output of an amplifier to the input
  - Negative Feedback: returned output opposes the source signal
  - Positive Feedback: returned output aids the source signal
- For Negative Feedback
  - In an Op-amp, the negative feedback returns a fraction of the output to the inverting input terminal forcing the differential input to zero.
  - Since the Op-amp is ideal and has infinite gain, the differential input will exactly be zero. This is called a virtual short circuit
  - Since the input impedance is infinite the current flowing into the input is also zero.
  - These latter two points are called the summing-point constraint.

Operational Amplifier Analysis Using the Summing Point Constraint

- In order to analyze Op-amps, the following steps should be followed:
  1. Verify that negative feedback is present
  2. Assume that the voltage and current at the input of the Op-amp are both zero (Summing-point Constraint
  3. Apply standard circuit analyses techniques such as Kirchhoff's Laws, Nodal or Mesh Analysis to solve for the quantities of interest.

Example: Inverting Amplifier



1. Verify Negative Feedback: Note that a portion of v_o is fed back via R_2 to the inverting input. So if v_i increases and, therefore, increases v_o, the portion of v_o fed back will then have the affect of reducing v_i (i.e., negative feedback).
2. Use the summing point constraint.
3. Use KVL at the inverting input node for both the branch connected to the source and the branch connected to the output

$$v_{in} = i_1 R_1 + 0 \text{ since } v_i \text{ is zero due to the summing - point constraint}$$
$$i_1 = i_2 \text{ due to the summing - point constraint}$$
$$v_0 = -i_2 R_2 + 0 \text{ since } v_i \text{ is zero}$$
$$= -\frac{R_2}{R_1} v_{in} \text{ which is independent of } R_L \text{ (note that the output is opposite to the input : inverted)}$$

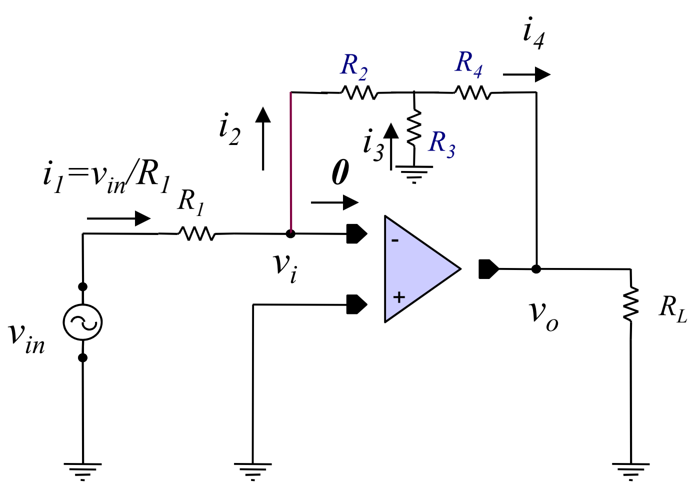
$$Z_{in} = \frac{v_{in}}{i_1} = \frac{i_1 R_1}{i_1} = R_1$$

Op-amp

- Because we assumed that the Op-amp was ideal, we found that with negative feedback we can achieve a gain which is:

1. Independent of the load
2. Dependent only on values of the circuit parameter
3. We can choose the gain of our amplifier by proper selection of resistors.

Another Example: Inverting Amplifier



1. Verify Negative Feedback:
2. Use the summing point constraint.
3. Use KVL at the inverting input node for the branch connected to the source and KCL & KVL at the node where the 3 resistors are connected

$$v_{in} = i_1 R_1 + 0 \text{ since } v_i \text{ is zero due to the summing-point constraint}$$

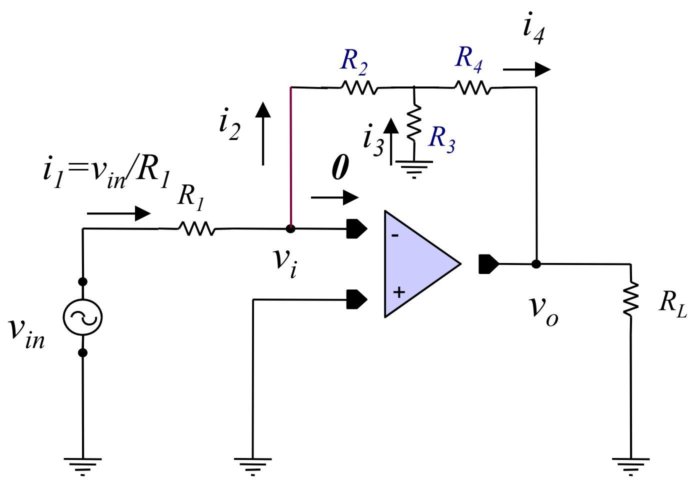
$$i_1 = i_2 \text{ due to the summing-point constraint}$$

$$v_i = i_2 R_2 - i_3 R_3 = 0 \Rightarrow i_2 R_2 = i_3 R_3 \text{ since } v_i \text{ is zero}$$

$$i_4 = i_3 + i_2$$

$$v_o = -R_4 i_4 - R_3 i_3$$

Another Example: Continued



$$i_2R_2 = i_3R_3 \Rightarrow i_3 = \frac{R_2}{R_3}i_2$$

$$v_{in} = i_1R_1 + 0; i_1 = i_2 \Rightarrow i_2 = \frac{v_{in}}{R_1}$$

$$i_4 = i_3 + i_2 = (\frac{R_2}{R_3} + 1)i_2 = (\frac{R_2}{R_3R_1} + \frac{1}{R_1})v_{in}$$

$$v_o = -R_4i_4 - R_3i_3 = -R_4(\frac{R_2}{R_3R_1} + \frac{1}{R_1})v_{in} - R_3\frac{R_2}{R_3}\frac{v_{in}}{R_1}$$

$$= -v_{in}(\frac{R_2R_4}{R_3R_1} + \frac{R_4}{R_1} + \frac{R_2}{R_1})$$

$$A_v = \frac{v_o}{v_{in}} = -(\frac{R_2R_4}{R_3R_1} + \frac{R_4}{R_1} + \frac{R_2}{R_1})$$

$$Z_{in} = R_{in} = \frac{v_{in}}{i_1} = R_1$$

$$v_{in} = i_1R_1 + 0$$

$$i_1 = i_2$$

$$i_2R_2 = i_3R_3$$

$$i_4 = i_3 + i_2$$

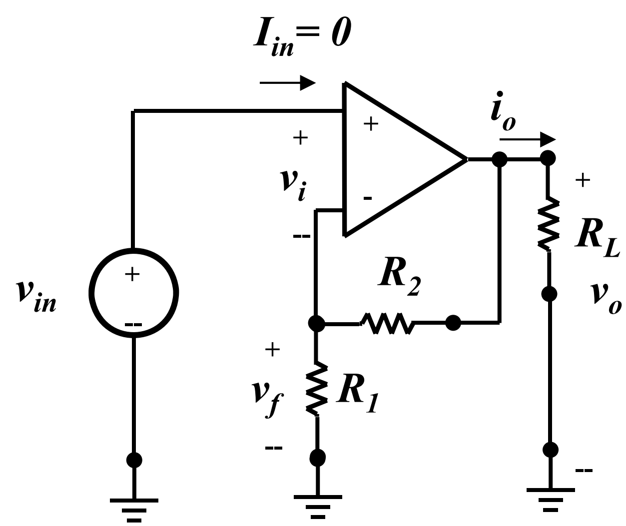
$$v_o = -R_4i_4 - R_3i_3$$

Why would we use this design over the simpler one?

1. **Same gain but with smaller values of resistance**
2. **Higher gain**

Non-inverting Amp

1. First check: negative feedback?
2. Next apply, summing point constraint
3. Use circuit analysis



$$v_{in} = v_i + v_f = 0 + v_f = v_f$$

$$v_f = \frac{R_1}{R_1 + R_2} v_o = v_{in};$$

$$A_v = \frac{v_o}{v_{in}} = \frac{R_2 + R_1}{R_1} = 1 + \frac{R_2}{R_1}$$

Since $i_{in} = 0; Z_{in} = \frac{v_{in}}{i_{in}} = \infty$

Note:

1. The gain is always greater than one
2. The output has the same sign as the input

Non-inverting Amp Special Case

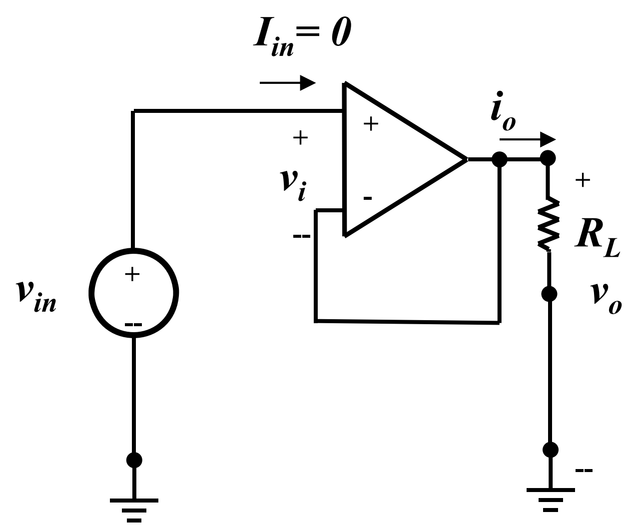
What happens if $R_2 = 0$?

$$v_{in} = v_i + v_f = 0 + v_f = v_f$$

$$v_f = \frac{R_1}{R_1 + 0} v_o = v_o = v_{in};$$

$$Av = \frac{v_o}{v_{in}} = \frac{0 + R_1}{R_1} = 1$$

$$\text{Since } i_{in} = 0; Z_{in} = \frac{v_{in}}{i_{in}} = \infty$$



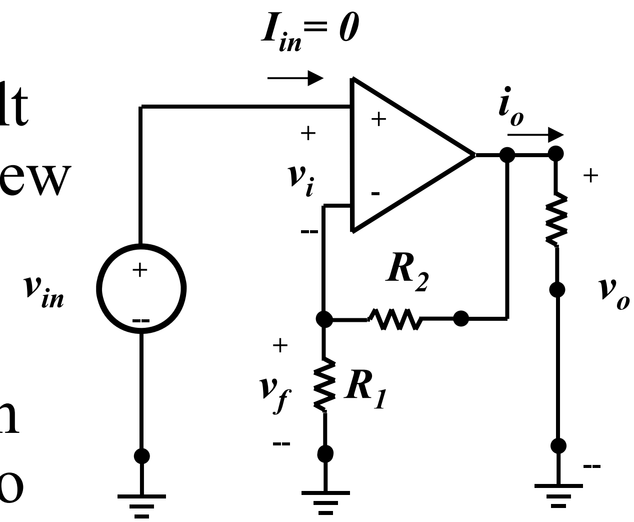
This is a unity gain amplifier and is also called a voltage follower.

Some Practical Issues when Designing Op-amps

- Since ratios of resistor values determines the gain, choosing the proper resistor values is crucial
  - Too small means large currents drawn
  - Too large yields another set of problems
- Open Loop Gain is not constant but a function of frequency
- Non-linearities of the amplifier
  - Voltage clipping
  - Slew rate
- DC imperfections
  - Offsets
  - Bias Currents

Selecting Resistor Values

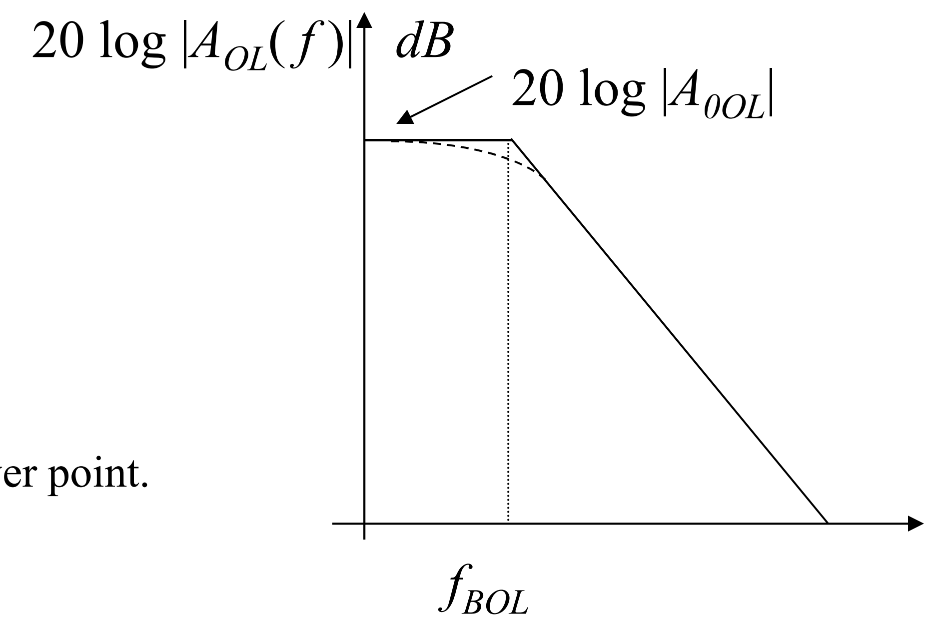
- Let say we want a gain of 10. This means that $R_2 = 9R_1$.
- If we chose R_1=1Ω, then for a 10 volt output, there will be 1 A flowing threw R_1 and R_2.
- THIS IS DANGEROUS!!!!
- On the other hand if R_1=10 $M\Omega$, then there may be unwanted effects due to pickup of induced signals
- Therefore choosing values between 100Ω and 1MΩ is optimum



$$Av = 1 + \frac{R_2}{R_1}$$

Frequency Issues

- Let's assume that the open loop gain of our Op-amp is a function of frequency.



$$A_{OL}(f) = \frac{A_{oOL}}{1 + j(f / f_{BOL})}$$

where A_{oOL} is the open-loop gain for $f = 0$,

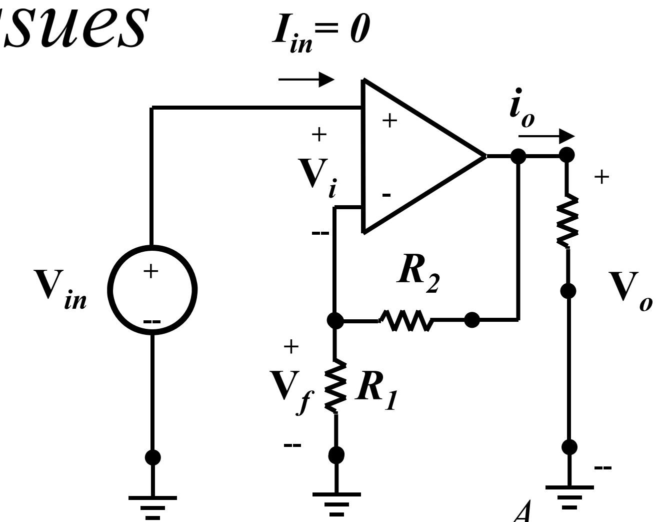
f_{BOL} is called the open-loop break frequency since when $f = f_{BOL}$

then $|A_{OL}(f)| = A_{oOL} / \sqrt{2}$ or at the half power point.

Note that when $f = A_{oOL} f_{BOL}$, $|A_{OL}(f)| \to 1$

This is will define an important relationship for the amplifier when feedback is used

Frequency Issues



$$A_{OL}(f) = \frac{A_{oOL}}{1 + j(f / f_{BOL})}$$

Using phasors:

$$\mathbf{V}_f = \frac{R_1}{R_1 + R_2} \times \mathbf{V}_O = \beta\ \mathbf{V}_O;\ \text{where } \beta = \frac{R_1}{R_1 + R_2}$$

$$\mathbf{V}_{in} = \mathbf{V}_i + \beta\mathbf{V}_O = \frac{\mathbf{V}_O}{A_{OL}} + \beta\mathbf{V}_O;\ \text{since } \mathbf{V}_O = \mathbf{V}_i A_{OL}$$

$$\therefore A_{CL} = \frac{\mathbf{V}_O}{\mathbf{V}_{in}} = \frac{A_{OL}}{1 + \beta A_{OL}}$$

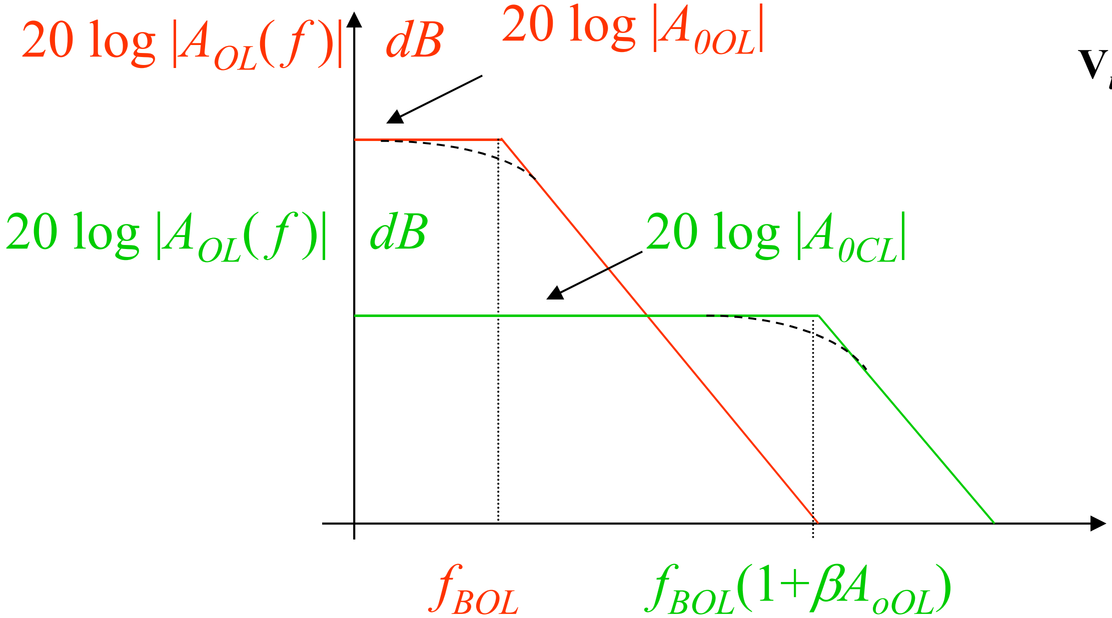
$$A_{CL}(f) = \frac{A_{OL}(f)}{1 + \beta A_{OL}(f)} = \frac{A_{OL}(f)}{1 + \beta A_{OL}(f)} = \frac{\frac{A_{oOL}}{1 + j(f / f_{BOL})}}{1 + \frac{\beta A_{oOL}}{1 + j(f / f_{BOL})}}$$

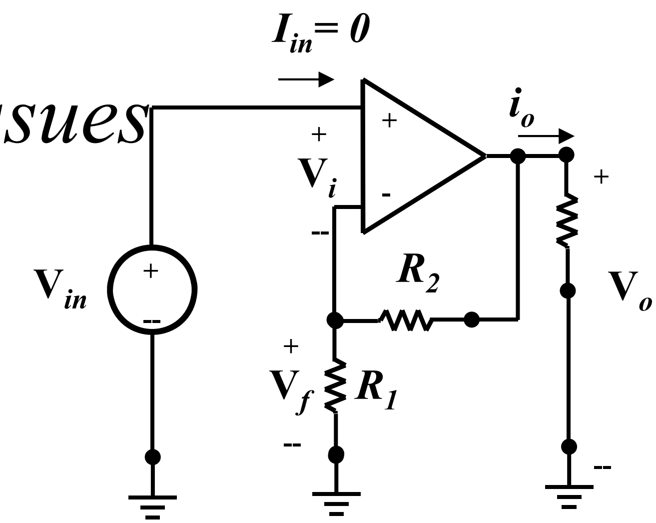
(Note for the ideal Op-amp $A_{OL} \to \infty$ and $A_{CL} \to \frac{1}{\beta} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$ which what we expected.)

$$= \frac{\frac{A_{oOL}}{1 + j(f / f_{BOL})}}{\frac{1 + j(f / f_{BOL})}{1 + j(f / f_{BOL})} + \frac{\beta A_{oOL}}{1 + j(f / f_{BOL})}} = \frac{A_{oOL}}{1 + \beta A_{oOL} + j(f / f_{BOL})}$$

$$= \frac{\frac{A_{oOL}}{1 + \beta A_{oOL}}}{1 + j\left(\frac{f}{f_{BOL}(1 + \beta A_{oOL})}\right)} = \frac{A_{oCL}}{1 + j\left(\frac{f}{f_{BCL}}\right)}$$

Frequency Issues





A interesting factor now comes to light:

$$A_{oCL} f_{BCL} = \frac{A_{oOL}}{1 + \beta A_{oOL}} f_{BOL} (1 + \beta A_{oOL}) = A_{oOL} f_{BOL}$$

The gain bandwidth product is constant!!!

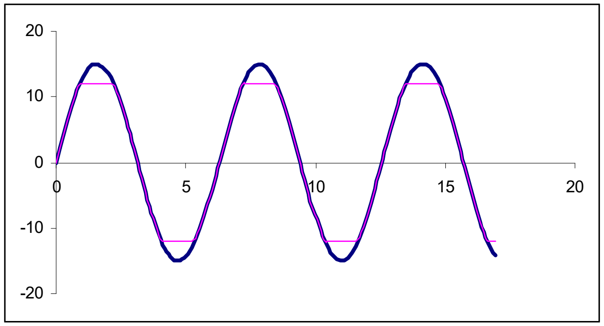
Where:

$$A_{oCL} = \frac{A_{oOL}}{1 + \beta A_{oOL}} \text{ and } f_{BCL} = f_{BOL}(1 + \beta A_{oOL})$$

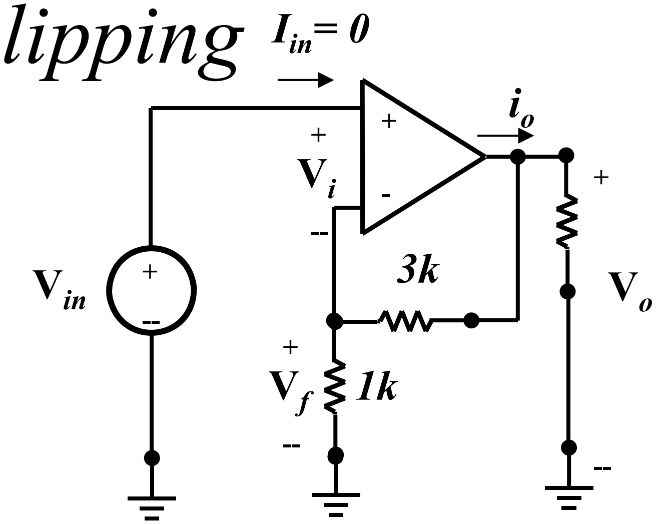
Example

- For an amplifier with Open-loop dc gain of 100 dB with Open-loop breakpoint of 40 Hz the Bandwidth product for β=1, 0.1, 0.01

β	A_{OCL}	$A_{OCL}(dB)$	f_{BCL}
1	0.9999	0	4 MHz
0.1	9.9990	20	400 kHz
0.01	99.90	40	40 kHz



Voltage clipping



- The Op-amp has a limit as to how large an output voltage and current can be produced. (See figure 2.28)
- For example for the circuit shown it has the following limitations: ±12 V and ±25 mA
  - a) If the load resistor is 10k *Ω*, what is the maximum input voltage which can be handled without clipping
  - b) Repeat for 100 *Ω*

$$A_{vCL} = 1 + 3/1 = 4$$

$$a) I_{o\max} = \frac{V_{o\max}}{R_L} + \frac{V_{o\max}}{R_1 + R_2} = \frac{12}{10^4} + \frac{12}{3000 + 1000}$$

$$= 4.2mA$$

For this case, maximum output voltage will occur before maximum output current is reached.

$$V_{in\max} = 12/4 = 3V$$

$$b) I_{o\max} = \frac{V_{o\max}}{R_L} + \frac{V_{o\max}}{R_1 + R_2} = \frac{12}{100} + \frac{12}{3000 + 1000} = 123mA$$

For this case, maximum output current will occur before maximum output voltage is reached.

$$I_{o\max} = \frac{V_{o\max}}{R_L} + \frac{V_{o\max}}{R_1 + R_2} = 25mA = \frac{V_{o\max}}{100} + \frac{V_{o\max}}{3000 + 1000}$$

$$V_{o\max} = 2.44V$$

$$V_{in\max} = 2.44/4 = 0.61V$$

Slew Rate

- Slew Rate is a phenomenon which occurs when the Op-Amp can not keep up the change in the input.
- Therefore, we identify the maximum rate of change of the Op-amp as the Slew Rate - SR

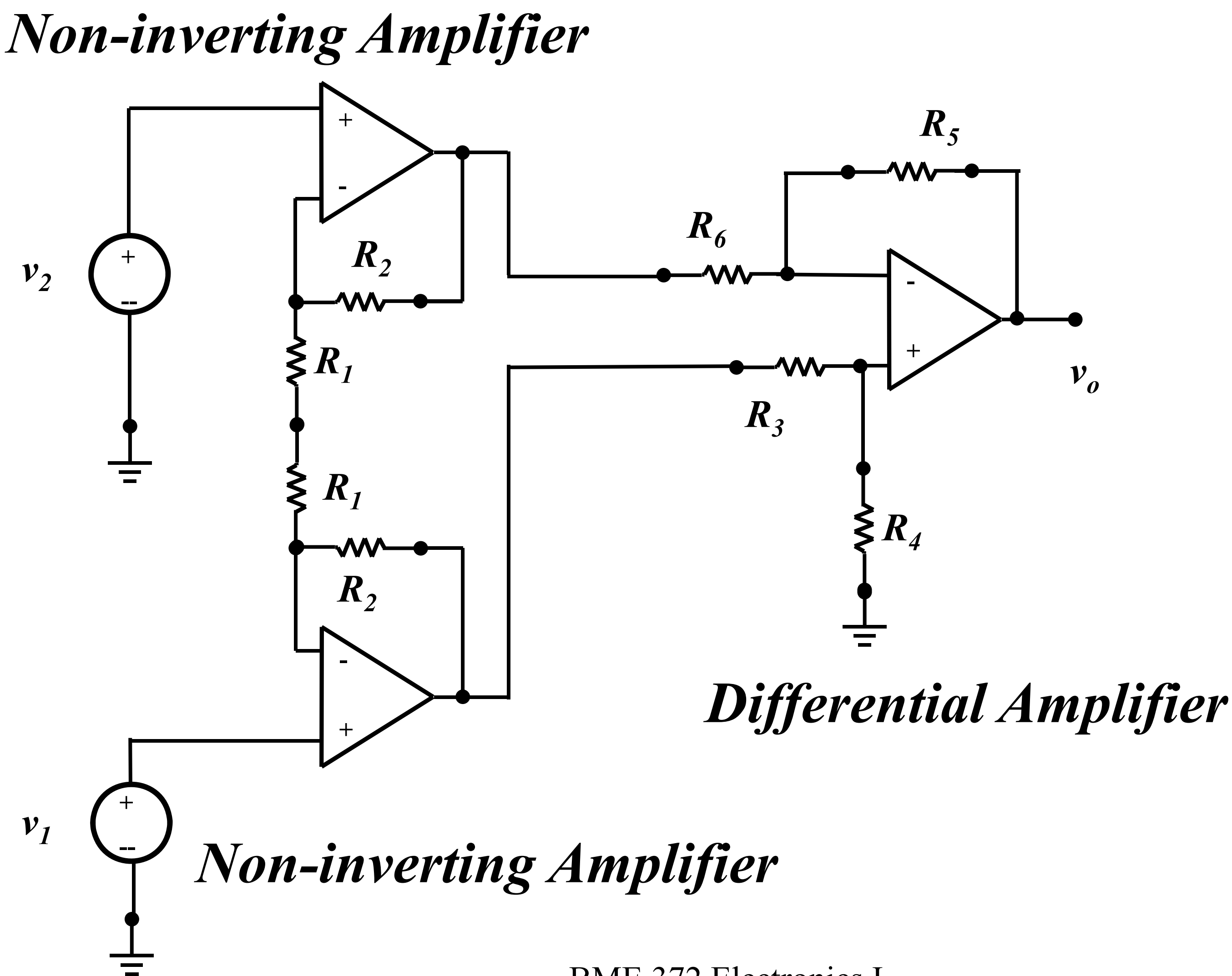
DC imperfections

- We saw that we have to provide DC voltages to an amplifier in order to provide it with the power to support amplification.
  – For a differential amplifier which must handle both positive and negative voltages
- The process of designing this DC circuitry is called biasing
- As a result, biasing currents flow through the amplifier which affects its performance.
- In particular, a voltage during to the biasing will appear at the output without any input signal.
- These extra voltage can be due to:
  – Bias currents flowing in the feedback circuitry
  – Bias current differentials
  – Voltage offsets due to the fact that the Op-amp circuitry is not ideal

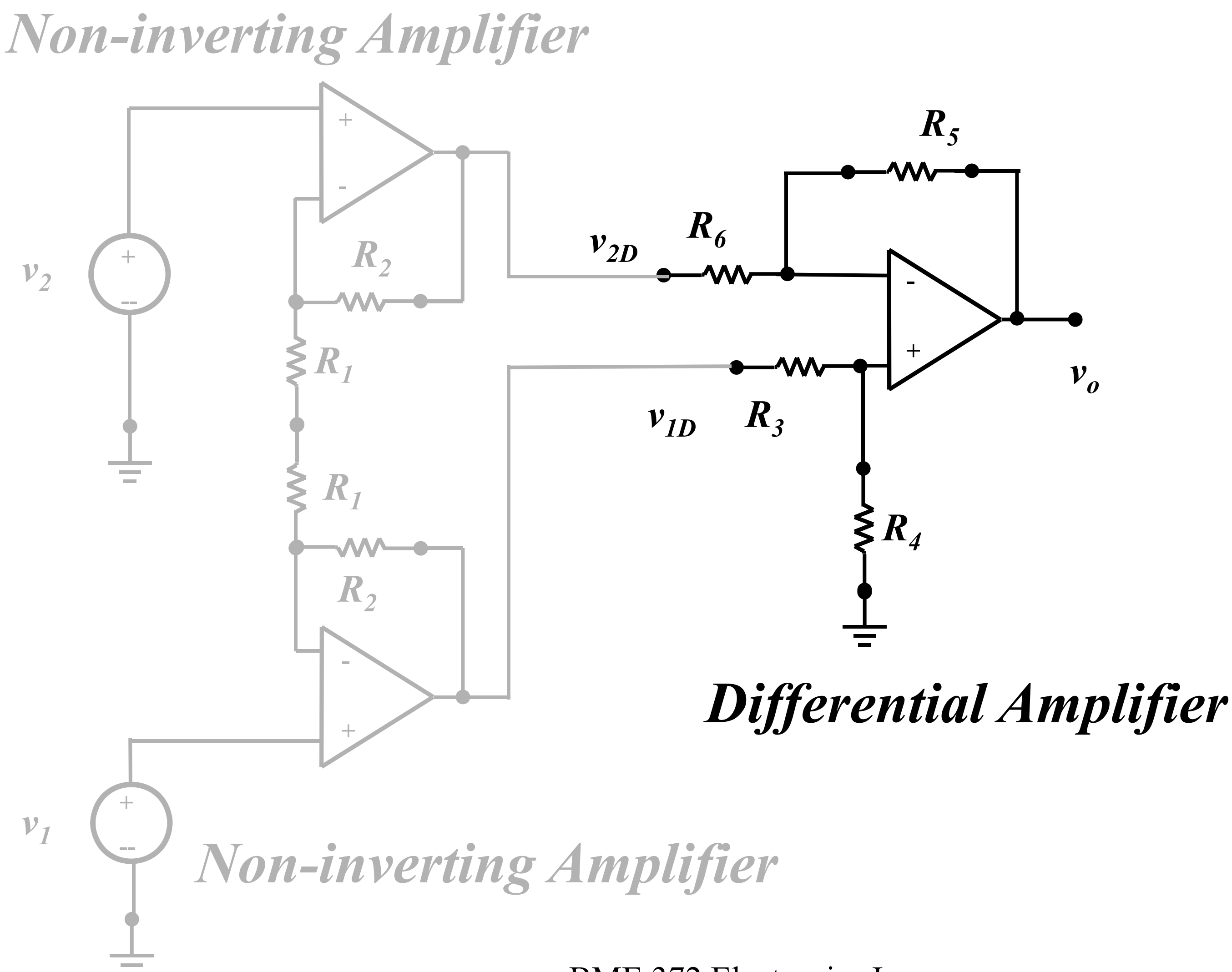
Special Amplifiers

- Summer (Homework Problem)
- Instrumentation Amplifier
  - Uses 3 Op-amps
  - One as a differential amplifier
  - Two Non-inverting Amps using for providing gain

Medical Instrumentation Amplifier

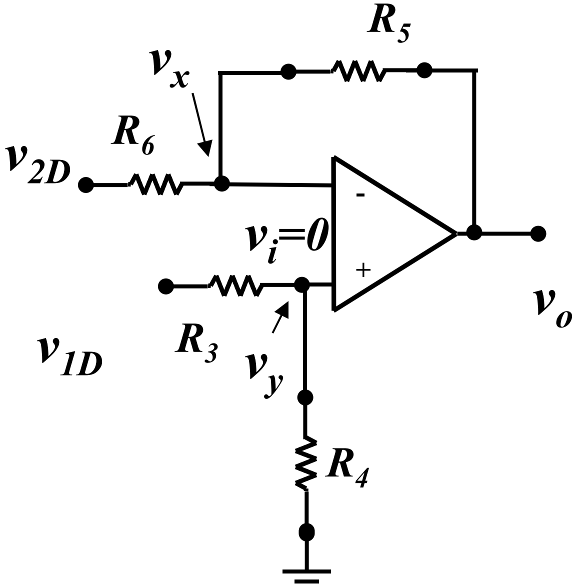


Medical Instrumentation Amplifier



Medical Instrumentation Amplifier

Differential Amplifier



Chose $\frac{R_5+R_6}{R_5}\frac{R_4}{R_3+R_4}=1$

$$R_4R_5+R_4R_6=R_5R_3+R_5R_4$$

$$R_4R_6=R_5R_3$$

$$\frac{R_6}{R_5}=\frac{R_3}{R_4}$$

$$\frac{v_{2D}-v_x}{R_6}=\frac{v_x-v_o}{R_5}$$

$$\frac{v_{2D}}{R_6}-v_x\left(\frac{1}{R_6}+\frac{1}{R_5}\right)=\frac{-v_o}{R_5}$$

$$\frac{v_{2D}}{R_6}-v_x\left(\frac{R_5+R_6}{R_6R_5}\right)=\frac{-v_o}{R_5}$$

$$v_y=\frac{R_4}{R_3+R_4}v_{1D}=v_x-v_i=v_x$$

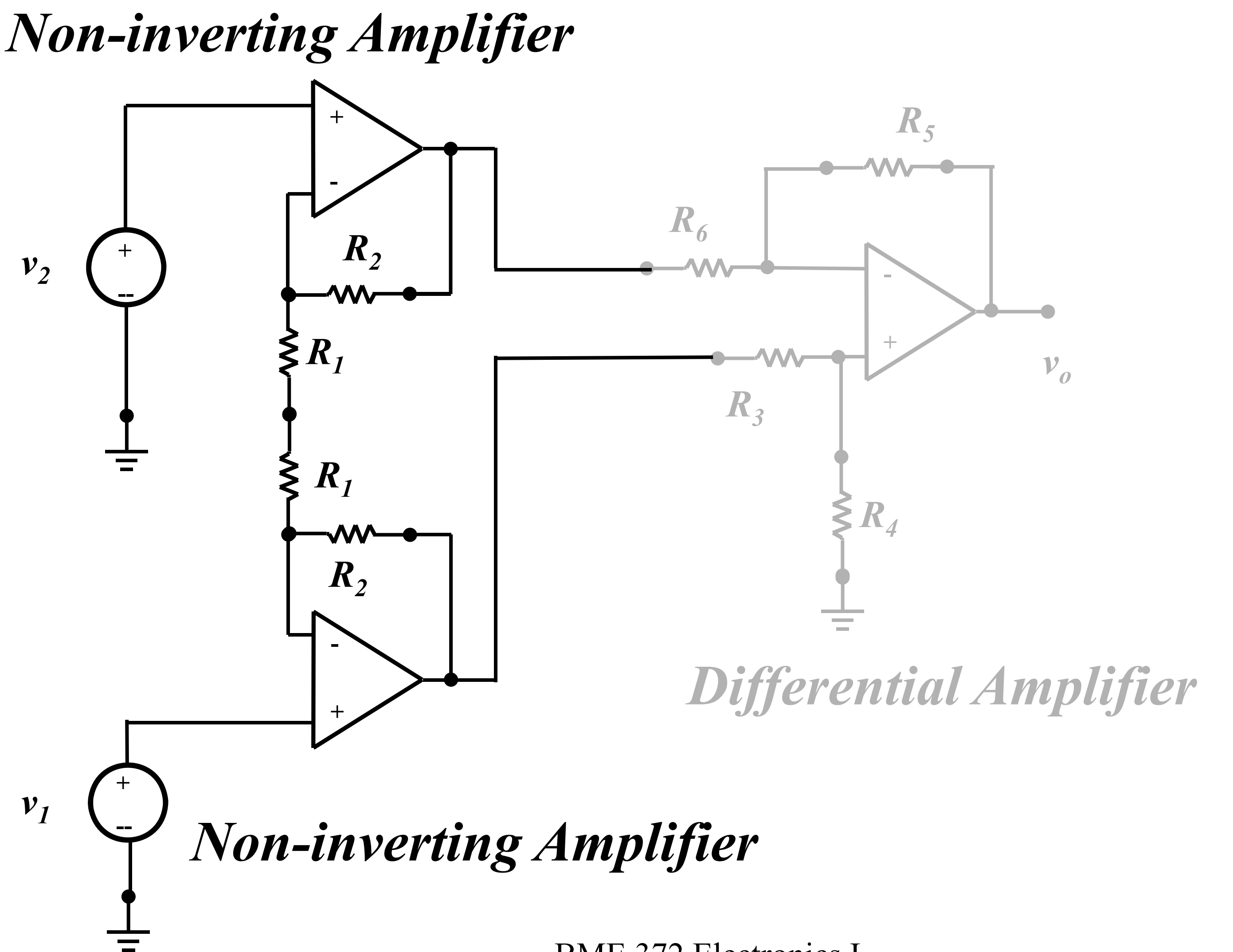
$$\frac{v_{2D}}{R_6}-\frac{R_4}{R_3+R_4}v_{1D}\left(\frac{R_5+R_6}{R_6R_5}\right)=\frac{-v_o}{R_5}$$

$$v_o=\frac{R_5}{R_6}\left(v_{1D}\frac{R_5+R_6}{R_5}\frac{R_4}{R_3+R_4}-v_{2D}\right)$$

Chose $\frac{R_5+R_6}{R_5}\frac{R_4}{R_3+R_4}=1$

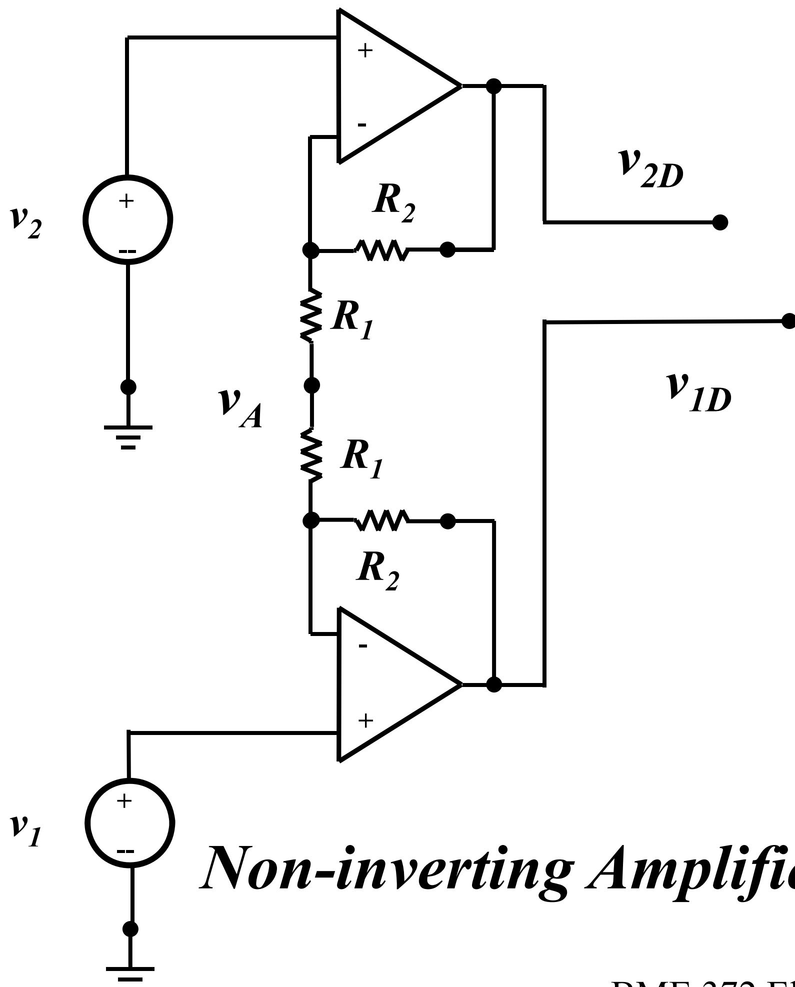
$$v_o=\frac{R_5}{R_6}(v_{1D}-v_{2D})$$

Medical Instrumentation Amplifier



Medical Instrumentation Amplifier

Non-inverting Amplifier



Non-inverting Amplifier

$$\frac{v_{2D} - v_2}{R_2} = \frac{v_2 - v_A}{R_1}$$

$$v_{2D} = R_2\left(\frac{1}{R_2} + \frac{1}{R_1}\right)v_2 - \frac{R_2}{R_1}v_A$$

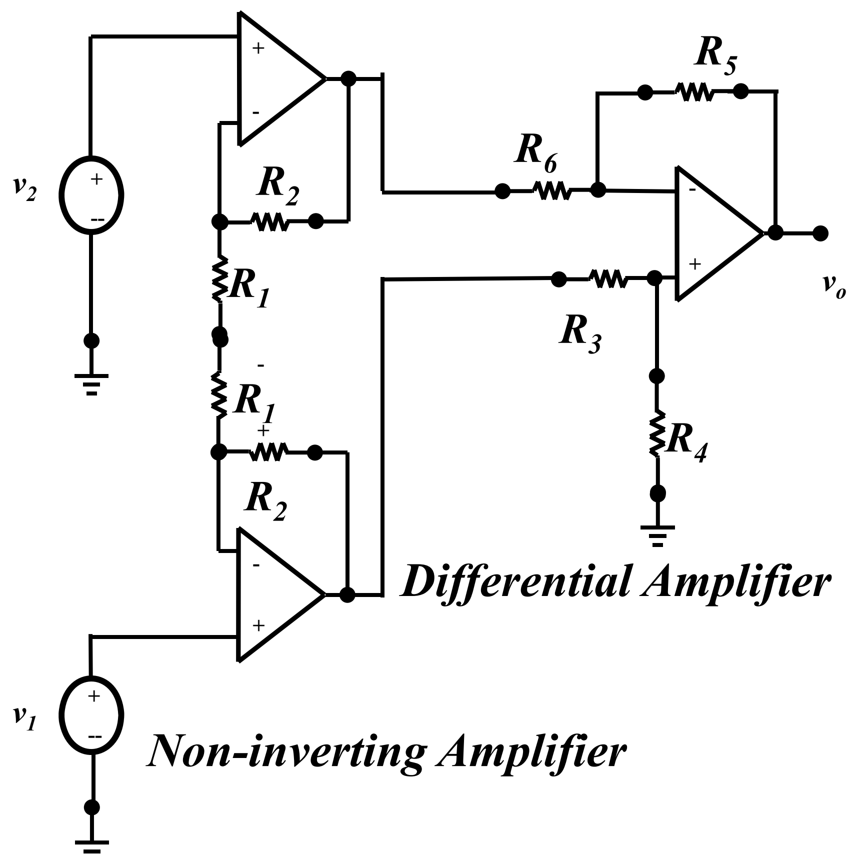
$$v_{2D} = \frac{R_1 + R_2}{R_1}v_2 - \frac{R_2}{R_1}v_A$$

Likewise

$$v_{1D} = \frac{R_1 + R_2}{R_1}v_1 - \frac{R_2}{R_1}v_A$$

Medical Instrumentation Amplifier

Non-inverting Amplifier



$$v_o = \frac{R_5}{R_6}(v_{1D} - v_{2D})$$

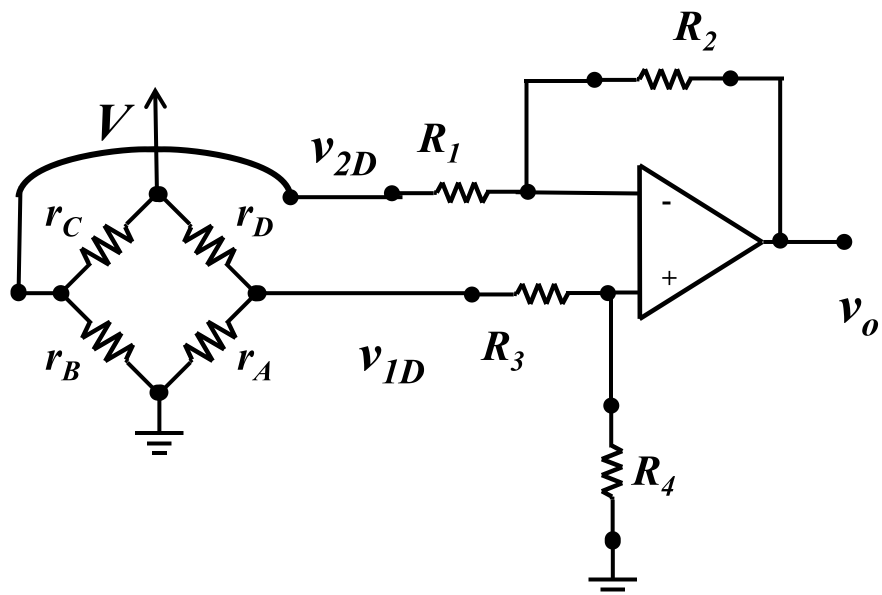
$$v_{2D} = \frac{R_1 + R_2}{R_1} v_2 - \frac{R_2}{R_1} v_A$$

$$v_{1D} = \frac{R_1 + R_2}{R_1} v_1 - \frac{R_2}{R_1} v_A$$

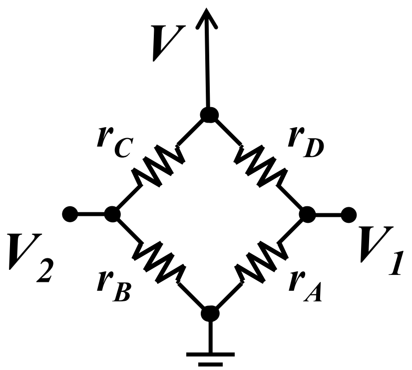
$$v_o = \frac{R_5}{R_6}[\frac{R_1 + R_2}{R_1} v_1 - \frac{R_2}{R_1} v_A - (\frac{R_1 + R_2}{R_1} v_2 - \frac{R_2}{R_1} v_A)]$$

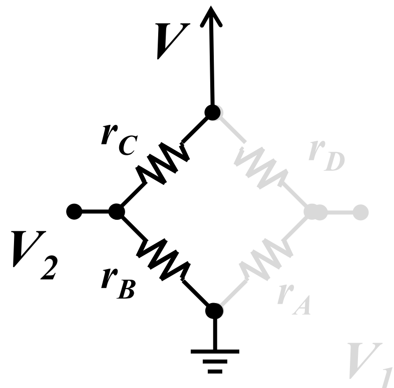
$$v_o = \frac{R_5}{R_6}(\frac{R_1 + R_2}{R_1})(v_1 - v_2) = \frac{R_5}{R_6}(1 + \frac{R_2}{R_1})(v_1 - v_2)$$

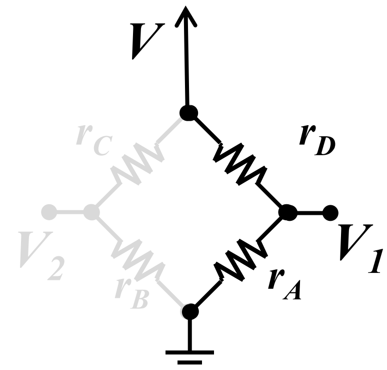
Wheatstone Bridge as a sensor



Wheatstone Bridge







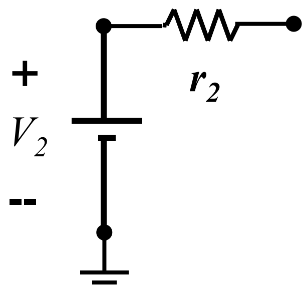
Using Thevinin's Theorem on the Wheatstone Bridge

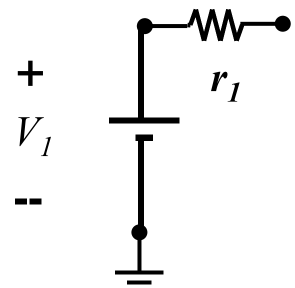
Left side

$$V_2 = \frac{r_B}{r_B + r_C} V; r_2 = \frac{r_B r_C}{r_B + r_C}$$

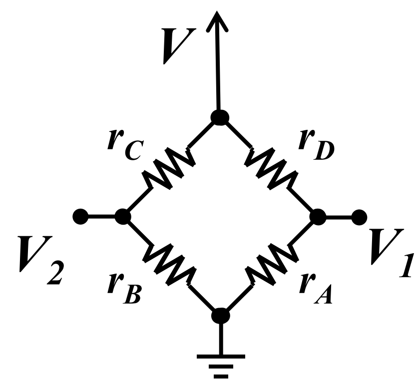
Right side

$$V_1 = \frac{r_A}{r_A + r_D} V; r_1 = \frac{r_A r_D}{r_A + r_D}$$





Wheatstone Bridge



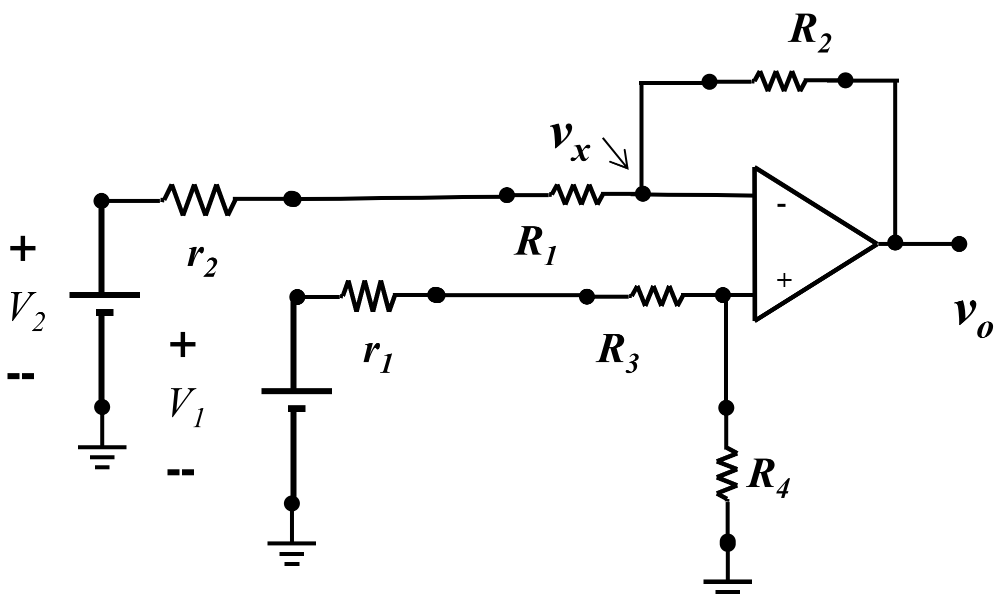
$$V_{Bridge} = V_2 - V_1 = \left(\frac{r_B}{r_B + r_C} - \frac{r_A}{r_A + r_D}\right)V$$

When bridge is balanced $\frac{r_B}{r_B + r_C} = \frac{r_A}{r_A + r_D} \Rightarrow r_B r_D = r_A r_C \Rightarrow \frac{r_A}{r_D} = \frac{r_B}{r_C}$

(nominally, $r_A = r_B = r_C = r_D$)

and $V_{Bridge} = 0$

Wheatstone Bridge



$$\frac{V_2 - v_x}{R_1 + r_2} = \frac{v_x - v_o}{R_2}$$

$$\frac{V_2}{R_1 + r_2} - v_x\left(\frac{1}{R_1 + r_2} + \frac{1}{R_2}\right) = \frac{-v_o}{R_2}$$

$$\frac{V_2}{R_1 + r_2} - v_x\left(\frac{R_1 + R_2 + r_2}{(R_1 + r_2)R_2}\right) = \frac{-v_o}{R_2}$$

$$v_x = v_y = \frac{R_4}{R_3 + r_1 + R_4} V_1$$

$$\frac{V_2}{R_1 + r_2} - \frac{R_4}{R_3 + r_1 + R_4} V_1\left(\frac{R_1 + R_2 + r_2}{(R_1 + r_2)R_2}\right) = \frac{-v_o}{R_2}$$

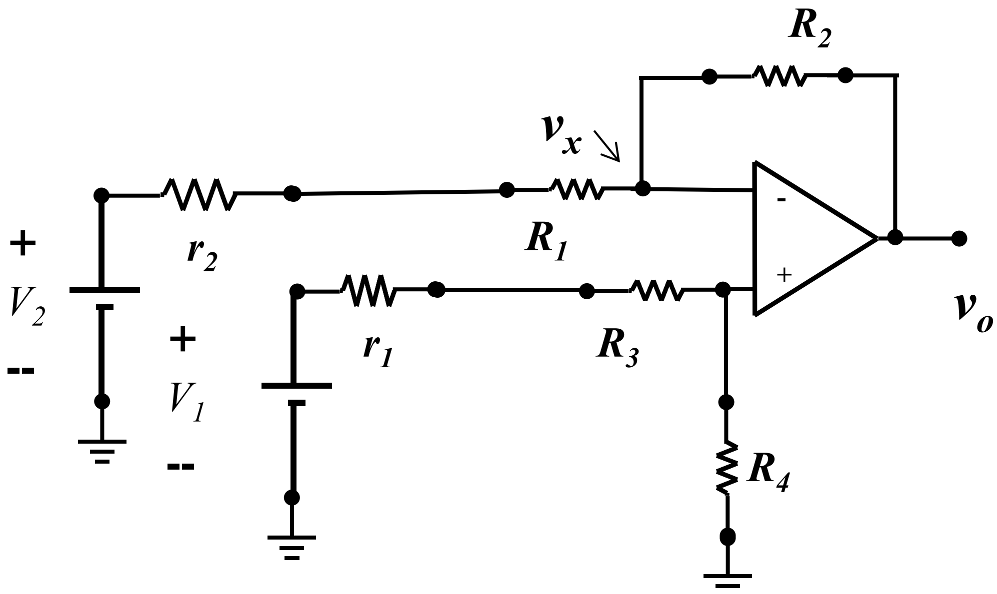
$$\frac{V_2}{R_1 + r_2} - \frac{R_4}{R_3 + r_1 + R_4}\left(\frac{R_1 + R_2 + r_2}{R_2}\right)\frac{V_1}{(R_1 + r_2)} = \frac{-v_o}{R_2}$$

$$v_o = \frac{R_2}{R_1 + r_2}\left[\left(\frac{R_4}{R_3 + r_1 + R_4}\right)\left(\frac{R_1 + R_2 + r_2}{R_2}\right)V_1 - V_2\right]$$

$$\text{Chose } \frac{R_1 + R_2 + r_2}{R_2}\,\frac{R_4}{R_3 + r_1 + R_4} = 1$$

$$v_o = \frac{R_2}{R_1 + r_2}(V_1 - V_2) = \frac{R_2}{R_1 + r_2}\left(\frac{r_A}{r_A + r_D} - \frac{r_B}{r_B + r_C}\right)V$$

Wheatstone Bridge



Chose $\frac{R_1+R_2+r_2}{R_2}\frac{R_4}{R_3+r_1+R_4}=1$

$$\frac{R_1+R_2+r_2}{R_2}=\frac{R_3+r_1+R_4}{R_4}$$

$$\frac{R_1+R_2+\frac{r_Br_C}{r_B+r_C}}{R_2}=\frac{R_3+\frac{r_Ar_D}{r_A+r_D}+R_4}{R_4}$$

Hard to deal with; then let's make sure that $r_2 << R_1+R_2$ and $r_1 << R_3+R_4$

$$\frac{R_1+R_2}{R_2}=\frac{R_3+R_4}{R_4}\Rightarrow R_2R_3+R_2R_4=R_4R_1+R_4R_2\Rightarrow R_2R_3=R_4R_1$$

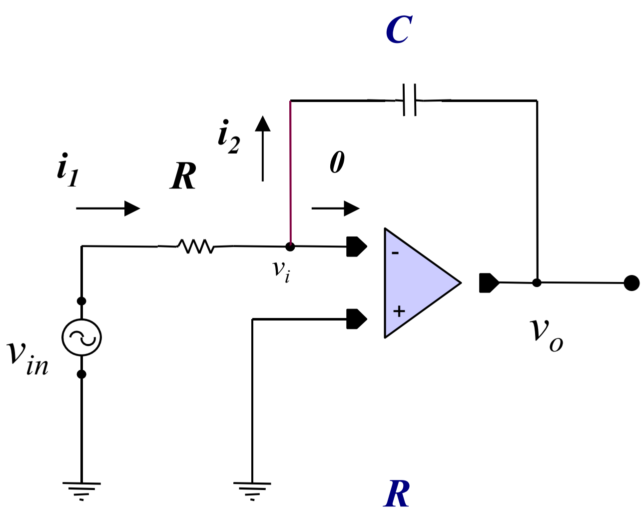
$$\frac{R_4}{R_3}=\frac{R_2}{R_1}$$

$$v_o=\frac{R_2}{R_1}\left(\frac{r_A}{r_A+r_D}-\frac{r_B}{r_B+r_C}\right)V$$

Note that the output depends on the unbalance of the bridge and when the bridge is balanced $v_o=0$

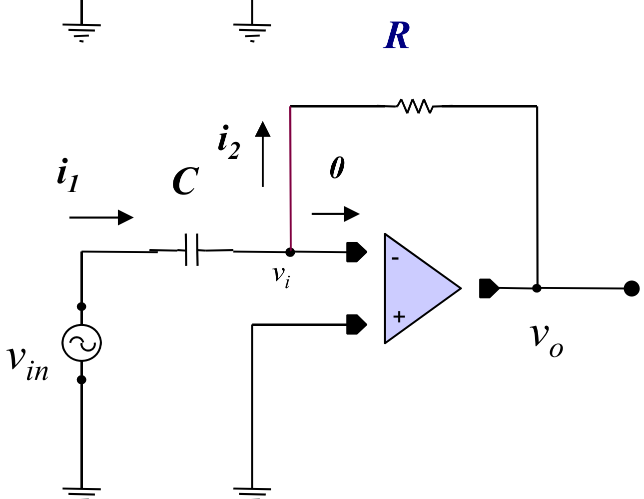
Gain is still $\frac{R_2}{R_1}$

Integrators and Differentiators



$$i_1(t) = \frac{v_{in}(t)}{R} = i_2(t)$$

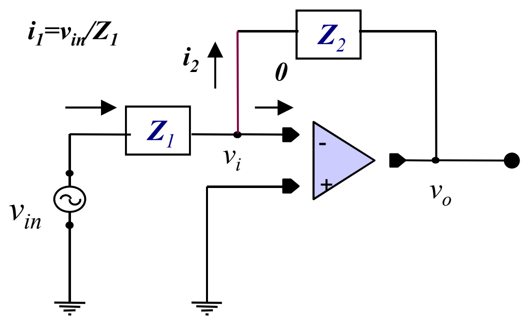
$$v_o = -\frac{1}{C}\int_0^t i_2(x)dx = -\frac{1}{RC}\int_0^t v_{in}(x)dx$$



$$i_1(t) = \frac{Cdv_{in}(t)}{dt} = i_2(t)$$

$$v_o = -i_2(t)R = -RC\frac{dv_{in}(t)}{dt}$$

Frequency Analysis



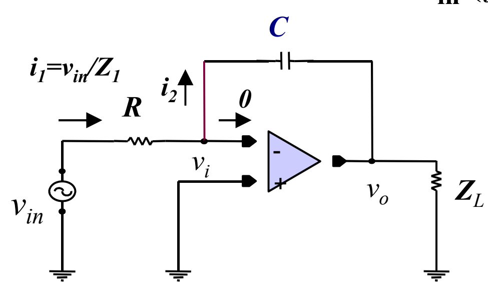
$$\mathbf{V_{in}}(j\omega) = \mathbf{I_1}(j\omega)\mathbf{Z_1}(j\omega) + 0 \text{ since } v_i \text{ is (virtually) zero}$$

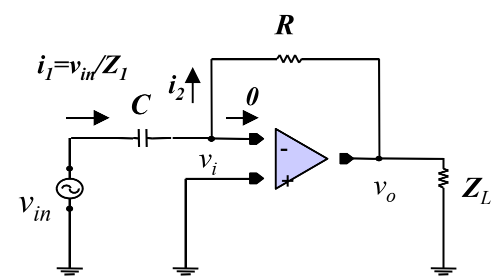
$$\mathbf{I_1}(j\omega) = \mathbf{I}_2(j\omega) \text{ due to the summing - point constraint}$$

$$\mathbf{V_o}(j\omega) = -\mathbf{I}_2(j\omega)\mathbf{Z}_2 + 0 \text{ since } v_i \text{ is (virtually) zero}$$

$$= -\frac{\mathbf{Z}_2}{\mathbf{Z_1}}\mathbf{V_{in}}(j\omega) \text{ which is independent of } \mathbf{Z_L}$$

$$\frac{\mathbf{V_o}(j\omega)}{\mathbf{V_{in}}(j\omega)} = -\frac{\mathbf{Z}_2}{\mathbf{Z_1}}$$

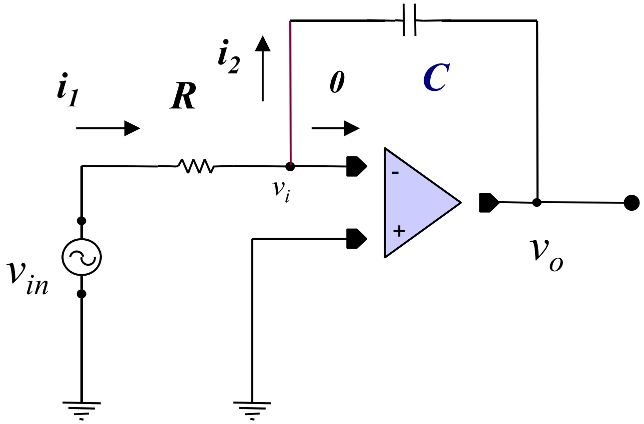




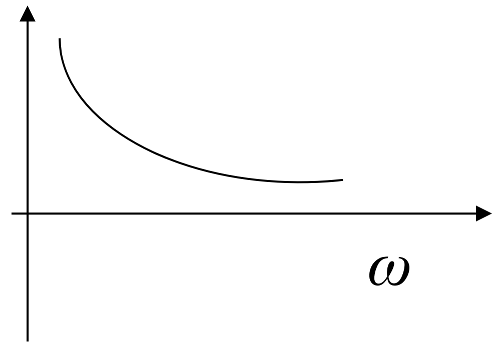
$$\frac{\mathbf{V_o}(j\omega)}{\mathbf{V_{in}}(j\omega)} = -\frac{\mathbf{Z}_2}{\mathbf{Z_1}} = -\frac{1}{j\omega RC} \text{ an integrator}$$

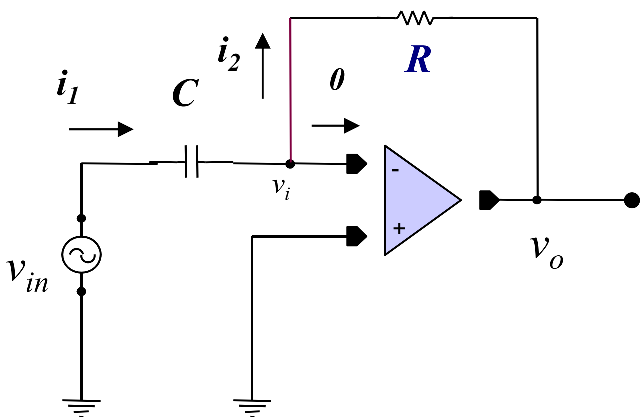
$$\frac{\mathbf{V_o}(j\omega)}{\mathbf{V_{in}}(j\omega)} = -\frac{\mathbf{Z}_2}{\mathbf{Z_1}} = -j\omega RC \text{ a differeniator}$$

Frequency Response

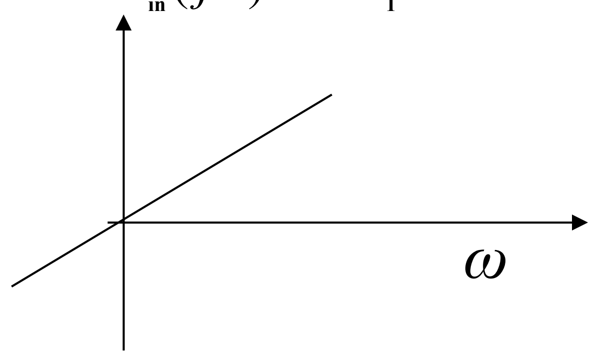


$$\frac{\mathbf{V_o}(j\omega)}{\mathbf{V_{in}}(j\omega)} = -\frac{\mathbf{Z_2}}{\mathbf{Z_1}} = -\frac{1}{j\omega RC}$$

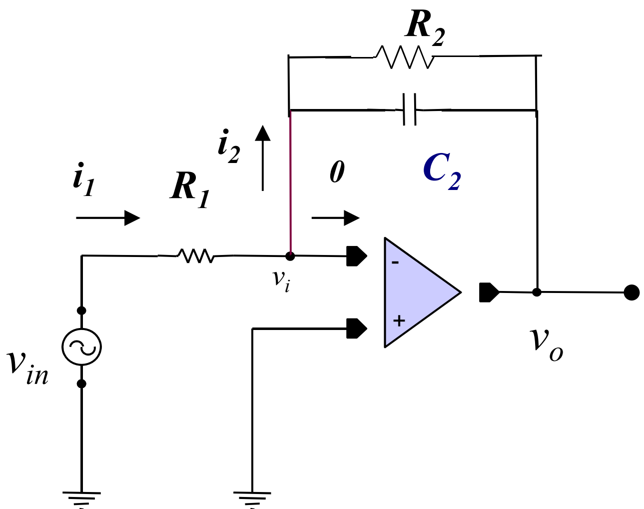




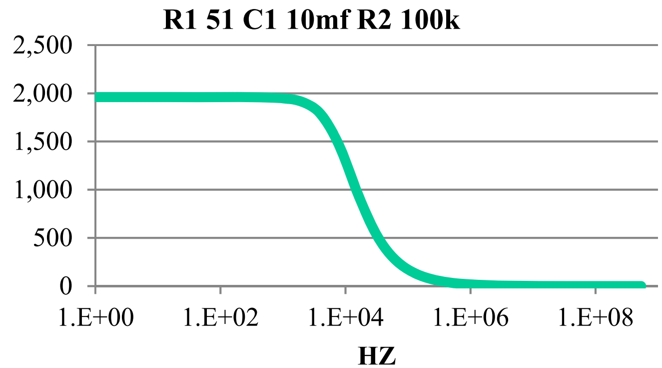
$$\frac{\mathbf{V_o}(j\omega)}{\mathbf{V_{in}}(j\omega)} = -\frac{\mathbf{Z_2}}{\mathbf{Z_1}} = -j\omega RC$$

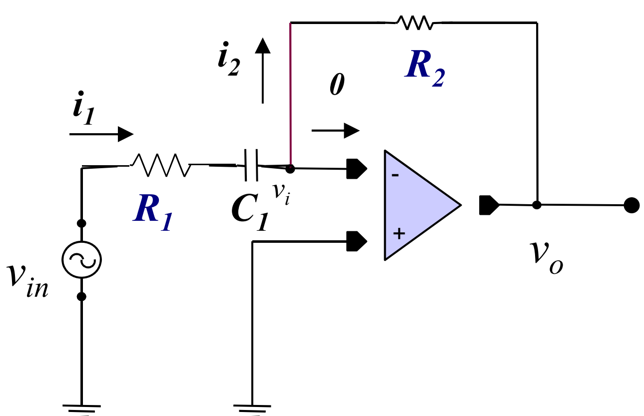


Frequency Response

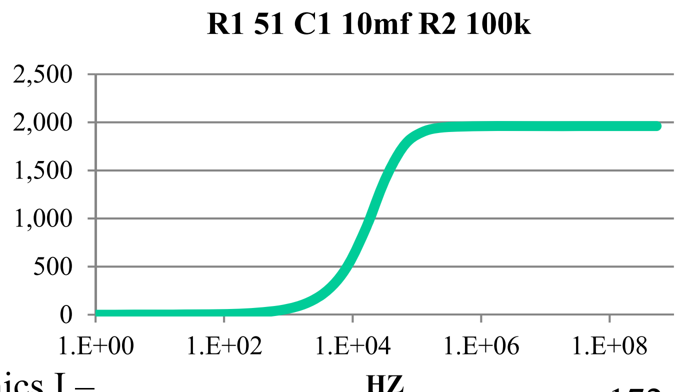


$$\frac{V_{out}}{V_{in}} = -\frac{Z_2}{Z_1} = -\frac{R_2}{R_1}\frac{1}{(1+j\omega C_2 R_2)} = \frac{R_2}{R_1}\frac{1}{\sqrt{1+(\omega C_2 R_2)^2}}\angle \pi - \tan^{-1}(\omega C_2 R_2)$$



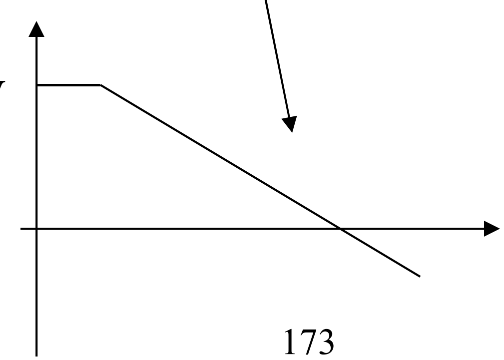


$$\frac{V_{out}}{V_{in}} = -\frac{Z_2}{Z_1} = -\frac{R_2}{R_1}\frac{j\omega C_1 R_1}{(1+j\omega C_1 R_1)} = \frac{R_2}{R_1}\frac{\omega C_1 R_1}{\sqrt{1+(\omega C_1 R_1)^2}}\angle -\frac{\pi}{2} - \tan^{-1}(\omega C_1 R_1)$$



Integrators and Differentiators

- Integrators and Differentiators are used in analog computers
- An analog computer solves a differential equations
- By using Integrators and Differentiators one can "program" a particular differential equation to be solved
- Usually only integrators are used since the gain of a differentiator occurs at high frequencies while the opposite is true for the integrator.
- Since the frequency response of an real Op-amp attenuates high frequencies, using a differentiator conflicts with the characteristics with a real Op-amp
- Also noise (high frequencies) are amplified by differentiators



R-Wave Detector

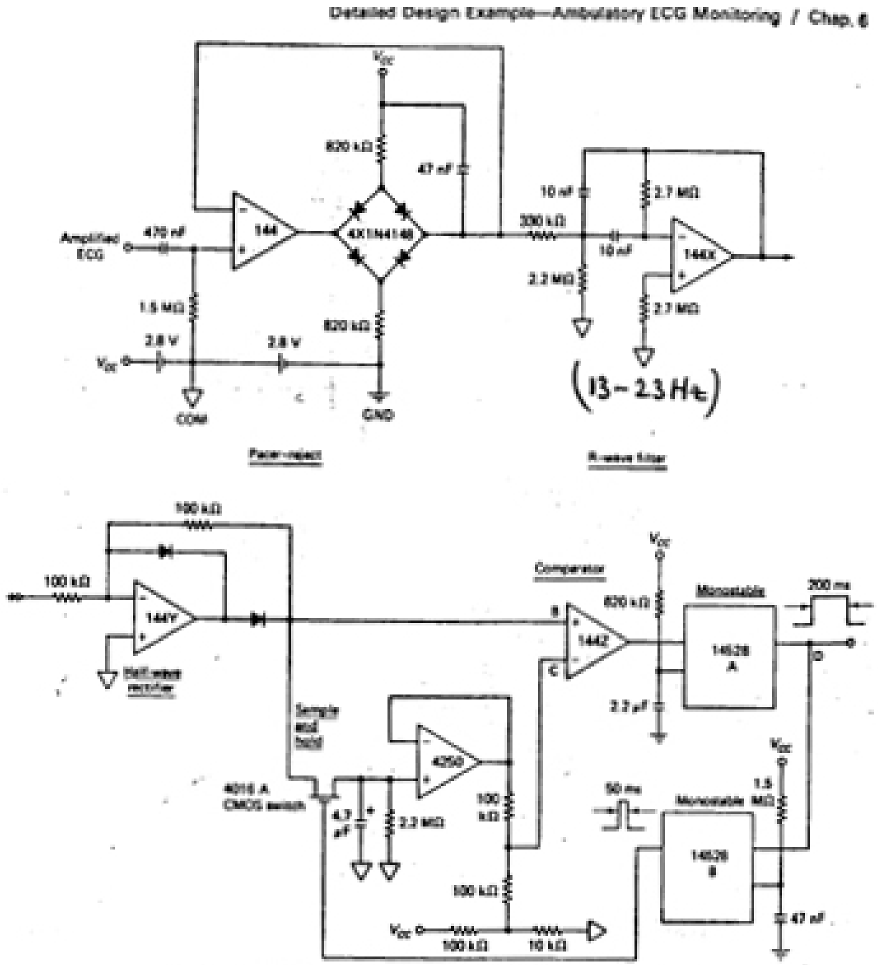
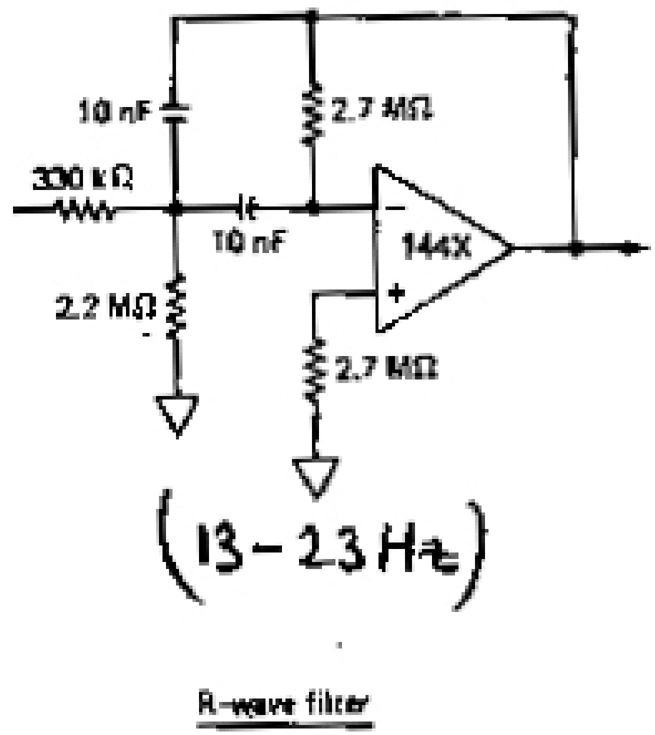


FIGURE 6.12 Circuit diagram of complete R-wave detector. (From Thakor, N. V. 1978. Reliable R-wave detection from ambulatory subjects. Biomed. Sci. Instrum. 14: 67–72. Used with permission of ISA.)

$$f_L = \frac{1}{2\pi R_1 C_1}$$

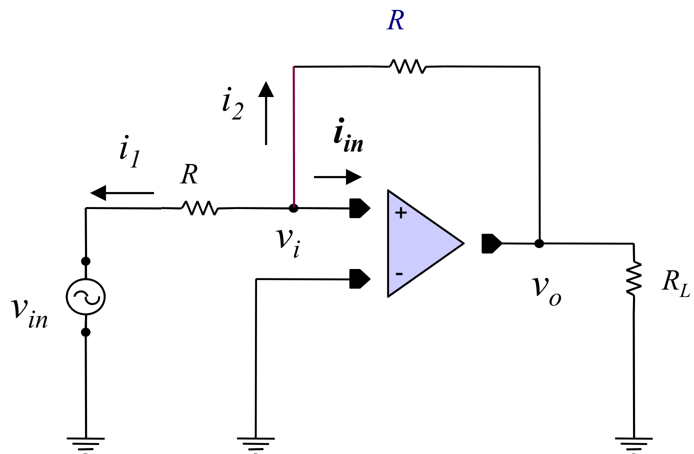
$$= \frac{1}{2\pi \times 680\,\text{k}\Omega \times 470\,\text{nF}}$$

$$= 0.5\,\text{Hz}$$



Positive Feedback

- What happens to our Op-amp circuit if positive feedback is used?



Using KCL at the input :

$$i_1 + i_2 + i_{in} = 0$$

$i_{in} = 0$; since Amplifier has infinite input impedance

$$\frac{v_i - v_{in}}{R} + \frac{v_i - v_o}{R} = 0$$

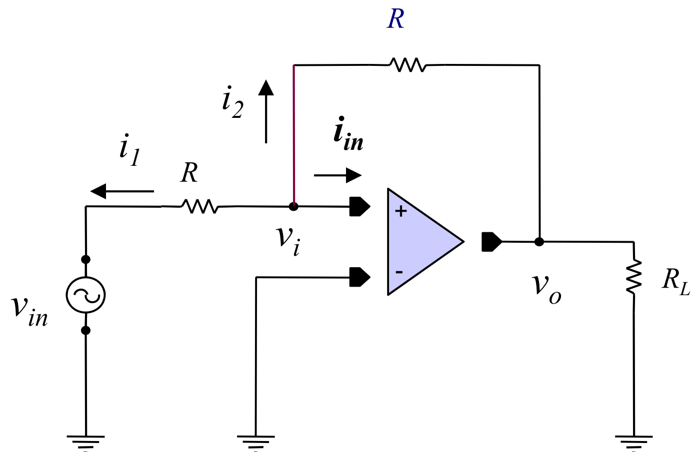
$v_o = A_{OL} v_i$ where A_{OL} is the open loop gain

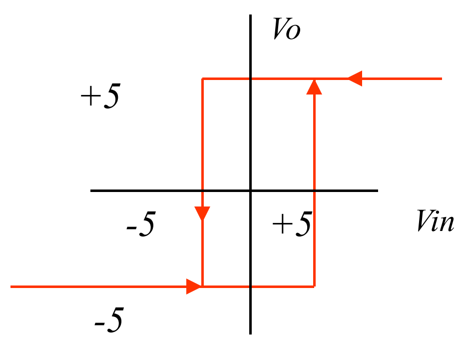
$$v_i = \frac{1}{2}(v_{in} + v_o) = \frac{1}{2}(v_{in} + A_{OL} v_i)$$

- Even if $v_{in} = 0$ and there is a slight voltage at v_i then
  - $v_o = A_{OL} v_i$ will increase v_i
  - v_o will grow even larger
  - Eventually this will reach an extreme since there is not infinite energy in the circuit

Positive Feedback

- Then our positive feedback design will operate between its positive and negative extremes, say $\pm 5V$





$$v_i = \frac{1}{2}(v_{in} + v_o)$$

For v_o to be at $+5V, v_i > 0$

$$v_i = \frac{1}{2}(v_{in} + v_o) = \frac{1}{2}(v_{in} + 5) > 0$$

This is true as long as $v_{in} > -5V$

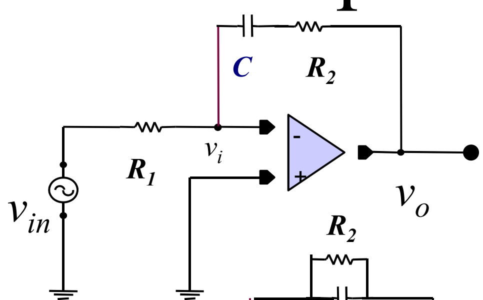
For v_o to be at $-5V, v_i < 0$

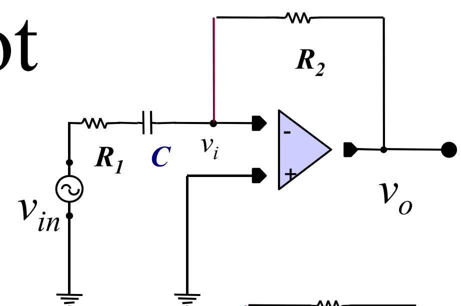
$$v_i = \frac{1}{2}(v_{in} + v_o) = \frac{1}{2}(v_{in} - 5) < 0$$

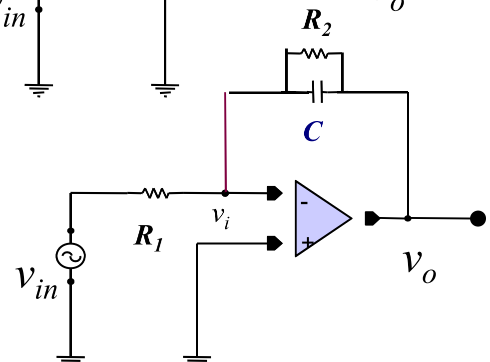
This is true as long as $v_{in} < 5V$

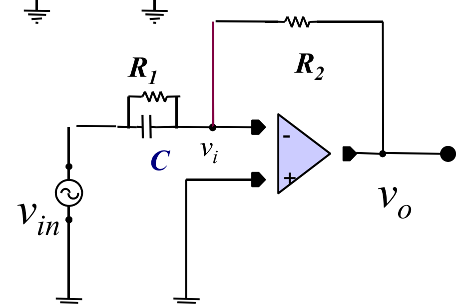
Homework

- Probs 2.2, 2.5, 2.6, 2.10, 2.22, 2.24, 2.25, 2.28
- Calculate and plot the output vs frequency for these circuits. R_1=1k, R_2=3k, C=1µf Use Matlab to perform the plot

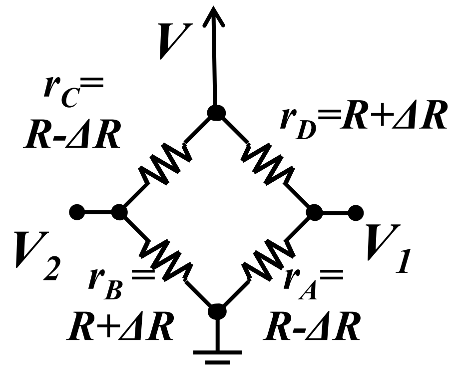








Homework



Wheatstone Bridge - Strain Gauge

- A strain gauge shown here is used with a difference amplifier. Calculate the amplifier output signal as a function of ΔR and difference amplifier resistors. Assume that $\Delta R << R$.
- For the strain gauge calculate the value of each of the difference amplifier resistors for a value of R=10Ω and a percent change in R of ±10% if the output of the amplifier is less than ±5 volts. Assume that the bridge is powered with 5 volts.

Homework

Calculate and plot the output vs frequency for this circuits. R_1=1k, R_2=3k, C=1μf. Use Matlab to perform the plot.