COVID-19 Return to Campus

Slide for use in Semester 2 classes

- Go to ***Return to campus resources and posters*** at COVID-19: Information for staff
- Contact your HSE Partners Amanda Burns or Matt Mackay for local area support and advice

School of Electrical Engineering and Robotics

EGB348 Electronics

Operational Amplifier Circuits

Jasmine Banks (2020)

Recommended Readings:

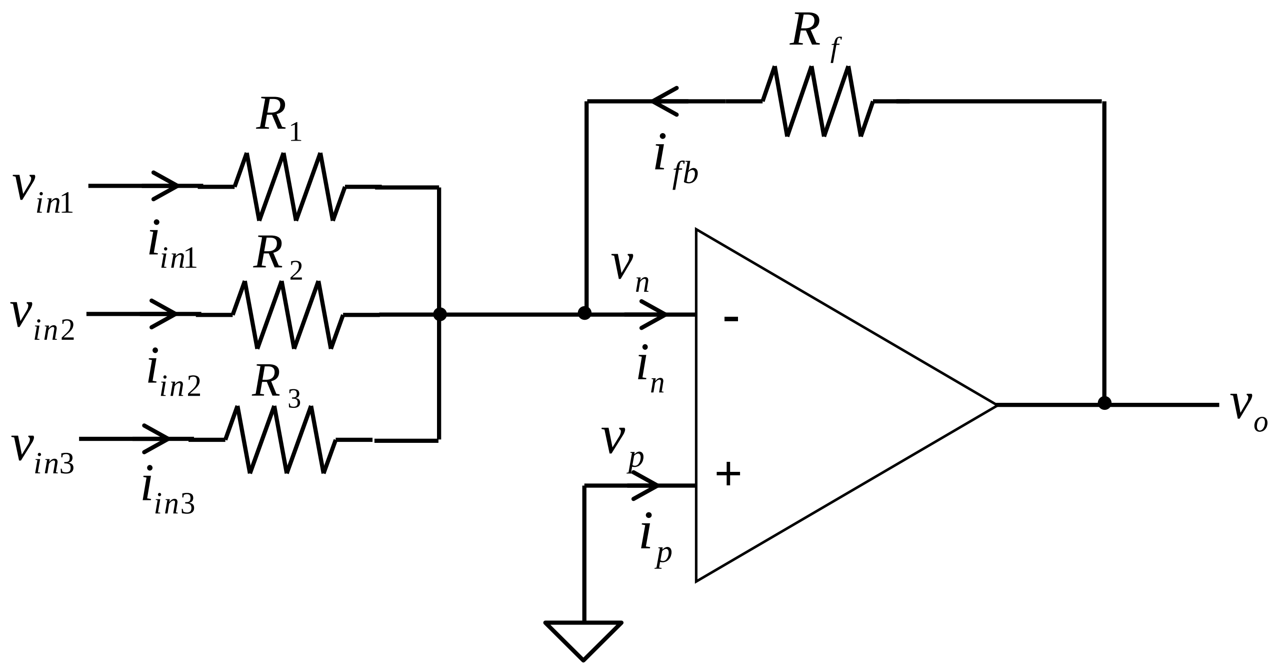
Hambley: Chapter 14, Horowitz and Hill: Chapter 4

Op Amp Circuits

- Op Amp Negative Feedback Circuits:
  - Summing and difference amps
  - Integrator and differentiator
  - Instrumentation amp
  - Precision half wave rectifier

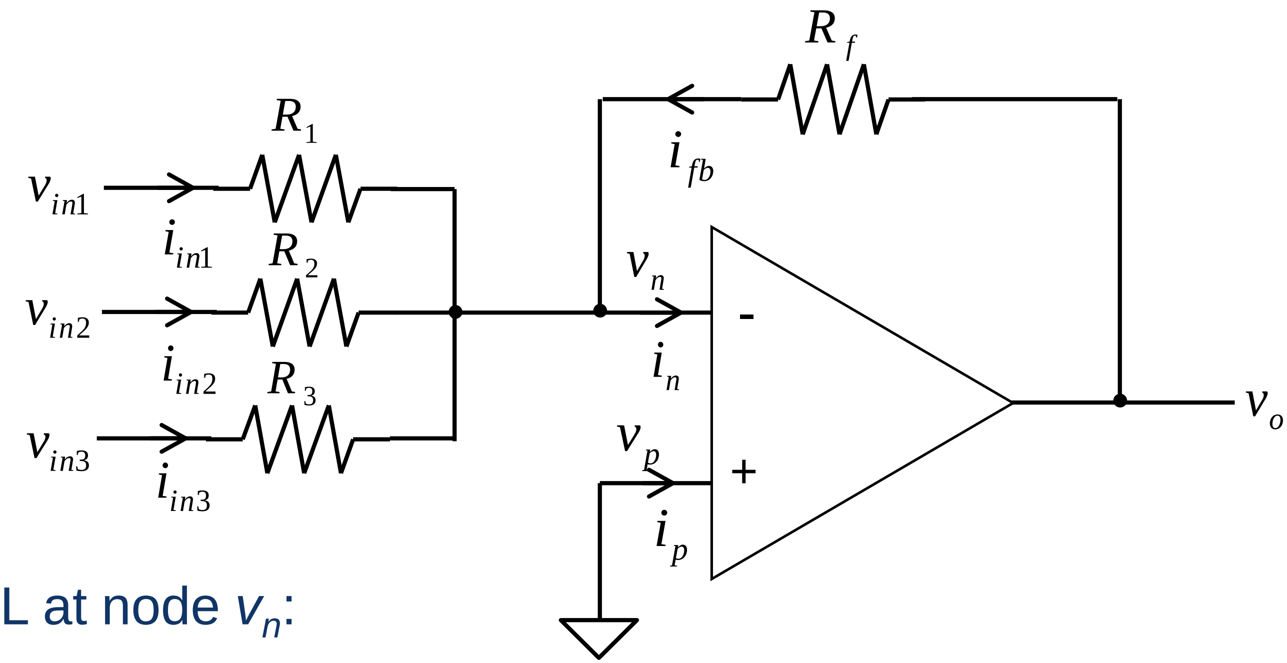
- Op Amp Positive feedback circuits:
  - Schmitt Trigger
  - Square wave generator (Astable Multivibrator)
  - Pulse generator (Monostable Multivibrator)

Summing Amplifier



- Golden Rule I : $v_n = v_p = 0$
- Golden Rule II : $i_n = i_p = 0$

Summing Amplifier



- KCL at node v_n:

$$v_o = -\left(\frac{R_f}{R_1} v_{in1} + \frac{R_f}{R_2} v_{in2} + \frac{R_f}{R_3} v_{in3} \right)$$

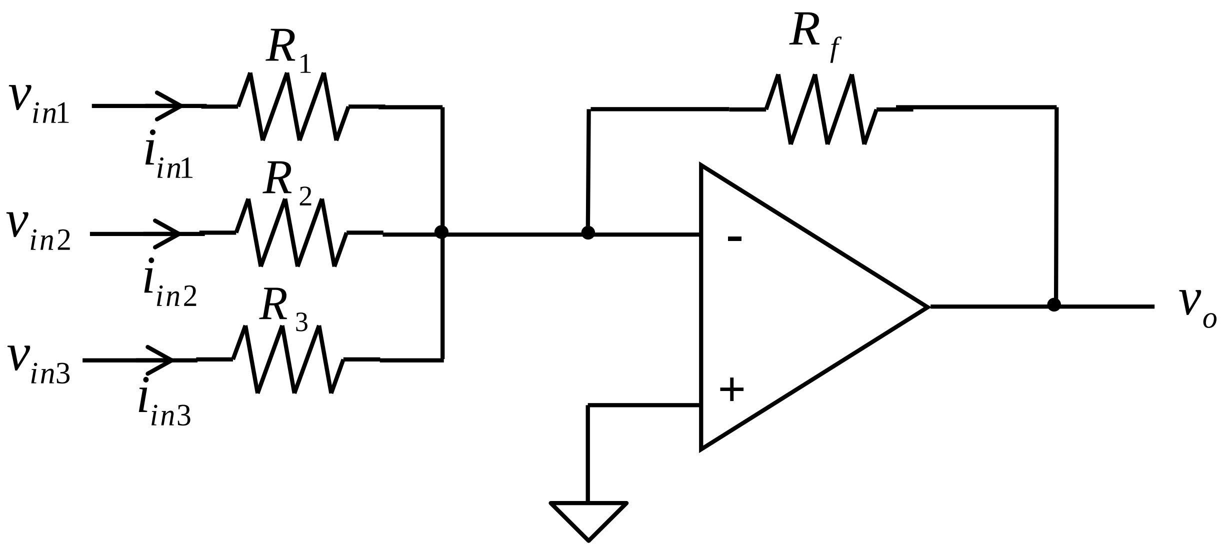
output is a weighted sum of inputs

Summing Amplifier

Example 1

- Design a 3 bit digital to analogue converter using a summing amplifier. Use R_f = 10kΩ.

3 bit binary number:	b2	b1	b0



Summing Amplifier

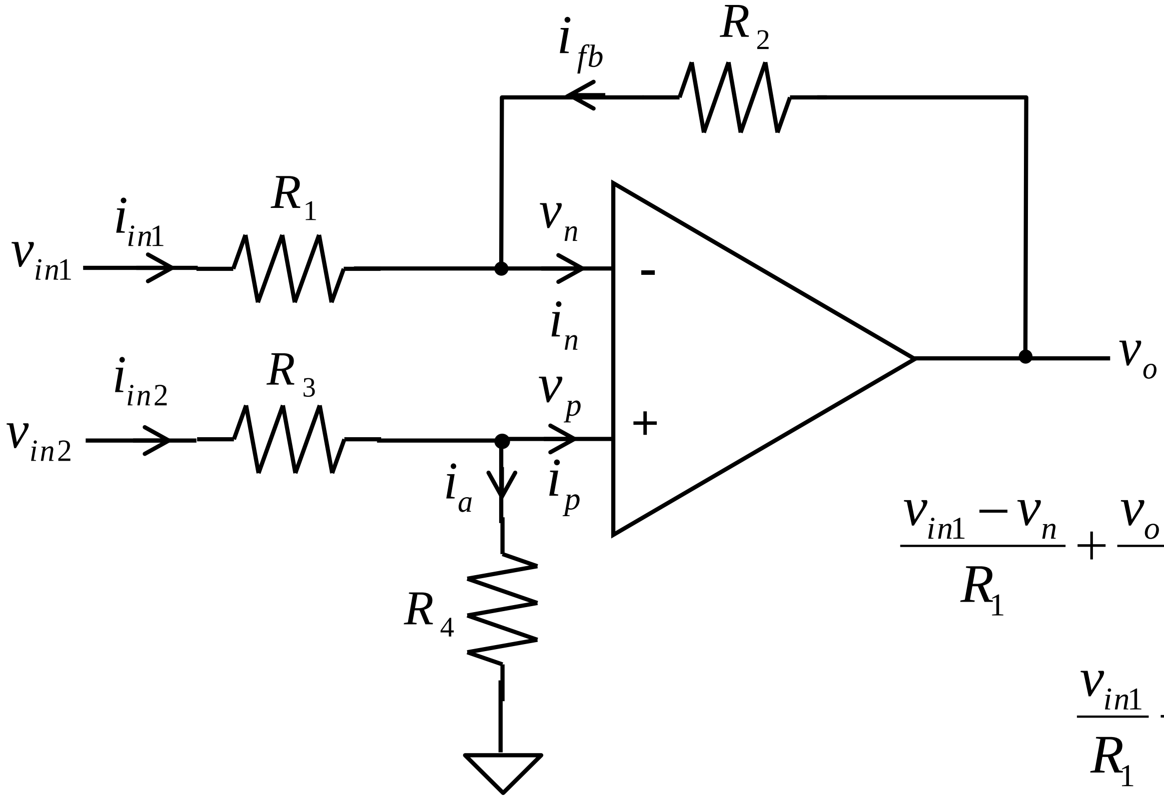
Example 1

- We would like:

- We have $v_o = -\left(\frac{R_f}{R_1} v_{in1} + \frac{R_f}{R_2} v_{in2} + \frac{R_f}{R_3} v_{in3} \right)$, with $R_f = 10\text{k}\Omega$

Difference Amplifier

- Amplify the difference between two inputs



- For an ideal op amp:

$$i_n = i_p = 0$$

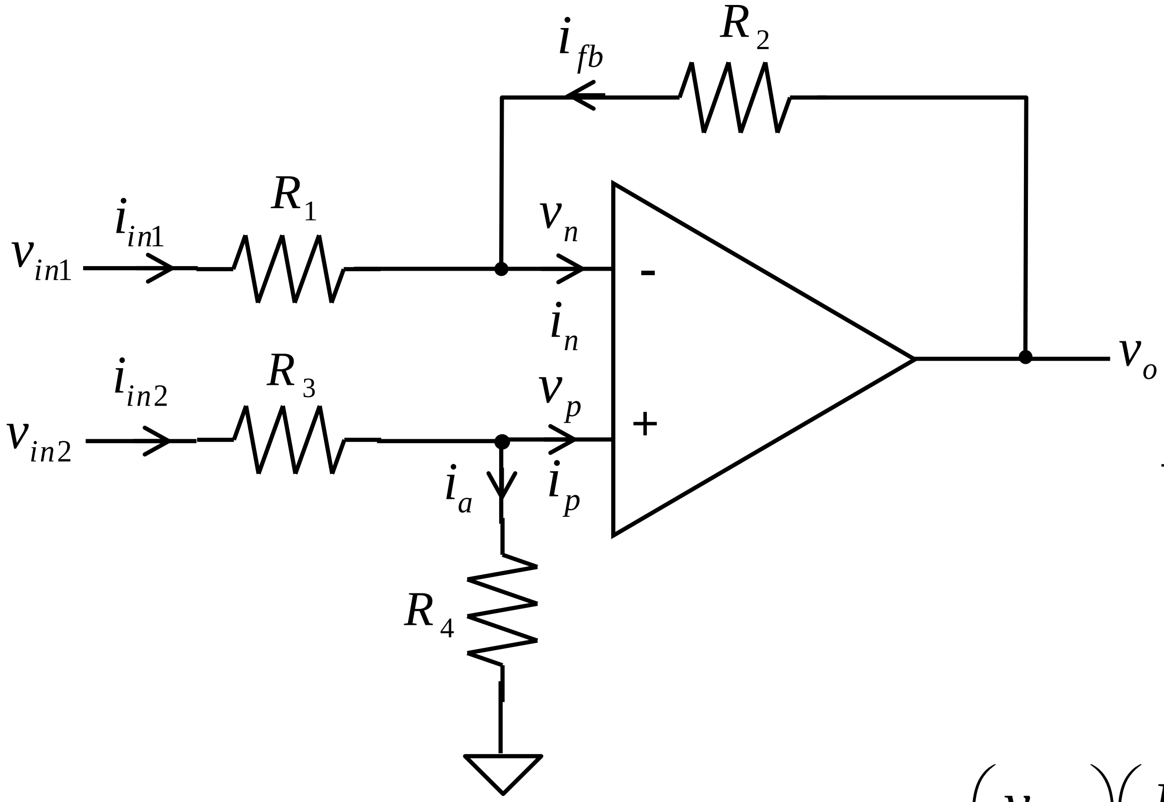
- Node v_n: $i_{in1} + i_{fb} = 0$

$$\frac{v_{in1} - v_n}{R_1} + \frac{v_o - v_n}{R_2} = 0$$

$$\frac{v_{in1}}{R_1} + \frac{v_o}{R_2} = v_n\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

$$\left(\frac{v_{in1}}{R_1} + \frac{v_o}{R_2}\right)\left(\frac{R_1 + R_2}{R_1 R_2}\right) = v_n \qquad \ldots(1)$$

Difference Amplifier



- Node v_p: $i_{in2} = i_a$

$$\frac{v_{in2} - v_p}{R_3} = \frac{v_p}{R_4}$$

$$\frac{v_{in2}}{R_3} = v_p\left(\frac{1}{R_3} + \frac{1}{R_4}\right)$$

$$\left(\frac{v_{in2}}{R_3}\right)\left(\frac{R_3 + R_4}{R_3 R_4}\right) = v_p \qquad \ldots(2)$$

Difference Amplifier

- Golden Rule I: $v_n = v_p$

- Combining (1) and (2):

$$\left(\frac{v_{in1}}{R_1}+\frac{v_o}{R_2}\right)\left(\frac{R_1R_2}{R_1+R_2}\right)=\frac{v_{in2}}{R_3}\left(\frac{R_3R_4}{R_3+R_4}\right)$$

$$v_o\left(\frac{R_1}{R_1+R_2}\right)=v_{in2}\left(\frac{R_4}{R_3+R_4}\right)-v_{in1}\left(\frac{R_2}{R_1+R_2}\right)$$

$$v_o=v_{in2}\left(\frac{R_4}{R_1}\right)\left(\frac{R_1+R_2}{R_3+R_4}\right)-v_{in1}\left(\frac{R_2}{R_1}\right)$$

Difference Amplifier

$$v_o = v_{in2}\left(\frac{R_4}{R_1}\right)\left(\frac{R_2}{R_4}\right)\left(\frac{R_1/R_2+1}{R_3/R_4+1}\right) - v_{in1}\left(\frac{R_2}{R_1}\right)$$

$$v_o = v_{in2}\left(\frac{R_2}{R_1}\right)\left(\frac{R_1/R_2+1}{R_3/R_4+1}\right) - v_{in1}\left(\frac{R_2}{R_1}\right)$$

$$v_o = \left(\frac{R_2}{R_1}\right)\left(v_{in2}\underbrace{\left(\frac{R_1/R_2+1}{R_3/R_4+1}\right)}_{=1} - v_{in1}\right)$$

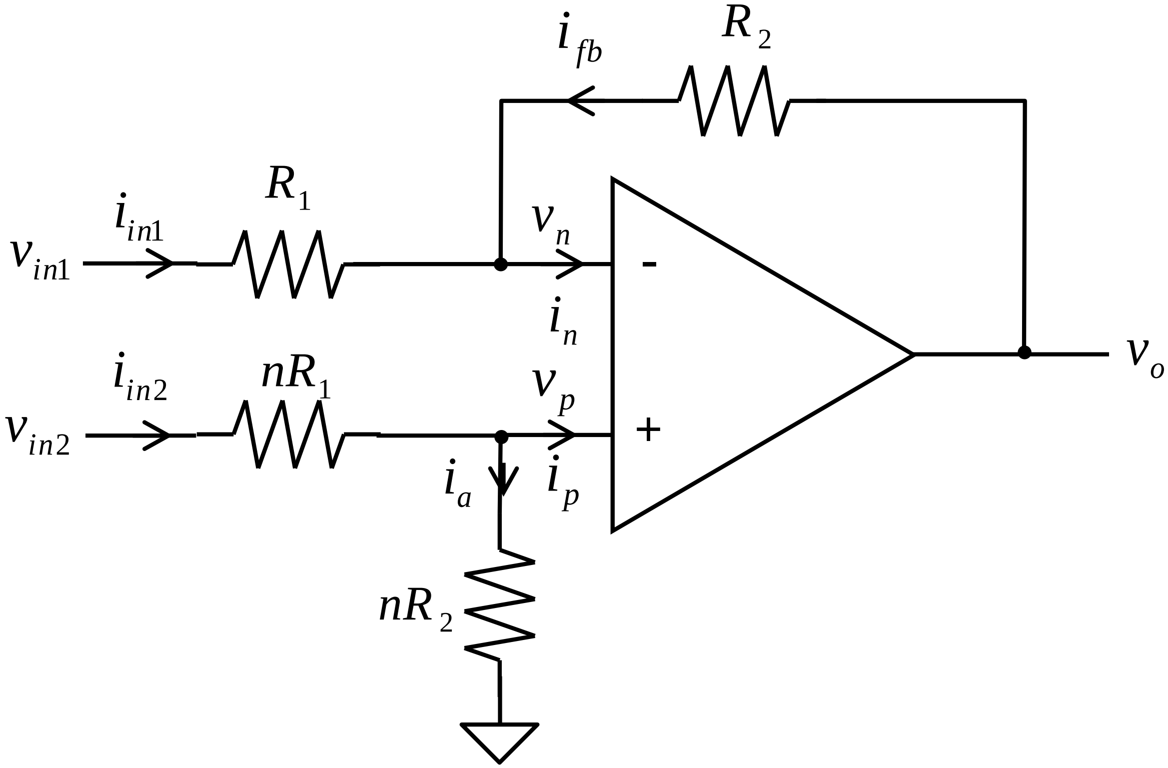
- We need:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4} \qquad \text{or} \qquad \begin{aligned} R_1 &= nR_3 \\ R_2 &= nR_4 \end{aligned}$$

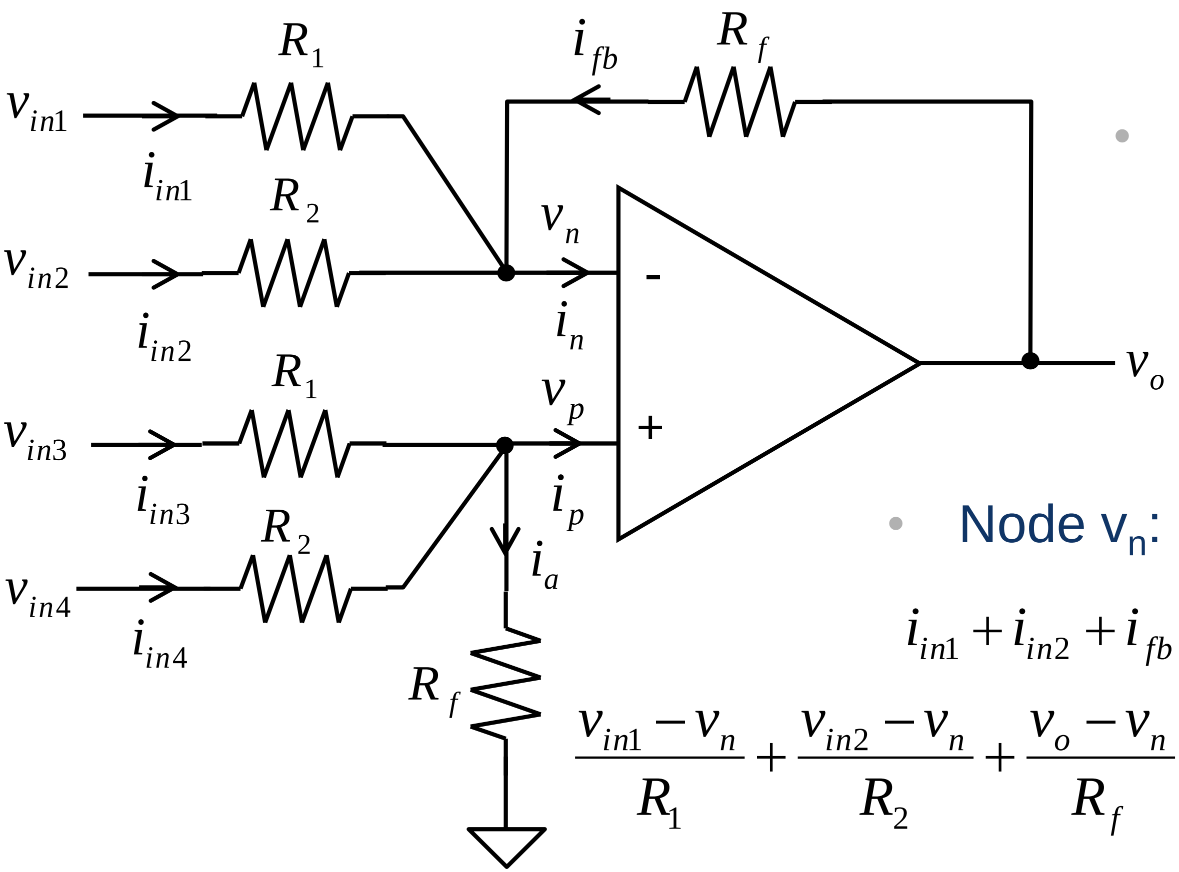
Difference Amplifier

- Then we have:

$$v_o = \left(\frac{R_2}{R_1}\right)\left(v_{in2} - v_{in1}\right)$$



Summing Difference Amplifier



- Ideal op amp:

$$i_n = i_p = 0$$

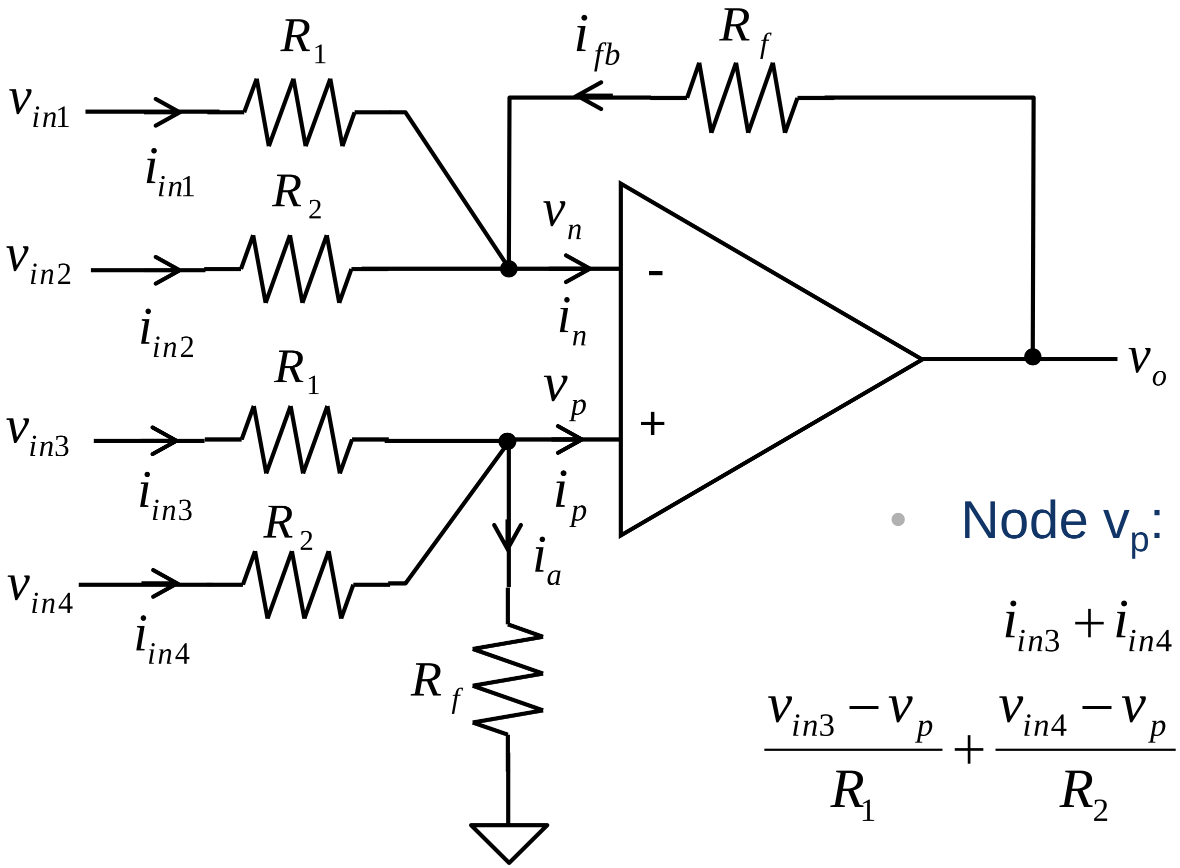
- Node v_n:

$$i_{in1} + i_{in2} + i_{fb} = 0$$

$$\frac{v_{in1} - v_n}{R_1} + \frac{v_{in2} - v_n}{R_2} + \frac{v_o - v_n}{R_f} = 0$$

$$\frac{v_{in1}}{R_1} + \frac{v_{in2}}{R_2} + \frac{v_o}{R_f} = v_n\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_f}\right) \quad \ldots(3)$$

Summing Difference Amplifier



- Node v_p:

$$i_{in3} + i_{in4} = i_a$$

$$\frac{v_{in3} - v_p}{R_1} + \frac{v_{in4} - v_p}{R_2} = \frac{v_p}{R_f}$$

$$\frac{v_{in3}}{R_1} + \frac{v_{in4}}{R_2} = v_p\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_f}\right) \quad ...(4)$$

Summing Difference Amplifier

- Golden Rule I: $v_n = v_p$
- Combining (1) and (2):

$$\frac{v_{in1}}{R_1} + \frac{v_{in2}}{R_2} + \frac{v_o}{R_f} = \frac{v_{in3}}{R_1} + \frac{v_{in4}}{R_2}$$

$$\frac{v_o}{R_f} = \frac{1}{R_1}\left(v_{in3} - v_{in1}\right) + \frac{1}{R_2}\left(v_{in4} - v_{in2}\right)$$

$$\boxed{v_o = \frac{R_f}{R_1}\left(v_{in3} - v_{in1}\right) + \frac{R_f}{R_2}\left(v_{in4} - v_{in2}\right)}$$

Summing Difference Amplifier

Example 2:

- Using R_f = 100kΩ, design a summing difference amp circuit to produce an output:

$$v_o = 20\left(v_{in3} - v_{in1}\right) - 10 v_{in2}$$

- The above can be expressed as:

$$v_o = 20\left(v_{in3} - v_{in1}\right) - 10\left(v_{in2} - 0\right)$$

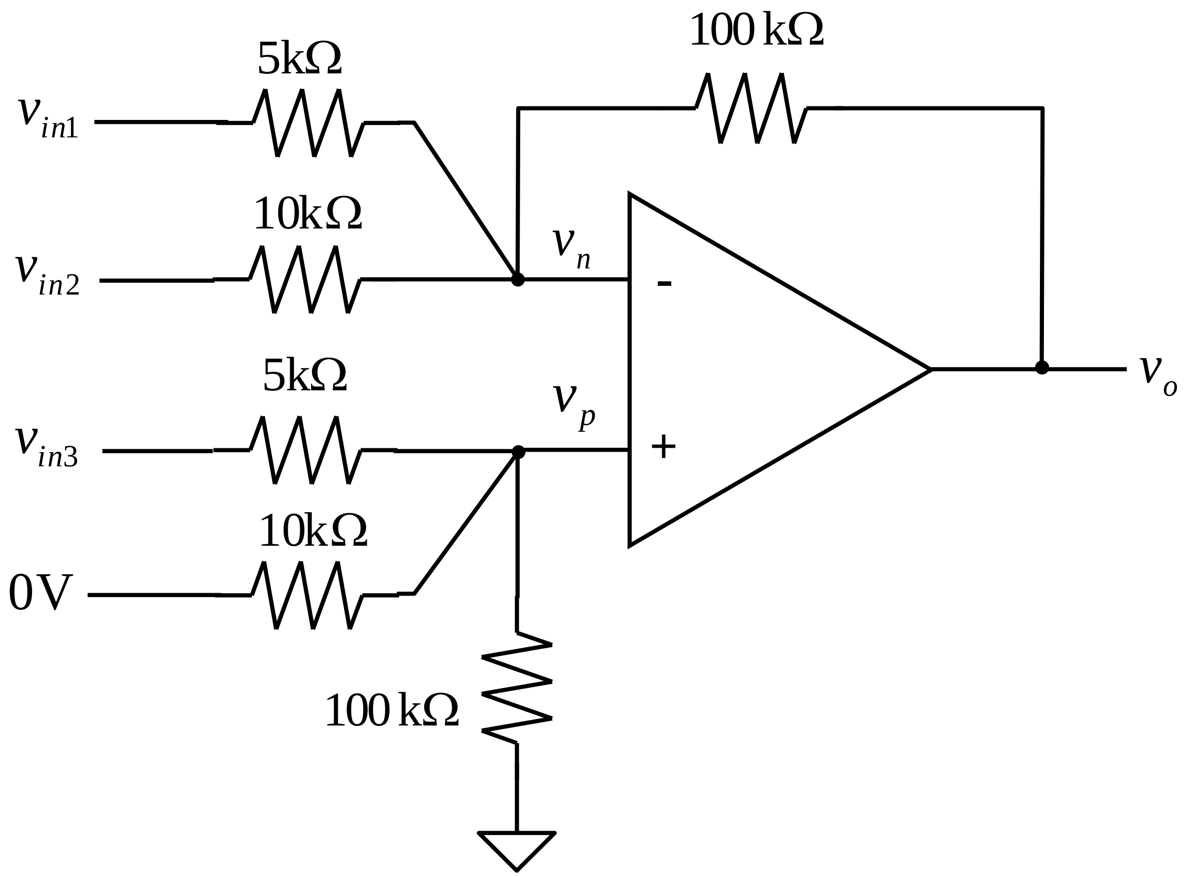
- Compare this with the output for the summing difference amp:

$$v_o = \frac{R_f}{R_1}\left(v_{in3} - v_{in1}\right) + \frac{R_f}{R_2}\left(v_{in4} - v_{in2}\right)$$

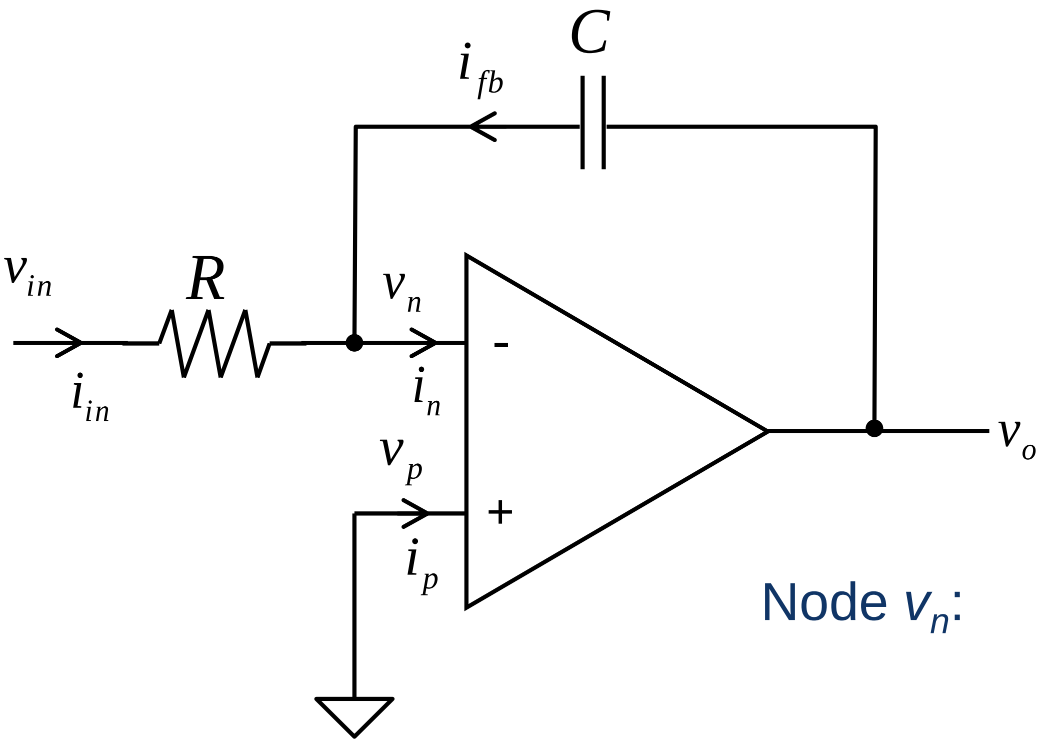
Summing Difference Amplifier

Example 2:

We need:



Integrator



$$i_{in} = \frac{v_{in}}{R}$$

v_o $$i_{fb} = C\frac{dv_o}{dt}$$

Node v_n:

$$\frac{v_{in}}{R} + C\frac{dv_o}{dt} = 0$$

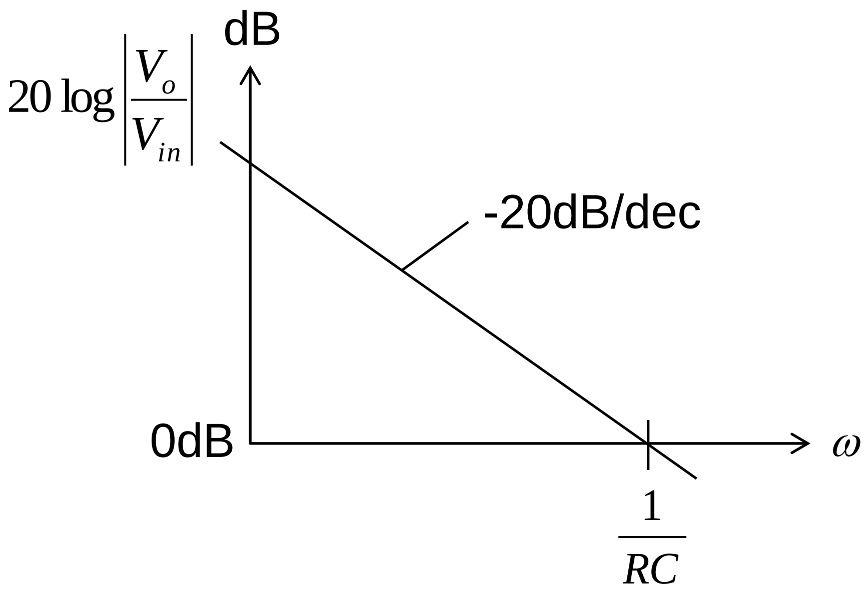
$$dv_o = -\frac{1}{RC} v_{in} dt$$

$$\boxed{v_o = -\frac{1}{RC}\int v_{in}(t)dt}$$

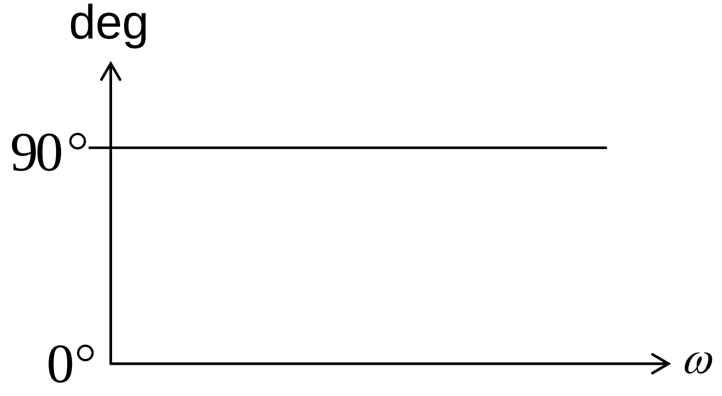
Integrator

- Frequency response:

Magnitude:



Phase:

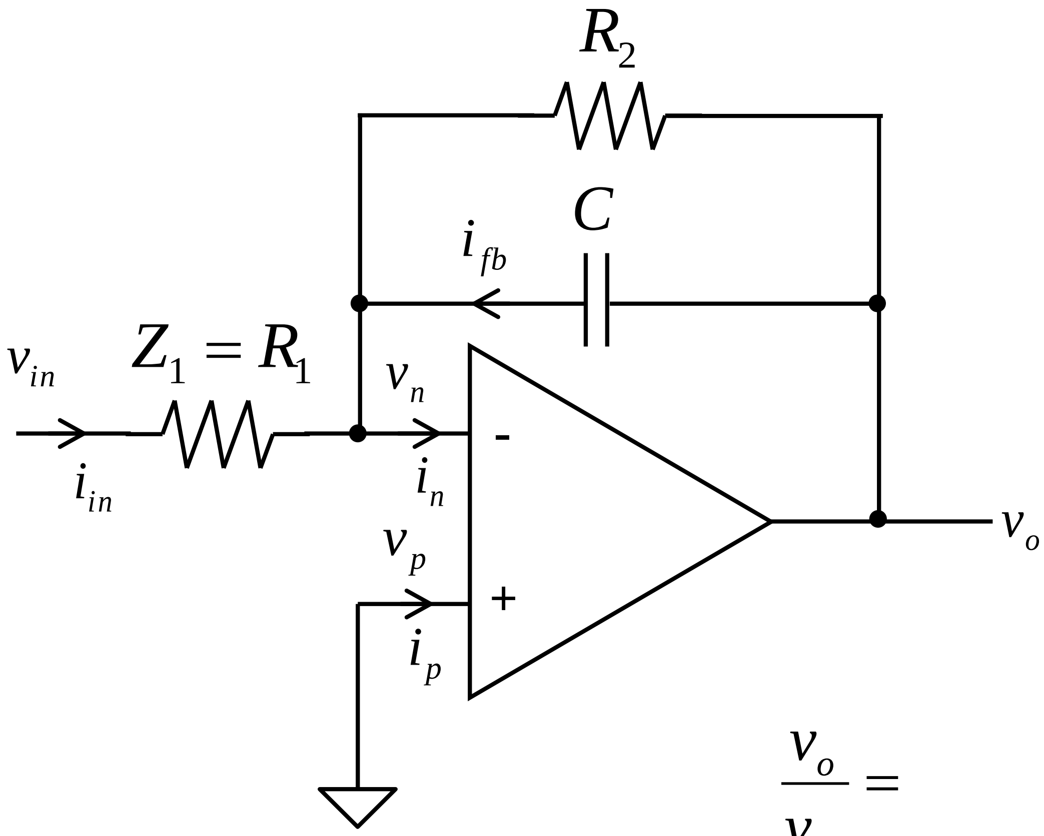


Integrator

- Problem with this integrator circuit:
  - No feedback at DC
  - High gain at low frequencies

  - Add a resistor which introduces a pole that limits the gain at low frequencies.

Integrator



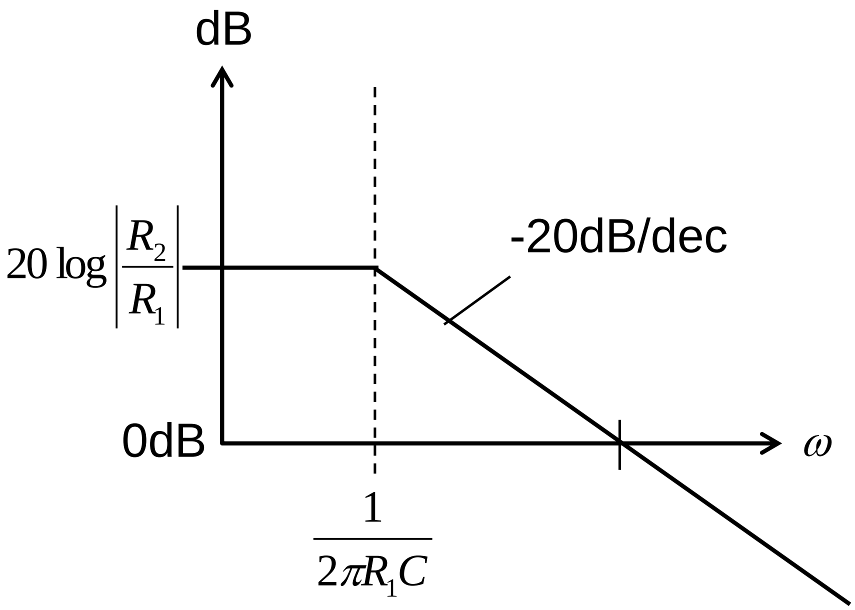
$$\frac{v_o}{v_{in}} =$$

Integrator

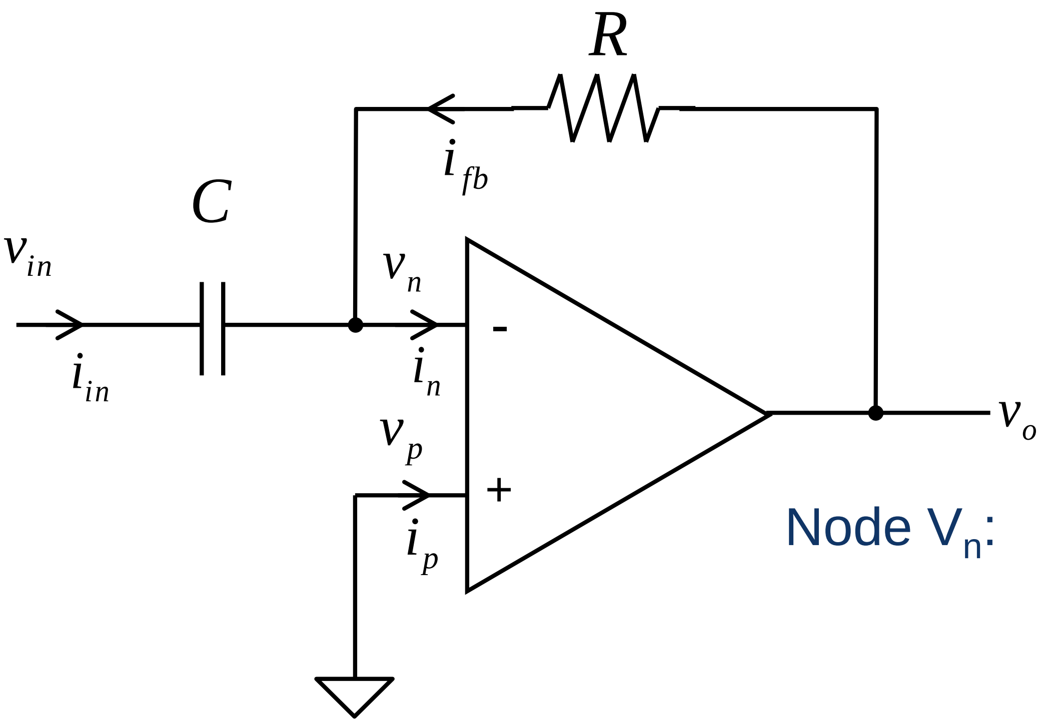
- Frequency response:

Magnitude:

$$20\log\left|\frac{V_o}{V_{in}}\right|$$



Differentiator



$$i_{in} = C\frac{dv_{in}}{dt}$$

$$i_{fb} = \frac{v_o}{R}$$

Node V_n:

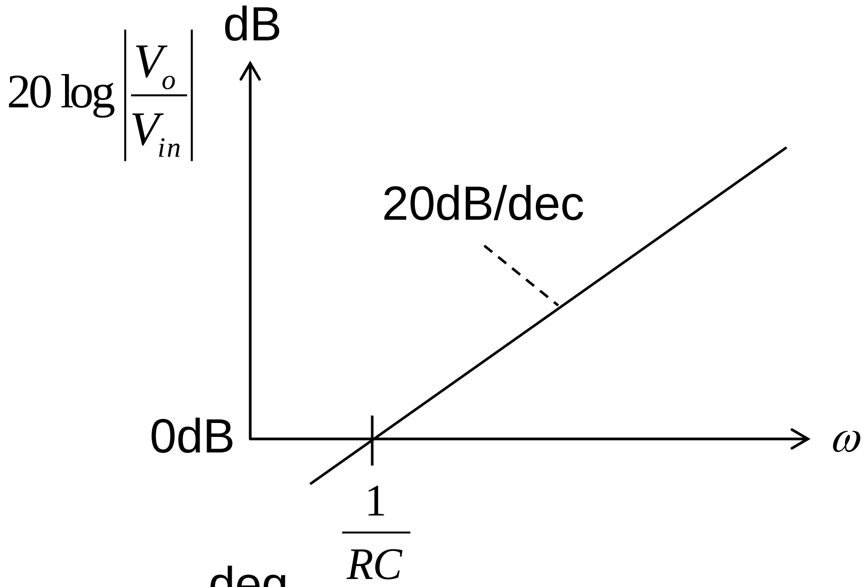
$$C\frac{dv_{in}}{dt} + \frac{v_o}{R} = 0$$

$$\boxed{v_o = -CR\frac{dv_{in}}{dt}}$$

Differentiator

- Frequency response:

Magnitude:

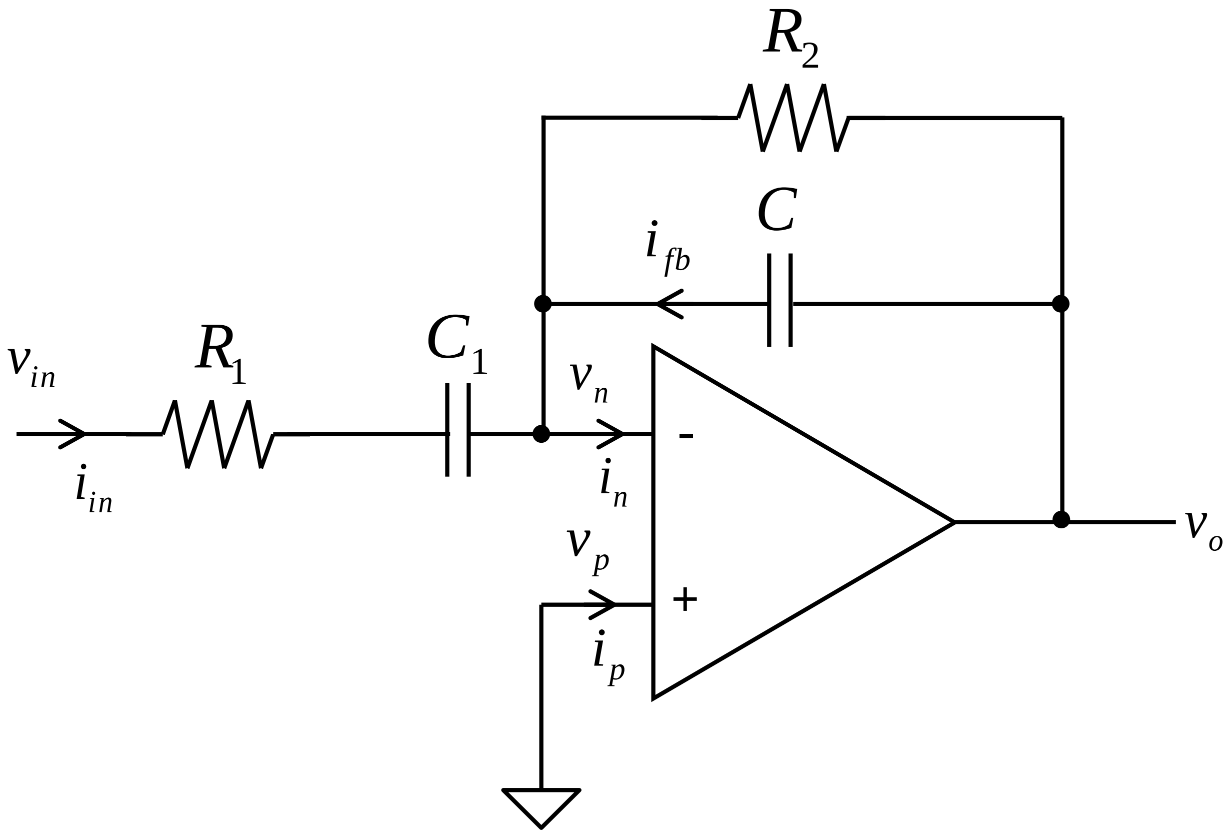


Phase:

Differentiator

- Problem with instability at high frequencies.
- Add two poles to roll off the gain

Differentiator

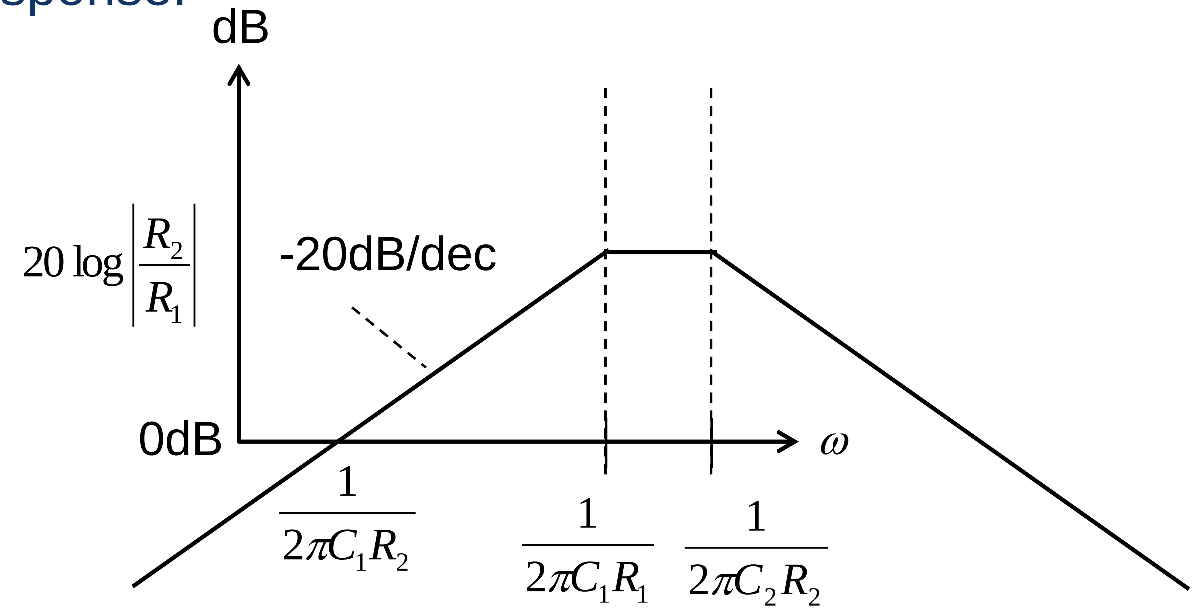


Differentiator

- Frequency response:

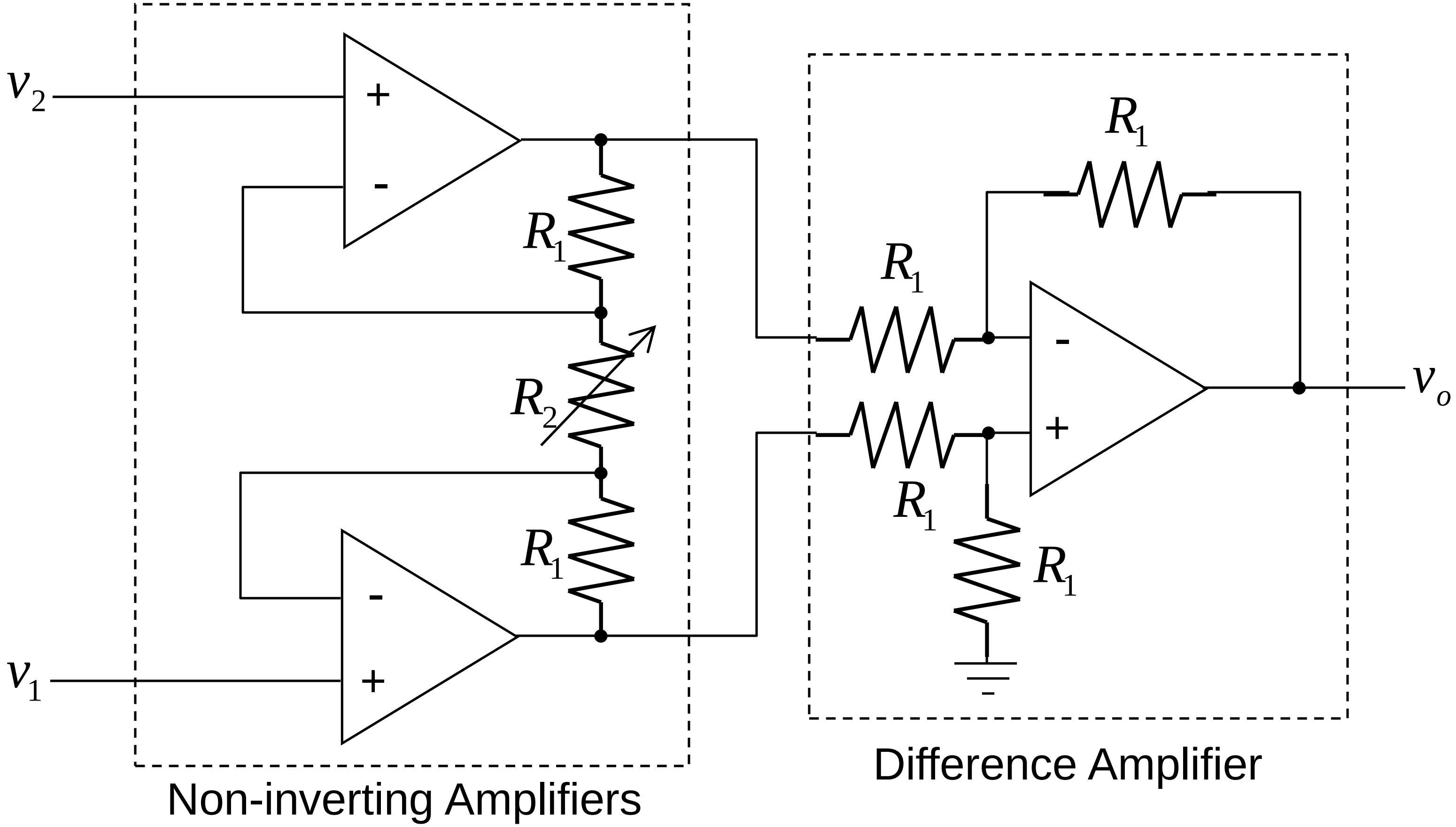
Magnitude:

$$20\log\left|\frac{V_o}{V_{in}}\right|$$

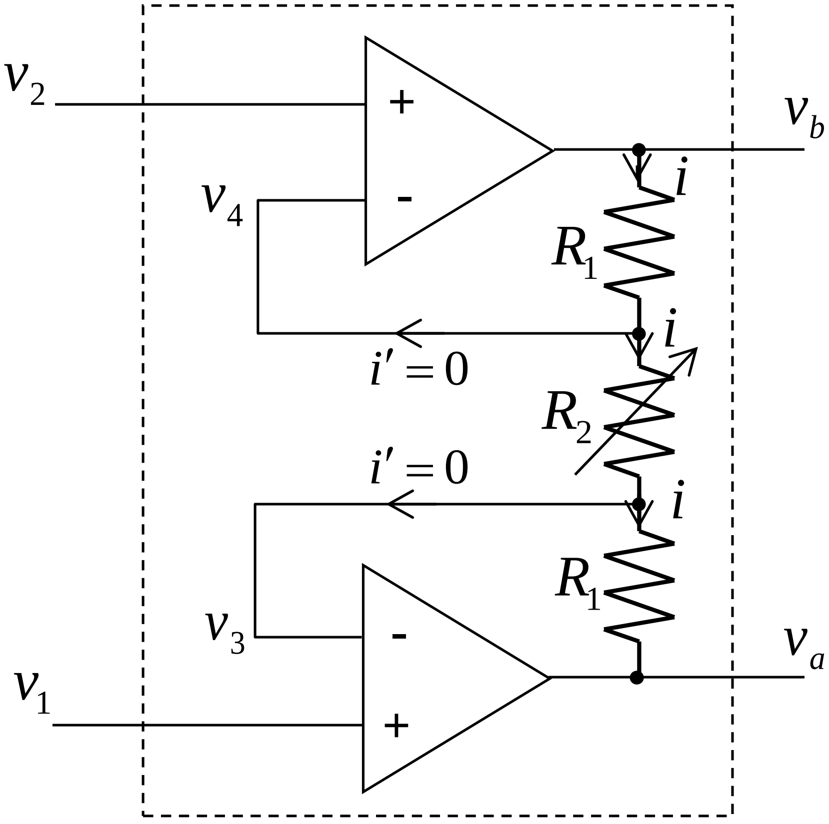


Instrumentation Amplifier

- This is a differential input amplifier system with very high input impedances.



Instrumentation Amplifier



Non-inverting Amplifiers

- Non inverting amplifier:

$$v_b - iR_1 - iR_2 - iR_1 = v_a$$

$$v_b - v_a = i(2R_1 + R_2)$$

  - due to virtual short:

$$v_4 = v_2; \qquad v_3 = v_1$$

$$i = (v_2 - v_1)/R_2$$

  - Therefore:

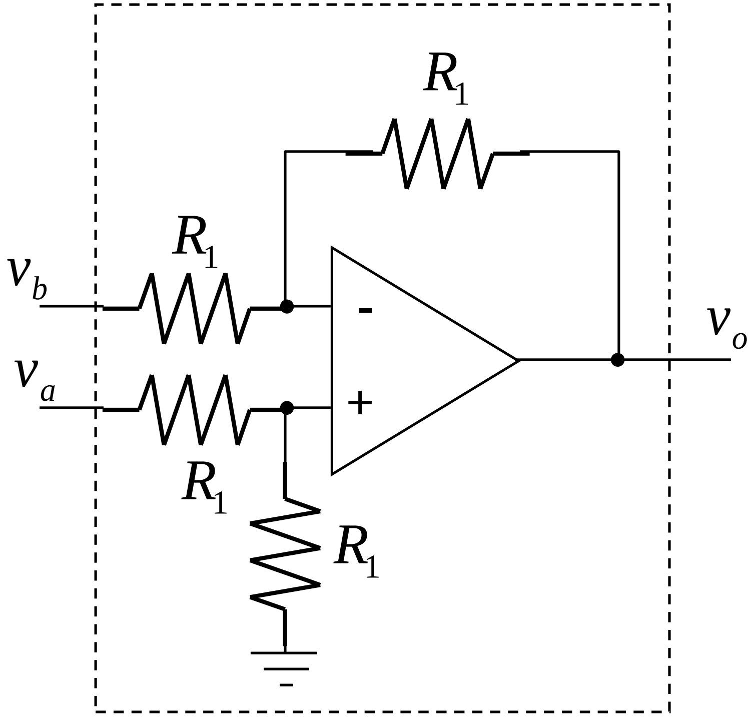
$$v_b - v_a = (v_2 - v_1)\left(\frac{2R_1}{R_2} + 1\right)$$

Instrumentation Amplifier

- Difference Amplifier:

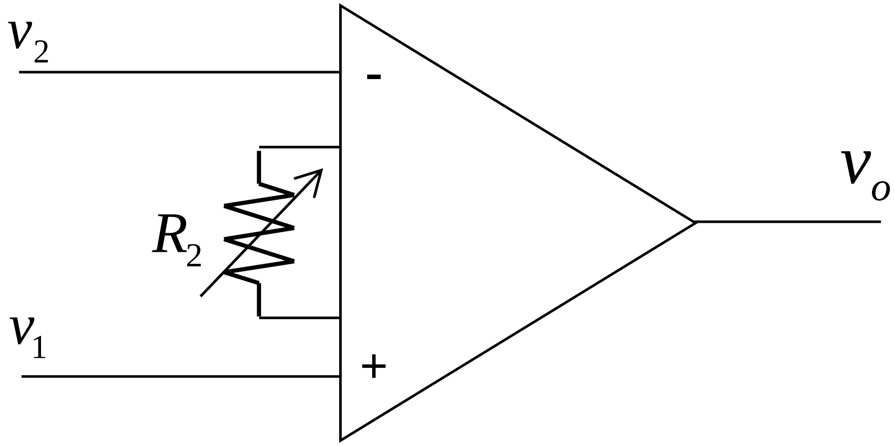
$$v_o = -(v_b - v_a)$$

$$v_o = -(v_2 - v_1)\left(\frac{2R_1}{R_2} + 1\right)$$



Difference Amplifier

Instrumentation Amplifier



$$v_o = -(v_2 - v_1)\left(\frac{2R_1}{R_2} + 1\right)$$

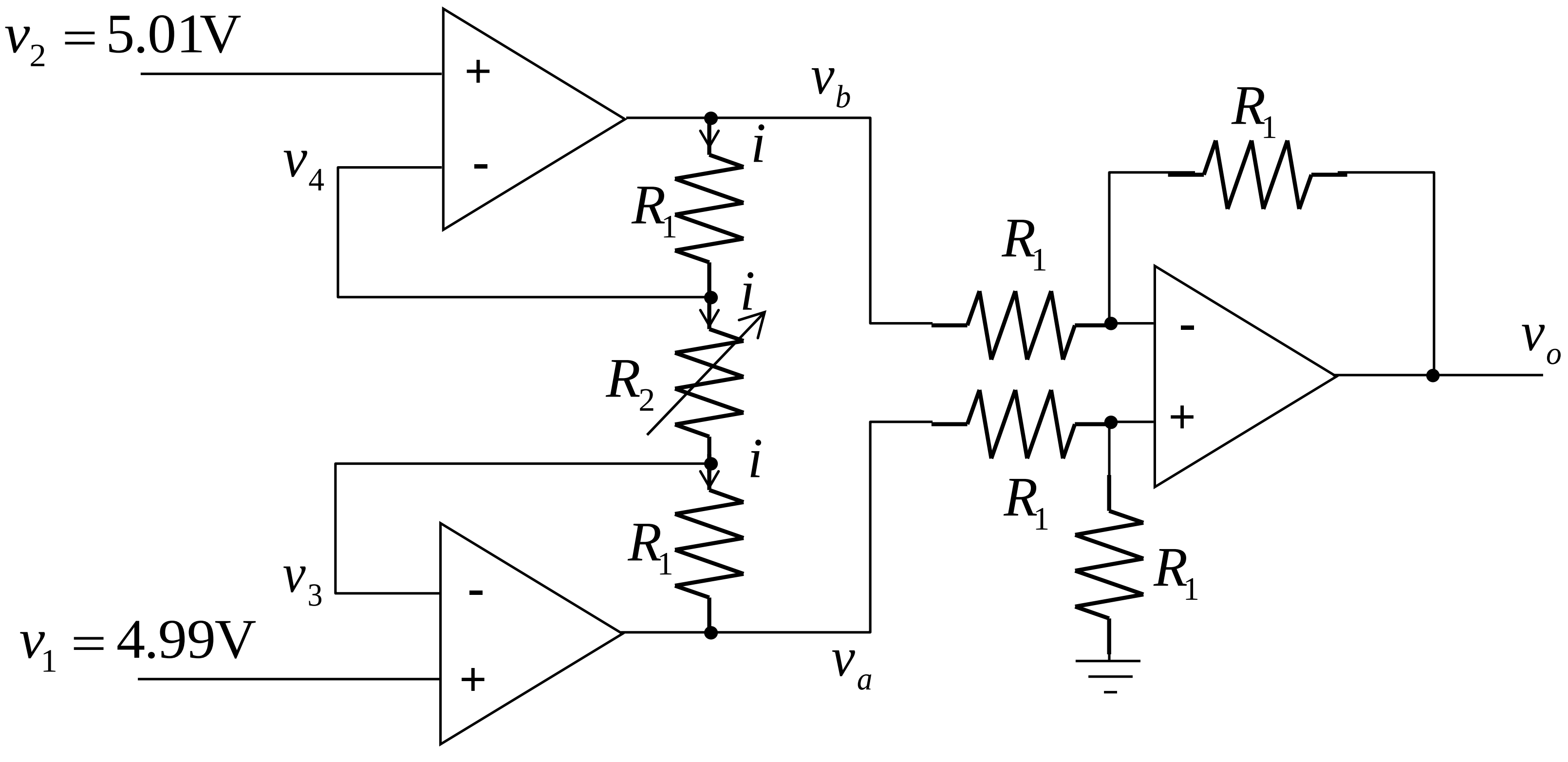
Instrumentation Amplifier

Example 3:

- Voltages v_2=5.01V and v_1=4.99V are input to an instrumentation amp. What are the values of v_b, v_a, i and v_o when R_1 = 30kΩ and R_2 = 2.7k?

Instrumentation Amplifier

Example 3:

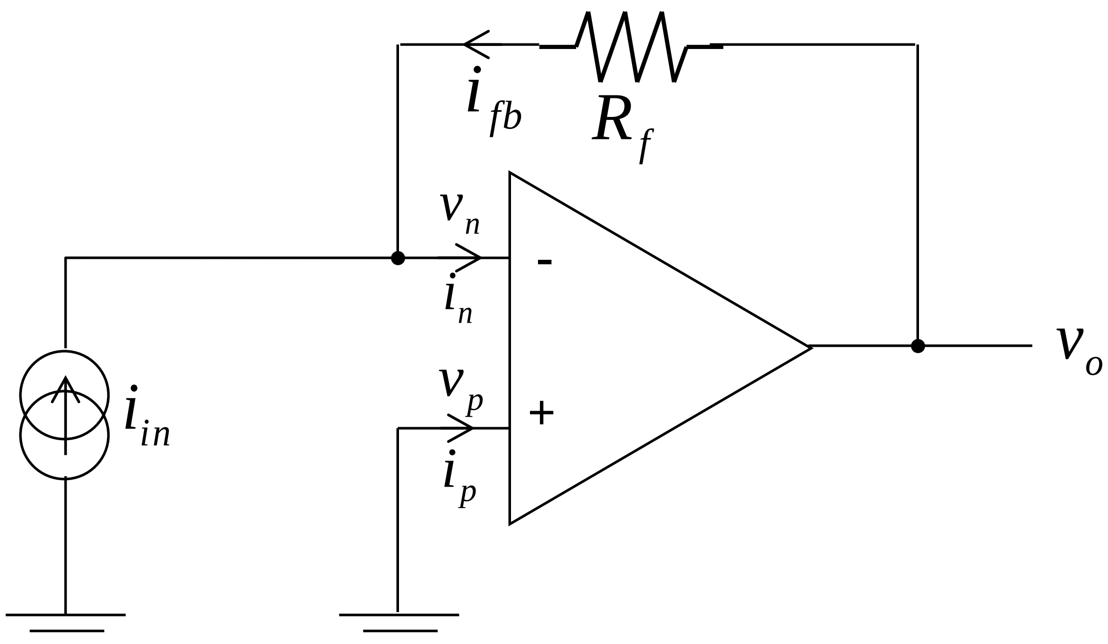


Instrumentation Amplifier

Example 3:

Current to Voltage Converter

- In some situations, the output of a device is a current, for example a photodiode or photodetector.
- We may need to convert this current to voltage.



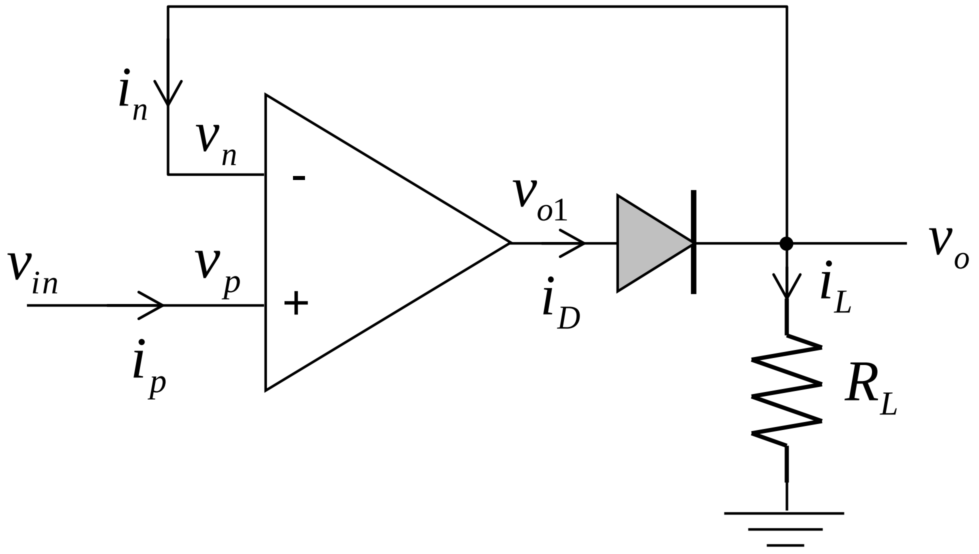
$$i_{in} = -i_{fb}$$

$$v_o = i_{fb} R_f$$

$$v_o = -i_{in} R_f$$

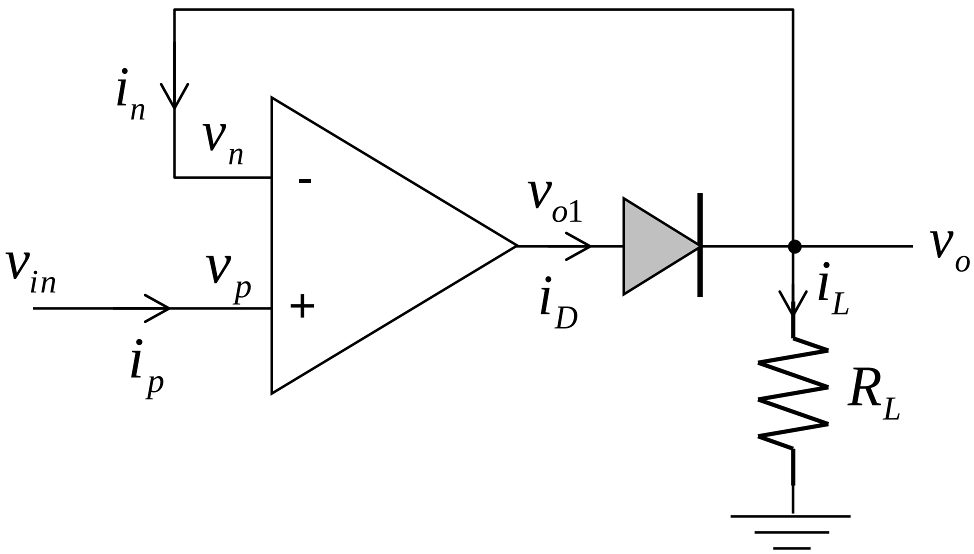
$$i_n = i_p = 0$$

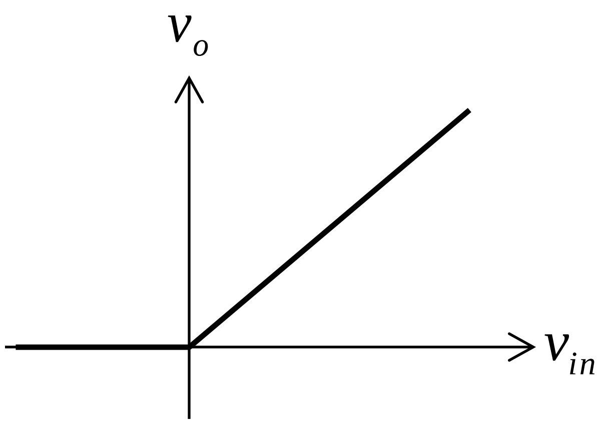
Precision Half Wave Rectifier



- For $v_{in} > 0$, the circuit behaves as a voltage follower, and $v_o = v_{in}$.
- The load current i_L is positive, and $i_D = i_L$.

Precision Half Wave Rectifier





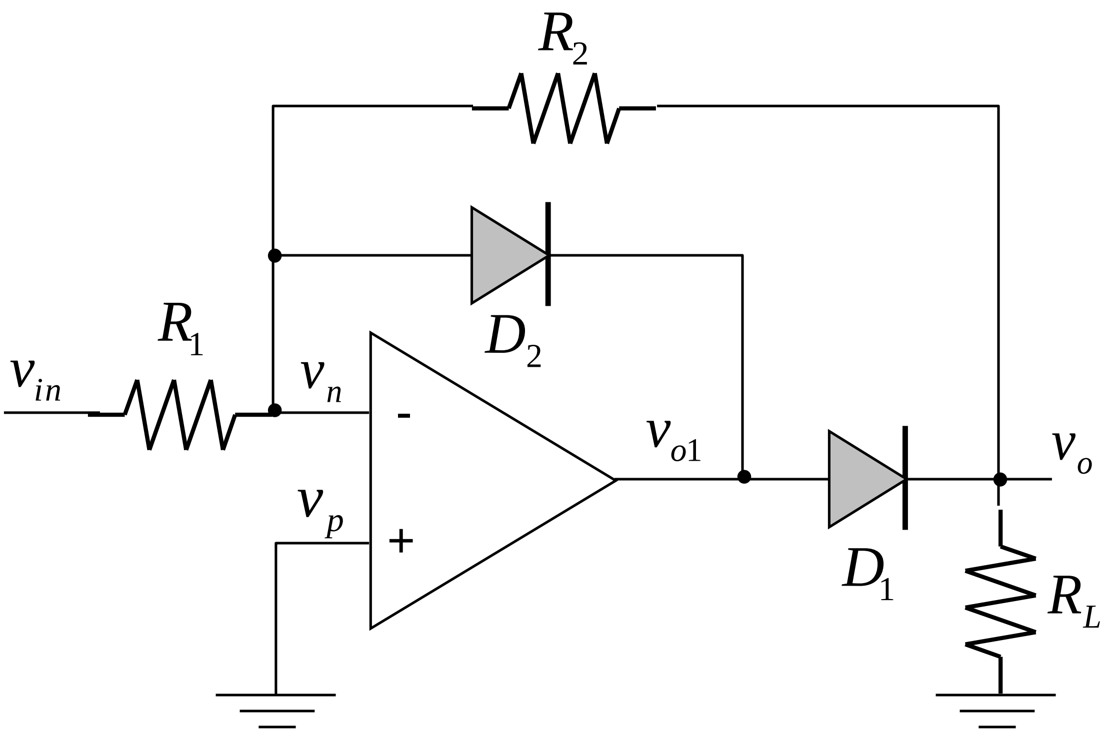
- For $v_{in} < 0$, v_o starts to go –ve, producing –ve i_L and i_D.
- However, i_D cannot go –ve due to the diode.
- The diode cuts off and the feedback loop is broken, $v_o = 0$.

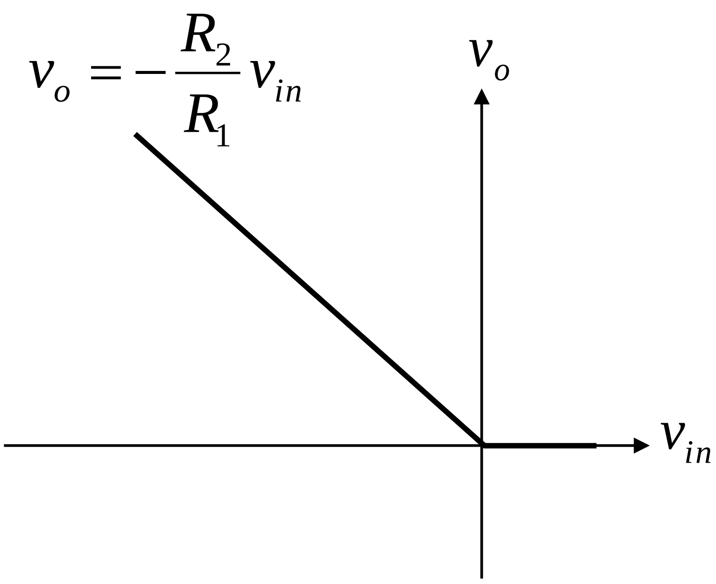
Precision Half Wave Rectifier

- Provides accurate rectification for very small input voltages and is sometimes called a *superdiode*.
- Problem for large negative input voltages
  - large voltage difference at op amp input, not a problem if the op amp has in-built protection.
  - v_{o1} is saturated at the negative supply. This is not harmful to the op amp, but internal circuits take time to recover from saturation, slowing down response time.

Non Saturating Precision Half Wave Rectifier

- The saturation problem can be solved with the circuit below.





Non Saturating Precision Half Wave Rectifier

- When v_{in} is positive, v_{o1} is driven negative. D_2 is switched on and v_{o1} becomes $-V_D$. D_1 is reverse biased. v_p is at virtual ground, and $v_o = 0V$.

- When v_{in} is negative, v_{o1} is driven positive and D_2 is switched off. D_1 is switched on and the feedback loop goes through D_1 and R_2. The circuit behaves like an inverting amplifier with gain $-R_2/R_1$.

Non Saturating Precision Half Wave Rectifier

Example 4:

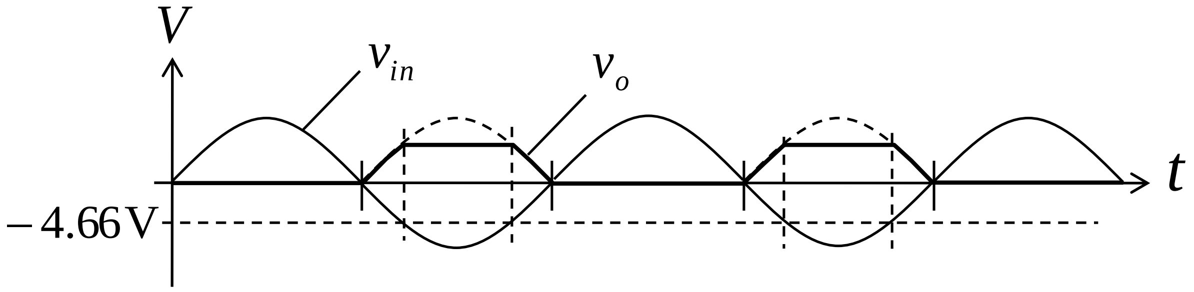
- Suppose the diodes have on-voltages of 0.6V, the power supply of the op amp is ±15V, R_1= 22kΩ and R_2 = 68kΩ. What are the values of v_o and v_{o1} when v_{in} = 2V, and -2V? Estimate the most negative input voltage for which the circuit will operate properly.

Non Saturating Precision Half Wave Rectifier

Example 4:

Non Saturating Precision Half Wave Rectifier

Example 4:

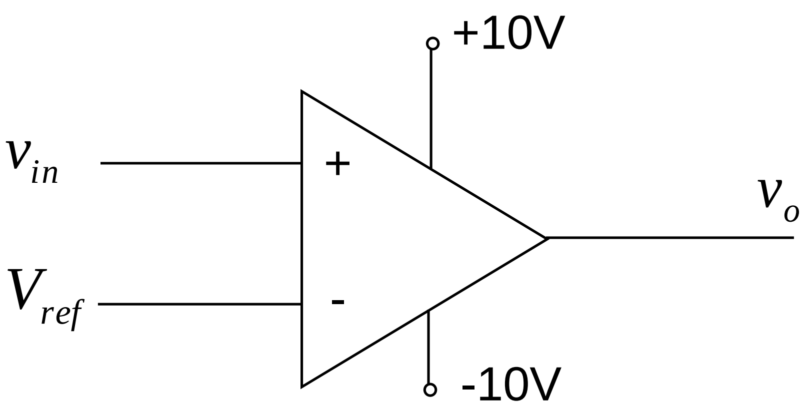


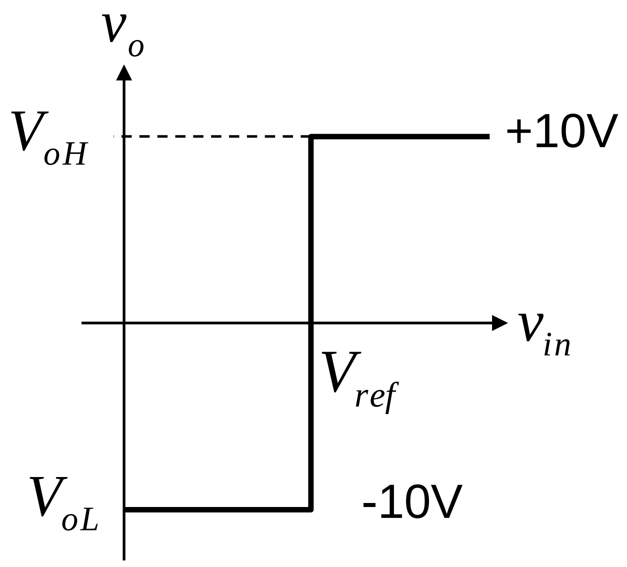
Circuits Using Positive Feedback

- All circuits up until now have used negative feedback.
- Positive feedback can be used to perform some useful non-linear functions, including:
  - Schmitt trigger
  - Square wave generator (Astable multivibrator)
  - Pulse generator (Monostable multivibrator)

Comparator

- Compares a voltage to a known reference level, V_{ref}.
- Output
  - logic 1 when $v_{in} > V_{ref}$
  - logic 0 when $v_{in} < V_{ref}$

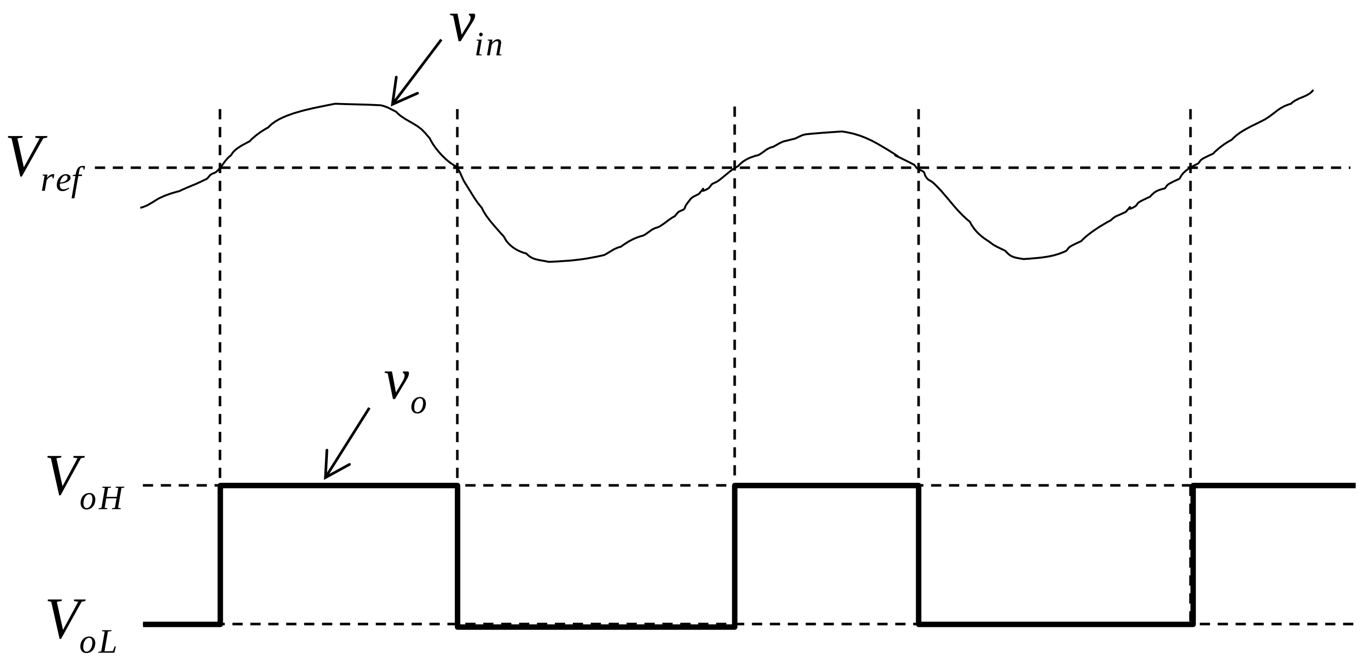




$$v_o = A_{v0}\left(v_p - v_n\right)$$

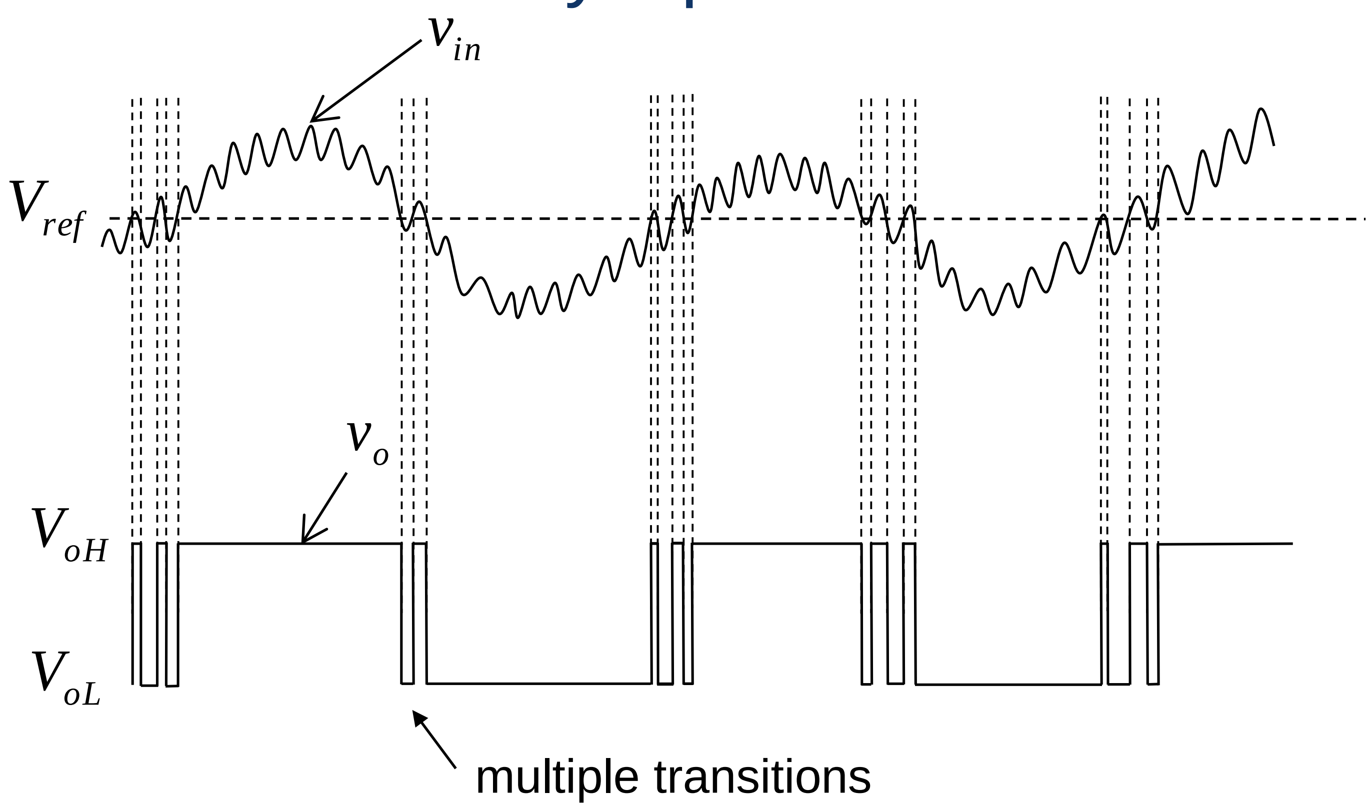
Comparator

- Example input/output waveforms:



Comparator

- Problem for noisy input:



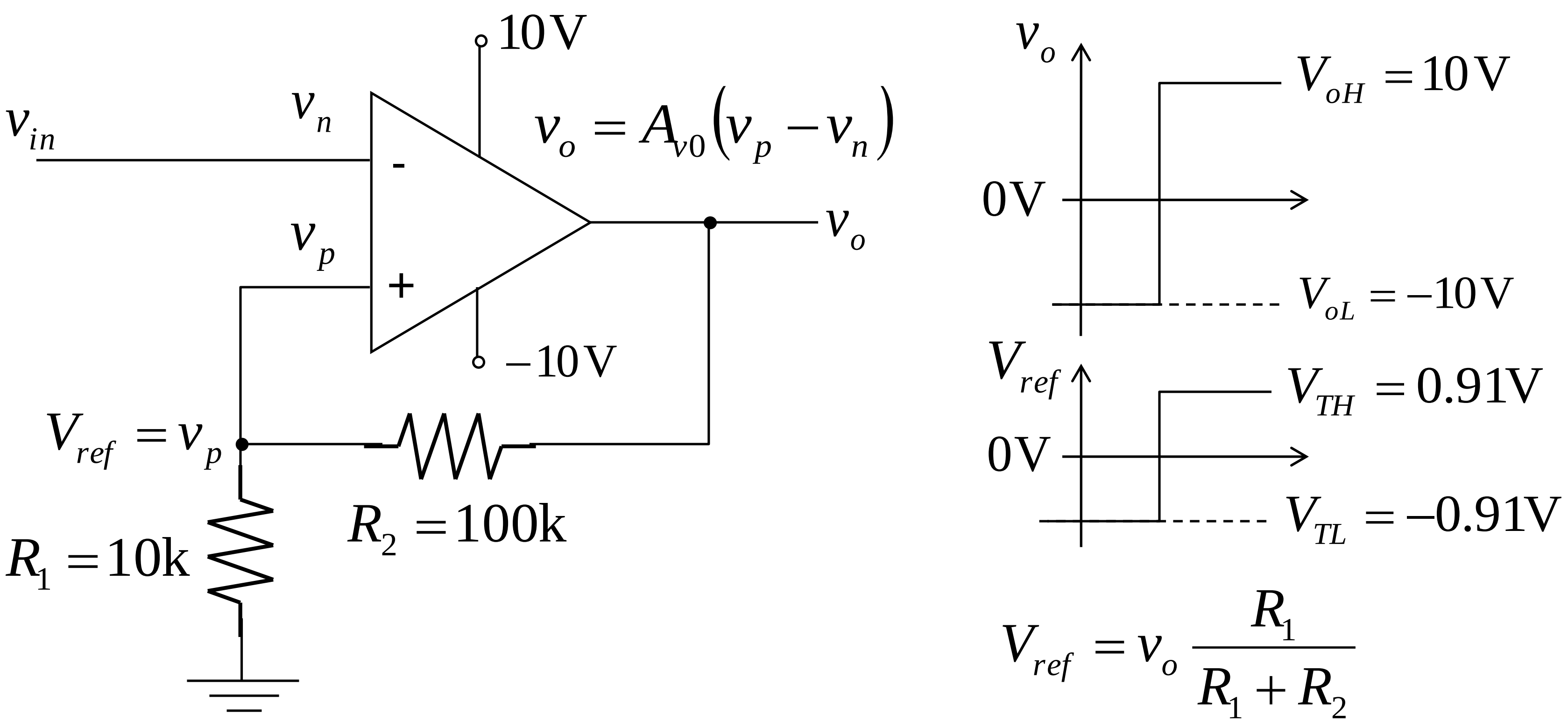
Schmitt Trigger

- The Schmitt trigger is like a comparator with two reference trigger levels.

- Positive feedback is used – note that the virtual short condition does not apply

Schmitt Trigger

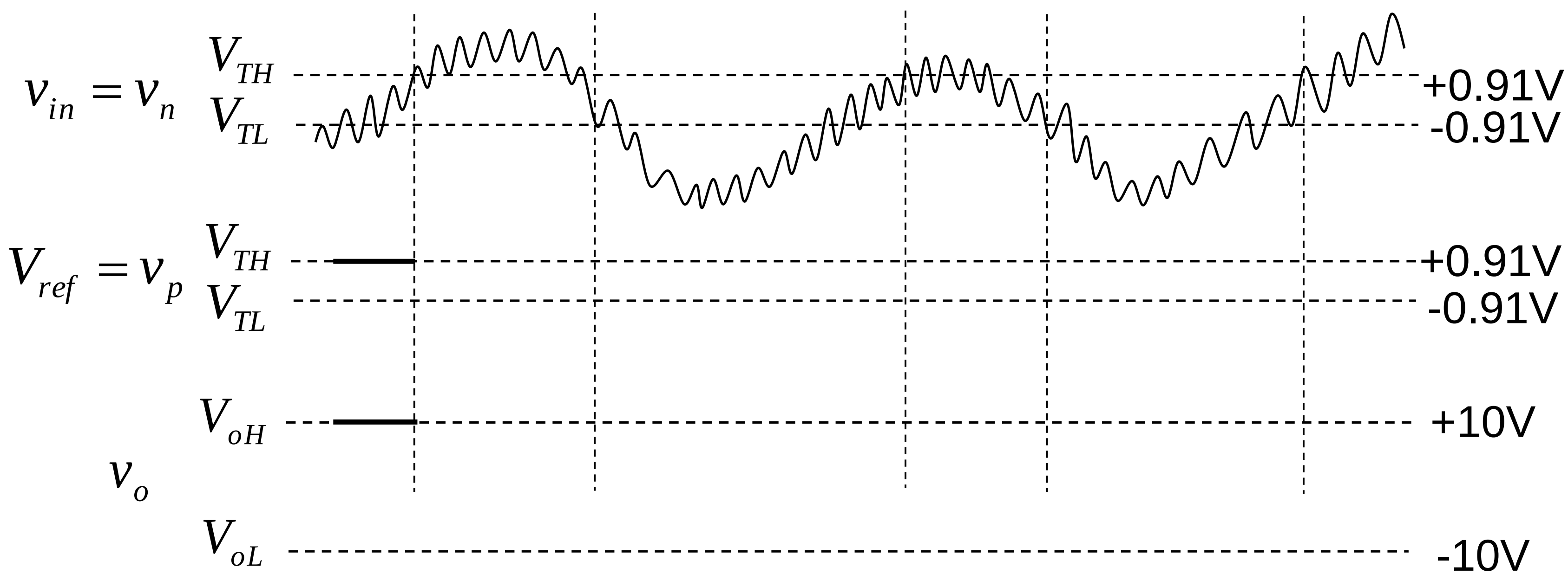
- The reference voltage v_{ref} depends on the output v_o.



$$V_{ref} = v_o \frac{R_1}{R_1 + R_2}$$

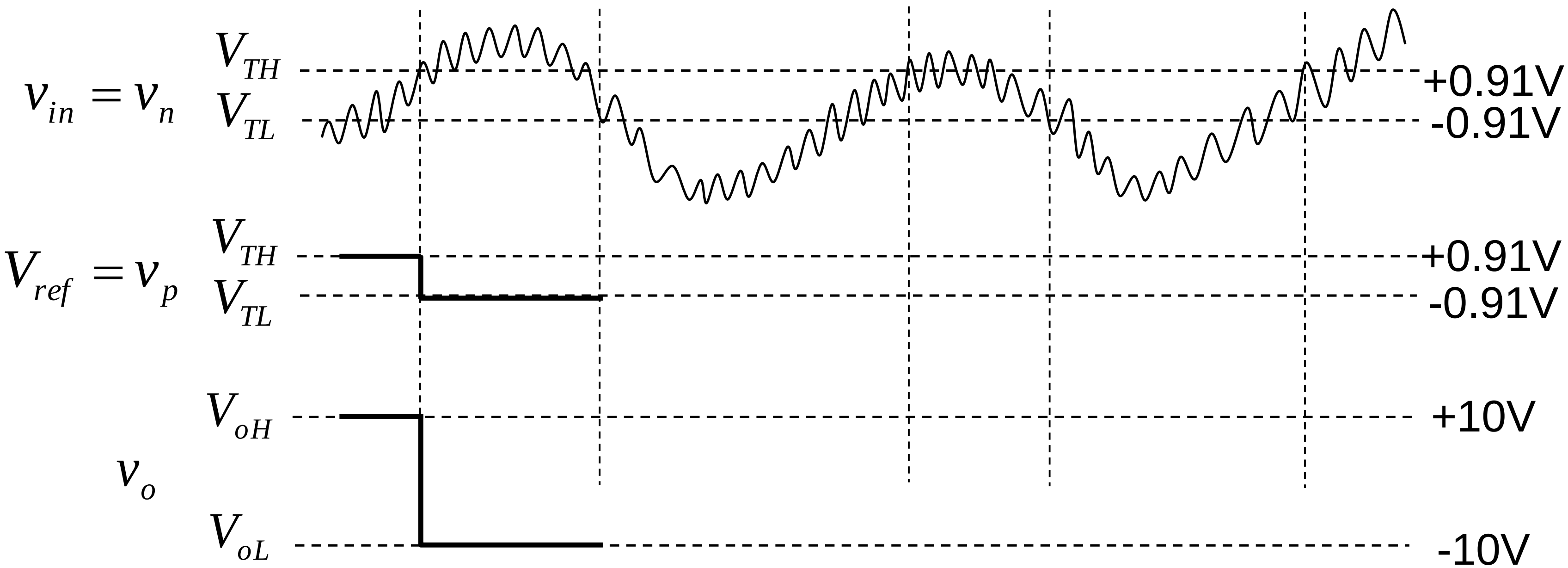
Schmitt Trigger

- Consider the case where $v_{in} < v_{TH}$.
- v_o is driven to v_{oH}
- V_{ref} is calculated from: $$V_{ref} = V_{oH} \frac{R_1}{R_1 + R_2}$$



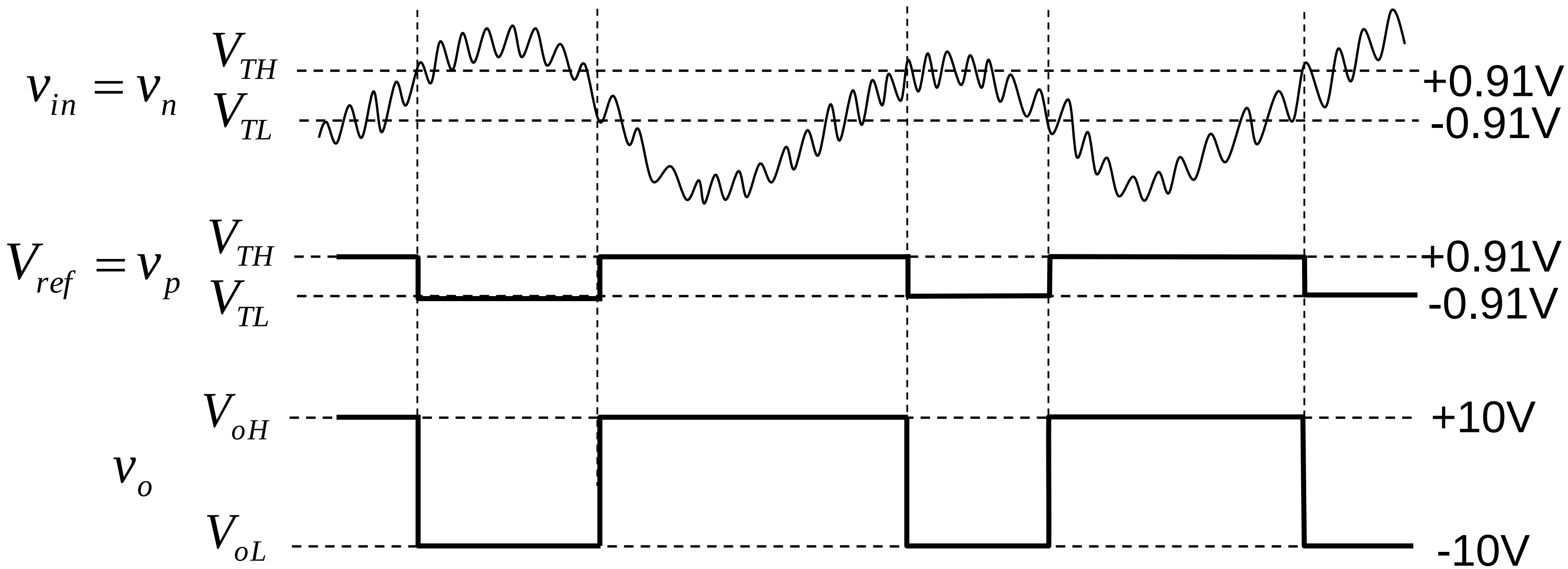
Schmitt Trigger

- When v_{in} increases and crosses V_{TH}, the output is driven low to V_{oL}.
- V_{ref} therefore becomes: $$V_{ref} = V_{TL} = V_{oL}\frac{R_1}{R_1 + R_2}$$
- while v_{in} remains higher than V_{ref}, the output will stay at V_{OL}.



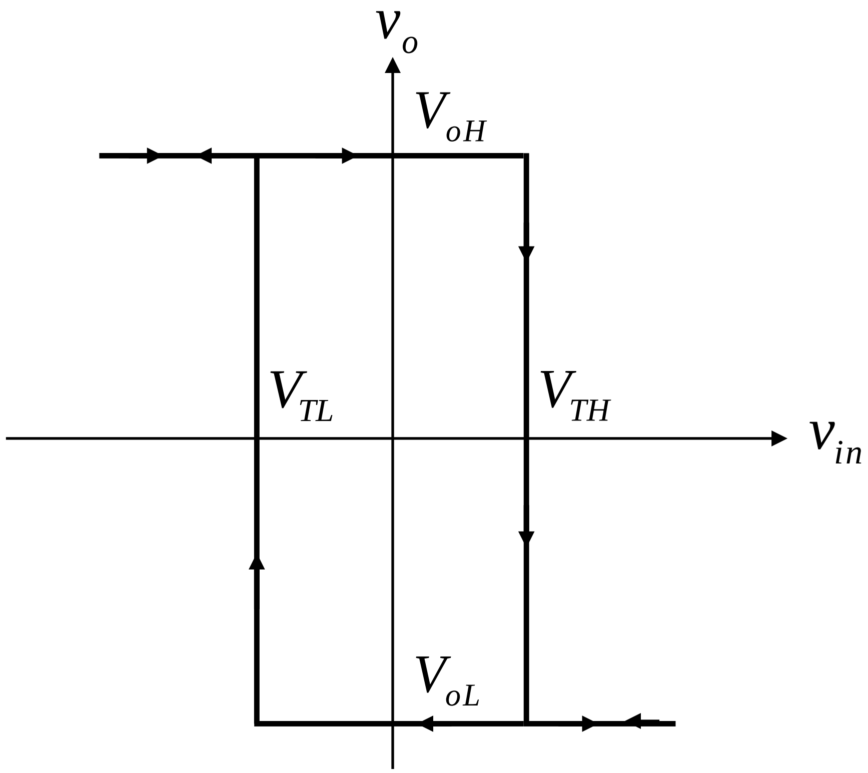
Schmitt Trigger

- When v_{in} decreases and crosses V_{TL}, the output is driven high to v_{oH}.
- V_{ref} therefore becomes: $$V_{ref} = V_{TH} = V_{oH} \frac{R_1}{R_1 + R_2}$$
- while v_{in} remains lower than V_{ref}, the output will stay at V_{OH}.



Schmitt Trigger

- The Schmitt trigger is said to exhibit *hysteresis*.
- Voltage transfer characteristic:

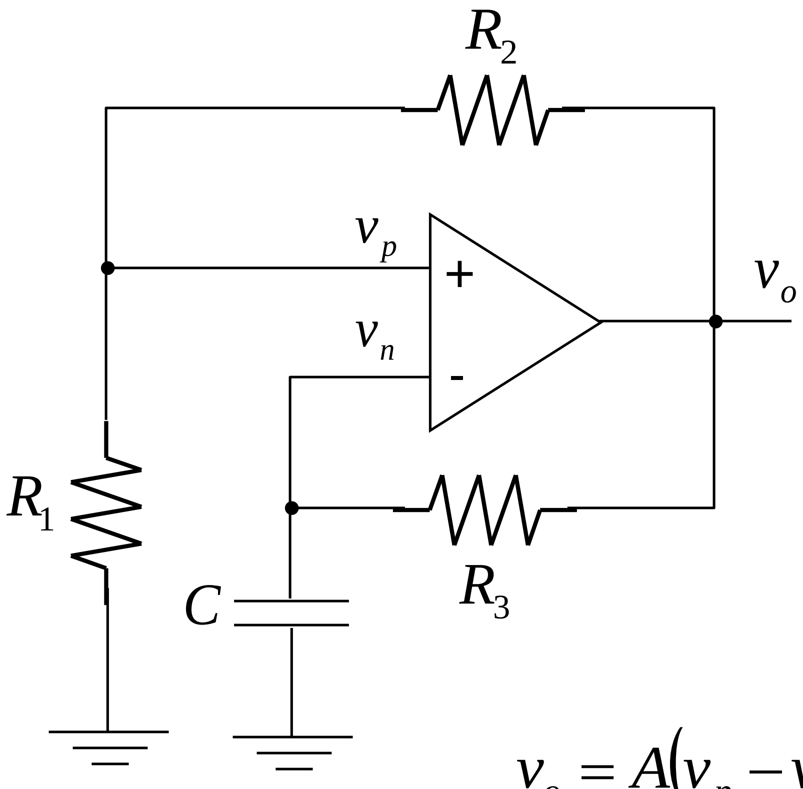


Multivibrator Circuits

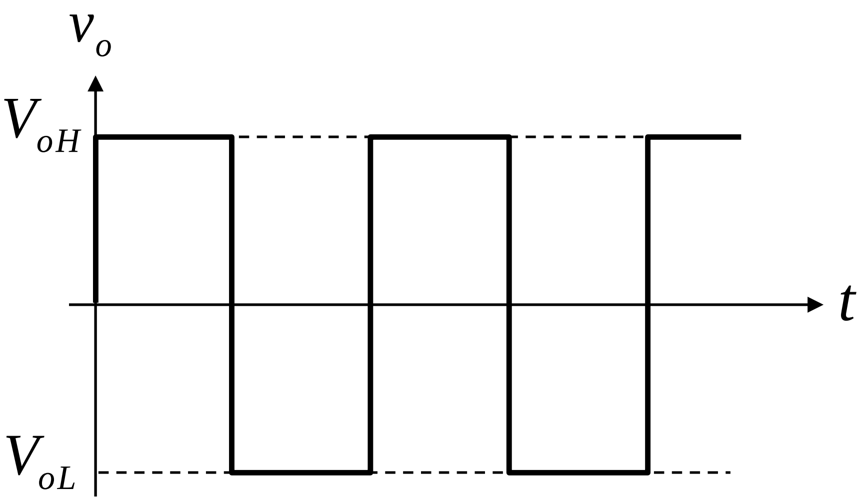
- Astable Multivibrator: Circuit oscillates between two unstable states.
- Monostable Multivibrator: Circuit has one stable state, and one unstable state. An input signal can cause the circuit to change into the unstable state for a short period of time.
- Bistable Multivibrator: Circuit has two stable states. Input signals can cause the circuit to change state. Examples are latches and flip-flops.

Square Wave Generator (Astable Multivibrator)

- Output oscillates between two states, v_{oH} and v_{oL}.



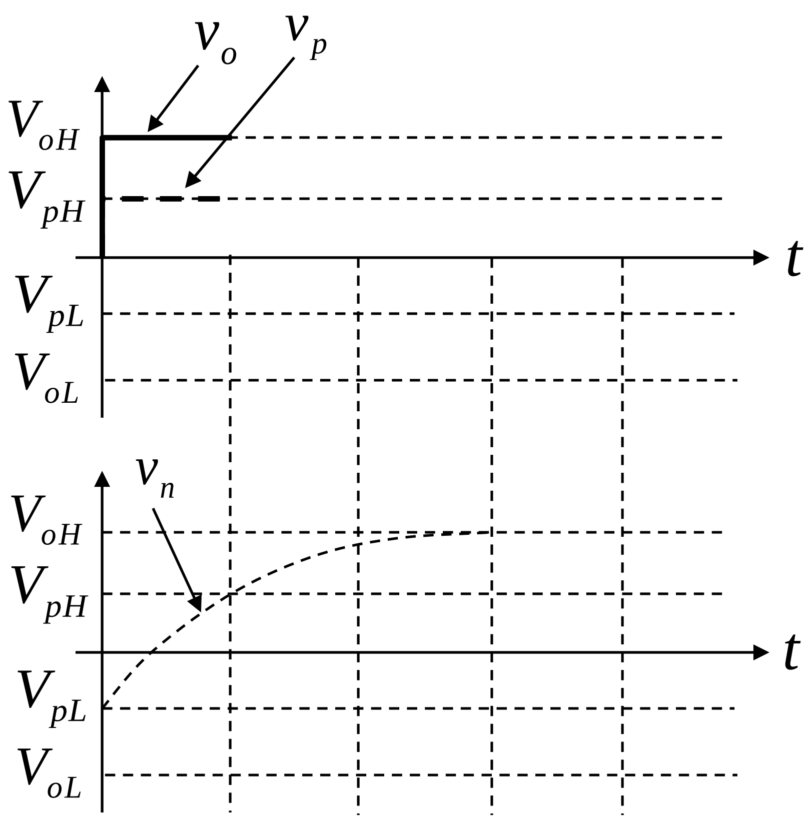
$$v_o = A\left(v_p - v_n\right)$$



Square Wave Generator

- Assume the output has just switched to V_{oH}.
- v_p therefore becomes:

$$v_p = V_{pH} = V_{oH} \frac{R_1}{R_1 + R_2}$$



- C charges towards V_{oH} through R_3, with time constant $\tau = R_3C$

Square Wave Generator

- General equation for voltage across a capacitor:

$$v_c(t) = V_{final} + \left(V_{initial} - V_{final}\right)e^{-\frac{t}{\tau}}$$

- Therefore the equation for capacitor charge is:

$$v_n = V_{oH} + \left(V_{pL} - V_{oH}\right)e^{-\frac{t}{R_3 C}}$$

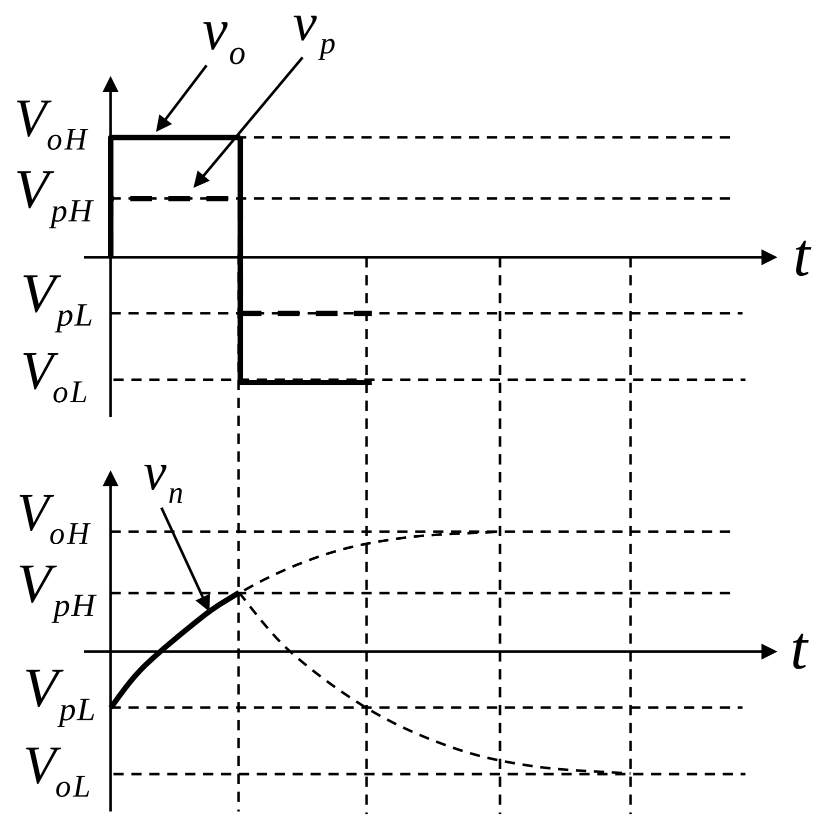
$$v_n = V_{oH} + \left(\frac{V_{oL} R_1}{R_1 + R_2} - V_{oH}\right)e^{-\frac{t}{R_3 C}}$$

Square Wave Generator

- When v_n crosses V_{pH}, output driven negative and $v_o = V_{oL}$.
- v_p therefore becomes:

$$V_p = V_{pL} = V_{oL}\frac{R_1}{R_1 + R_2}$$

- C discharges towards V_{oL} through R_3, with time constant $\tau = R_3C$



Square Wave Generator

- Equation for capacitor discharge:

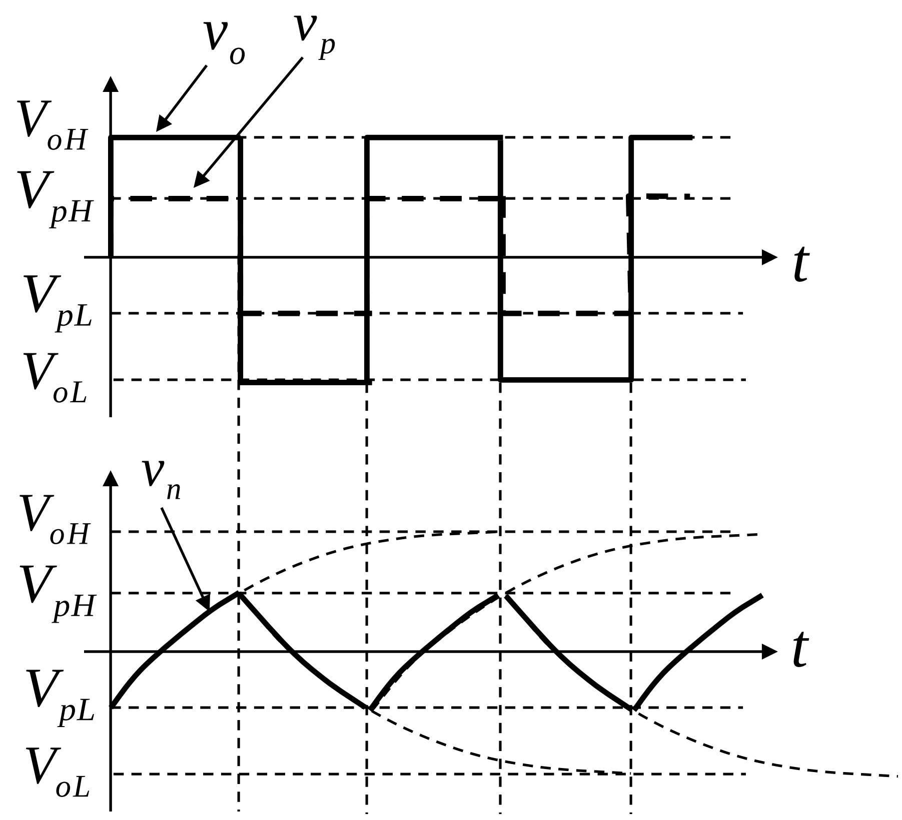
$$v_n = V_{oL} + \left(V_{pH} - V_{oL}\right) e^{-\frac{t}{R_3 C}}$$

$$v_n = V_{oL} + \left(\frac{V_{oH} R_1}{R_1 + R_2} - V_{oH}\right) e^{-\frac{t}{R_3 C}}$$

Square Wave Generator

- When v_n crosses V_{pL}, output driven positive and $v_o = V_{oH}$.

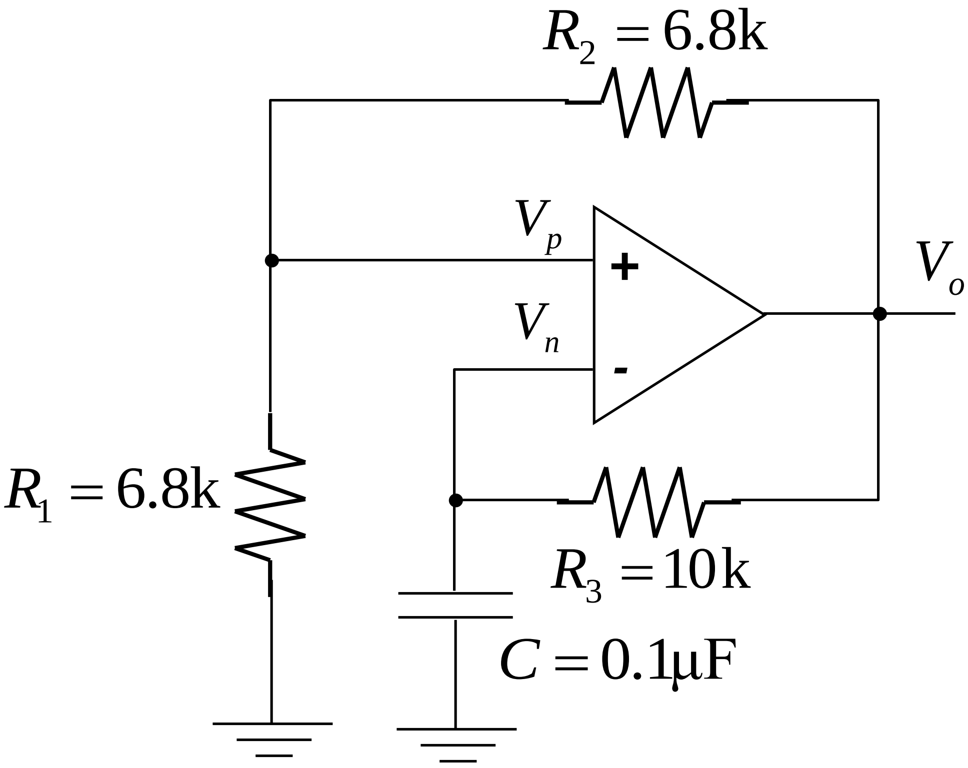
- The cycle repeats resulting in a square wave v_o.



Square Wave Generator

Example 5:

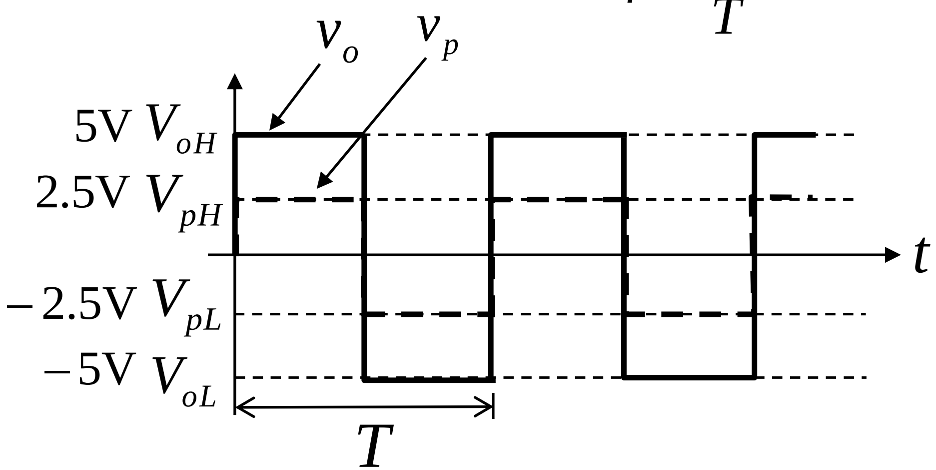
- What is the frequency of oscillation if V_{oH}=5V, V_{oL}= -5V, R_1 = R_2 = 6.8kΩ, R_3 = 10kΩ and C=0.1μF?

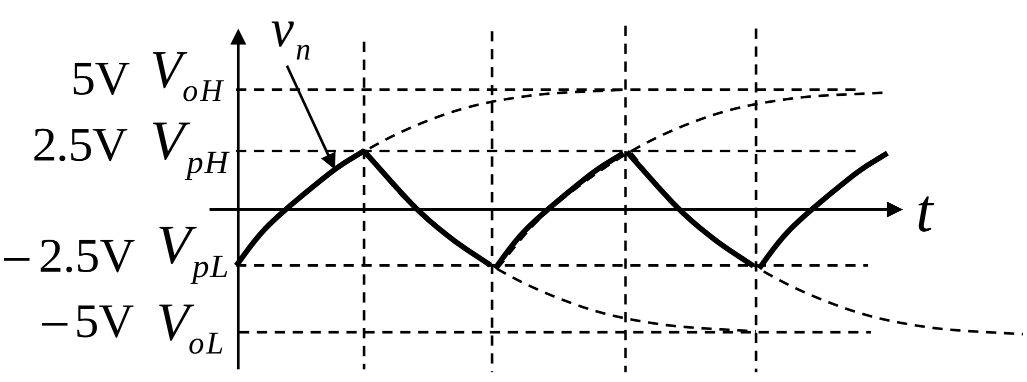


Square Wave Generator

Example 5:

$$f = \frac{1}{T}$$





Square Wave Generator

<u>Example 5:</u>

- Capacitor charge/discharge equation:

$$v_c(t) = V_{final} + \left(V_{initial} - V_{final}\right)e^{-\frac{t}{\tau}}$$

- Therefore, when the capacitor is charging:

- When v_n reaches V_{pH}:

Square Wave Generator

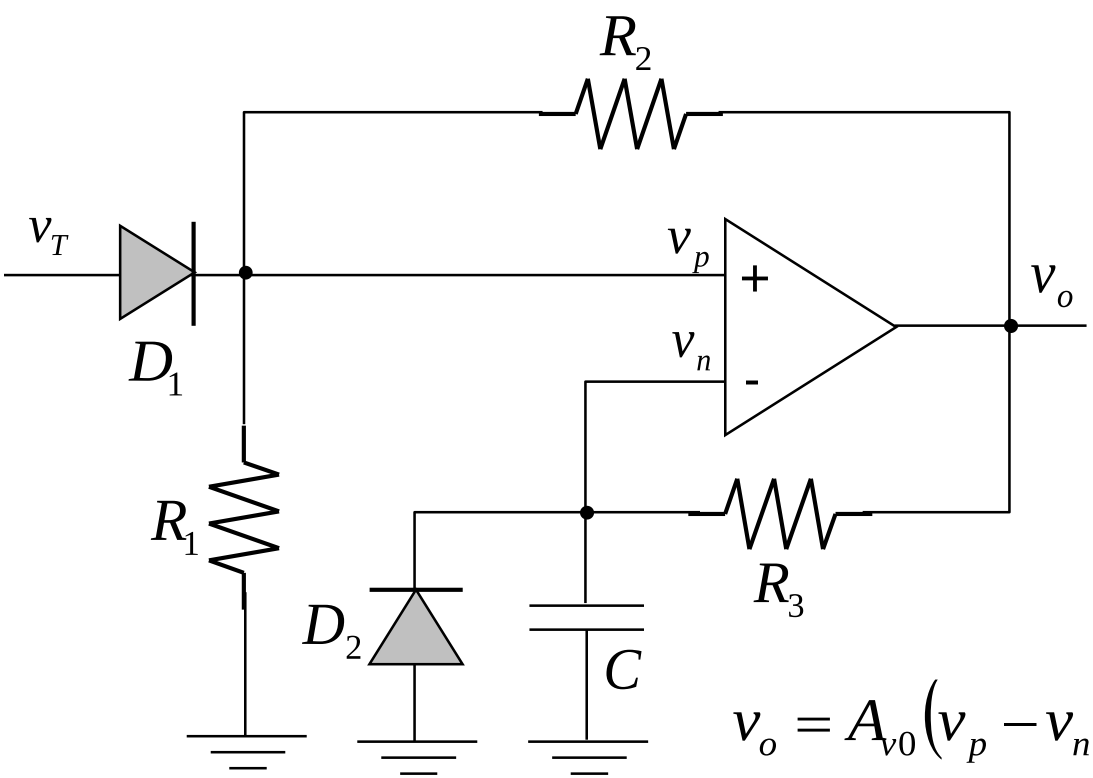
Example 5:

Square Wave Generator

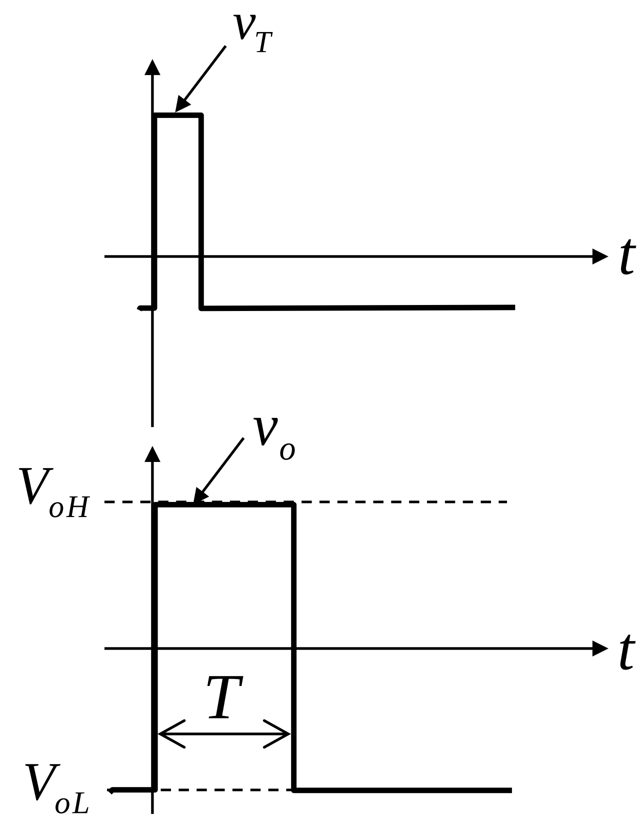
Example 5:

Pulse Generator (Monostable Multivibrator)

- Has one stable state.
- A single pulse of known duration is generated when a trigger signal is applied.



$$v_o = A_{v0}(v_p - v_n)$$

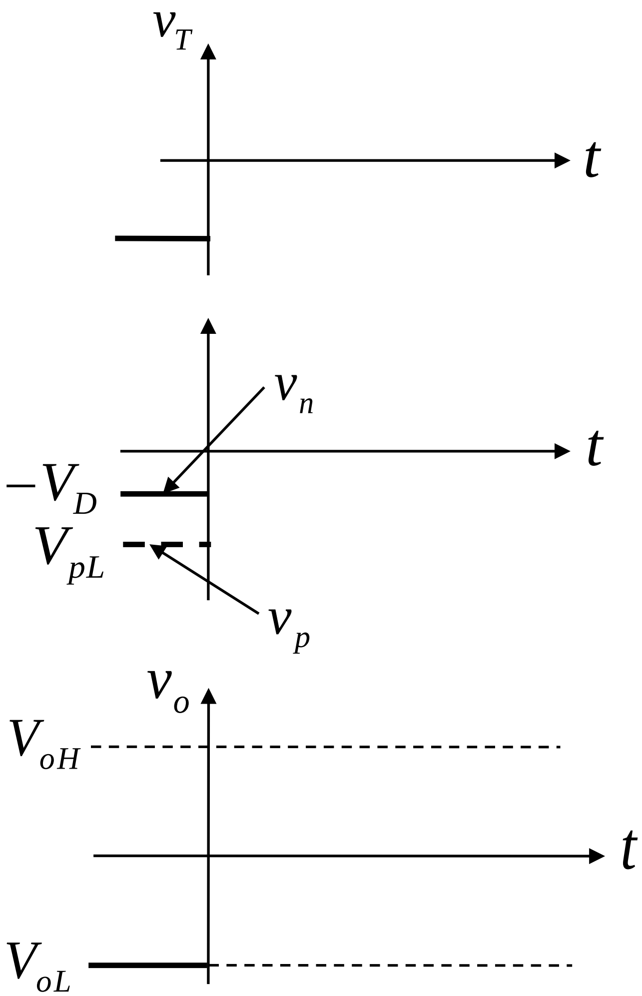


Pulse Generator

- The circuit rests in its quiescent state with $v_o = V_{oL}$.
- Voltage v_p is given by:

$$v_p = V_{pL} = V_{oL}\frac{R_1}{R_1 + R_2}$$

- While v_T remains less than $V_{pL}+V_D$, diode D_1 remains cut off.
- C discharges to V_{oL} until diode D_2 turns on, clamping v_n at $-V_D$.

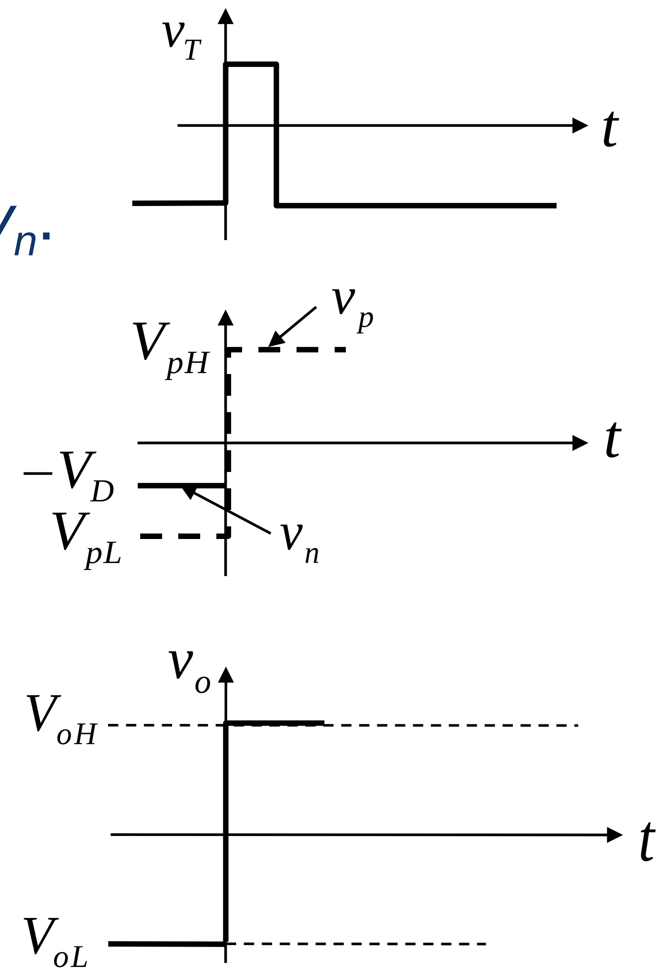


Pulse Generator

- A positive pulse is applied to v_T.
- Diode D_1 turns on, momentarily pulling node v_p greater than node v_n.
- This drives v_o positive to V_{oH}.
- Voltage at node v_p then becomes:

$$v_p = V_{pH} = V_{oH} \frac{R_1}{R_1 + R_2}$$

and diode D_1 then cuts off.

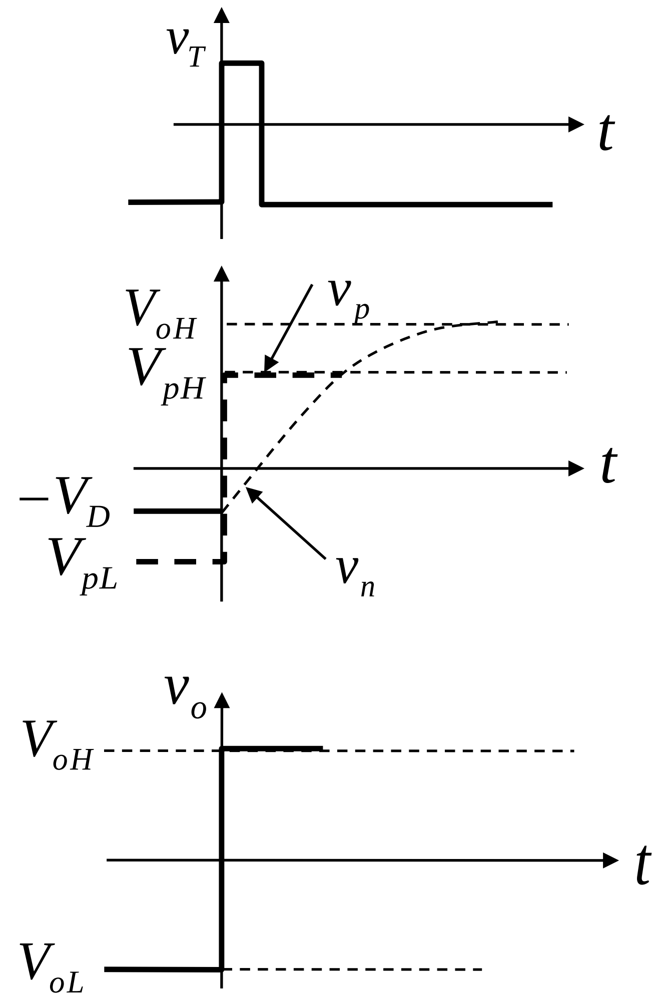


Pulse Generator

- Capacitor voltage v_n then charges through R_3 toward v_{oH}:

$$v_c(t) = V_{final} + \left(V_{initial} - V_{final}\right)e^{-\frac{t}{\tau}}$$

$$v_n(t) = V_{oH} + \left(-V_D - V_{oH}\right)e^{-\frac{t}{R_3 C}}$$



Pulse Generator

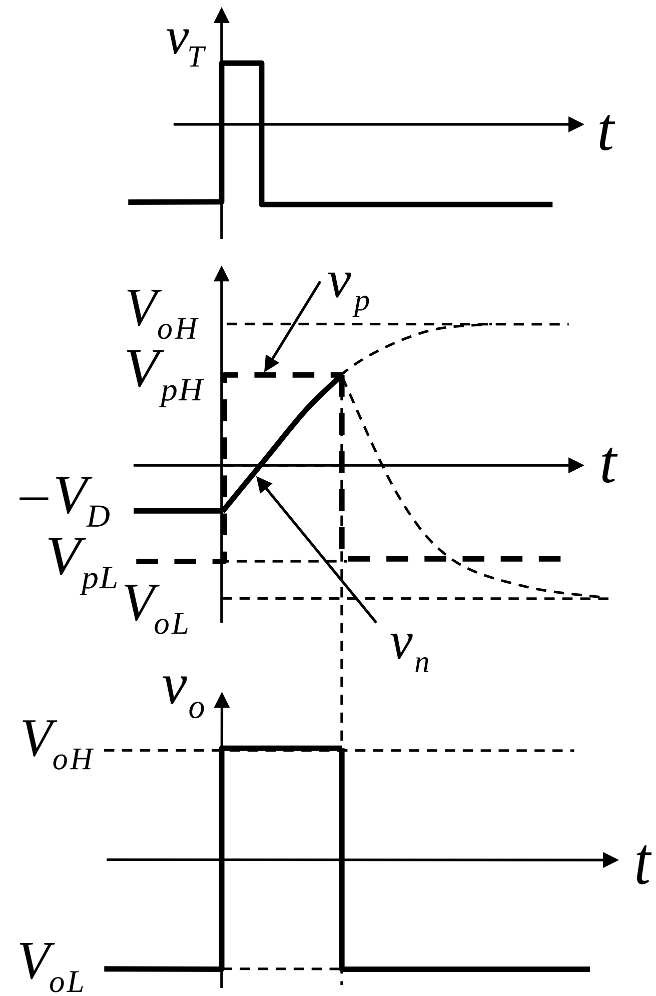
- When v_n crosses v_p, the output is driven negative to V_{oL}.
- Voltage v_p then becomes:

$$v_p = V_{pL} = V_{oL}\frac{R_1}{R_1+R_2}$$

- Capacitor C discharges through R_3 toward V_{oL}:

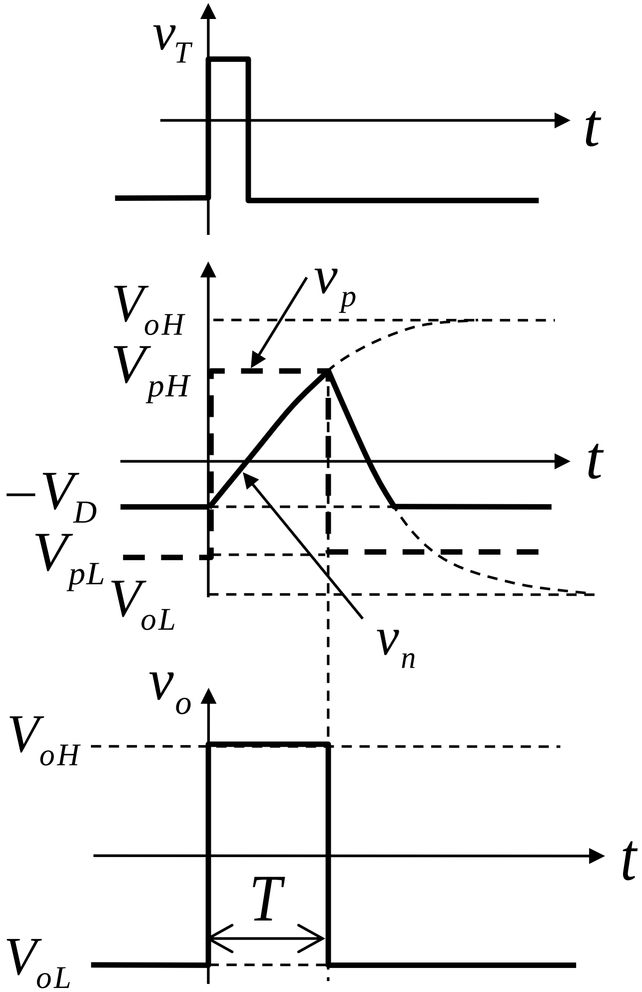
$$v_c(t) = V_{final} + \left(V_{initial} - V_{final}\right)e^{-\frac{t}{\tau}}$$

$$v_n(t) = V_{oL} + \left(V_{oH} - V_{oL}\right)e^{-\frac{t}{R_3C}}$$



Pulse Generator

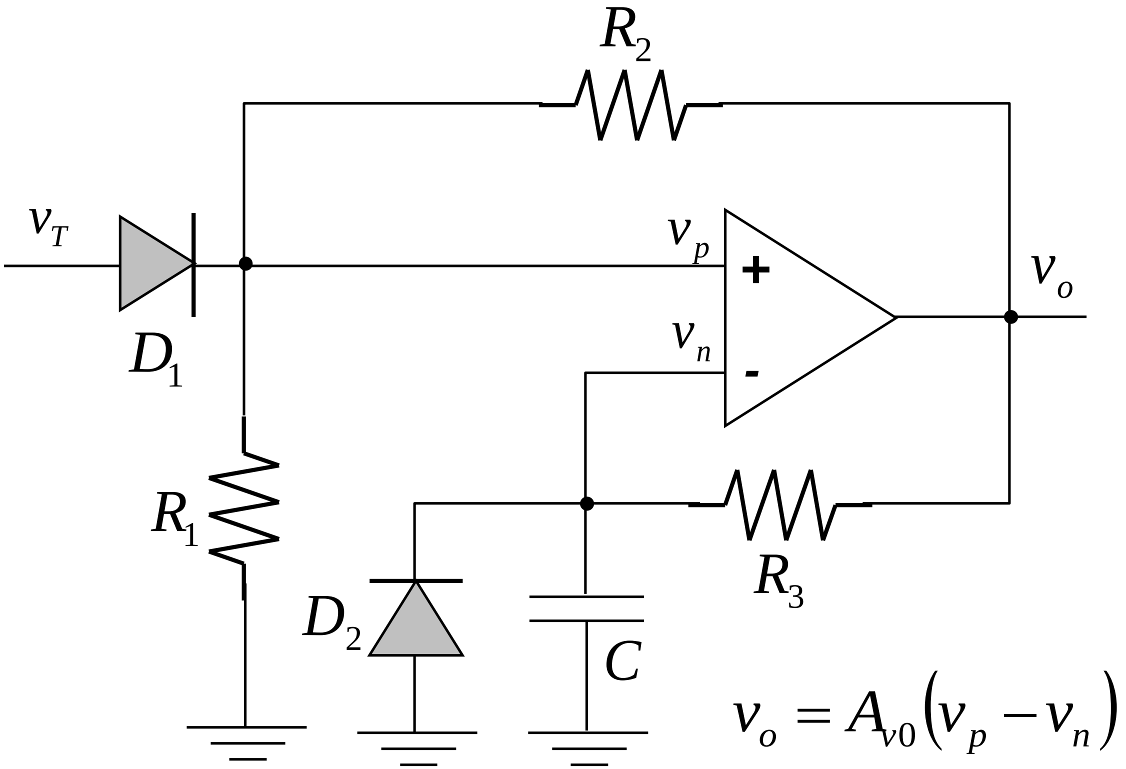
- C discharges to V_{oL} until diode D_2 turns on, clamping v_n at $-V_D$.
- The output v_o will remain at V_{oL} until another trigger pulse is applied.



Pulse Generator

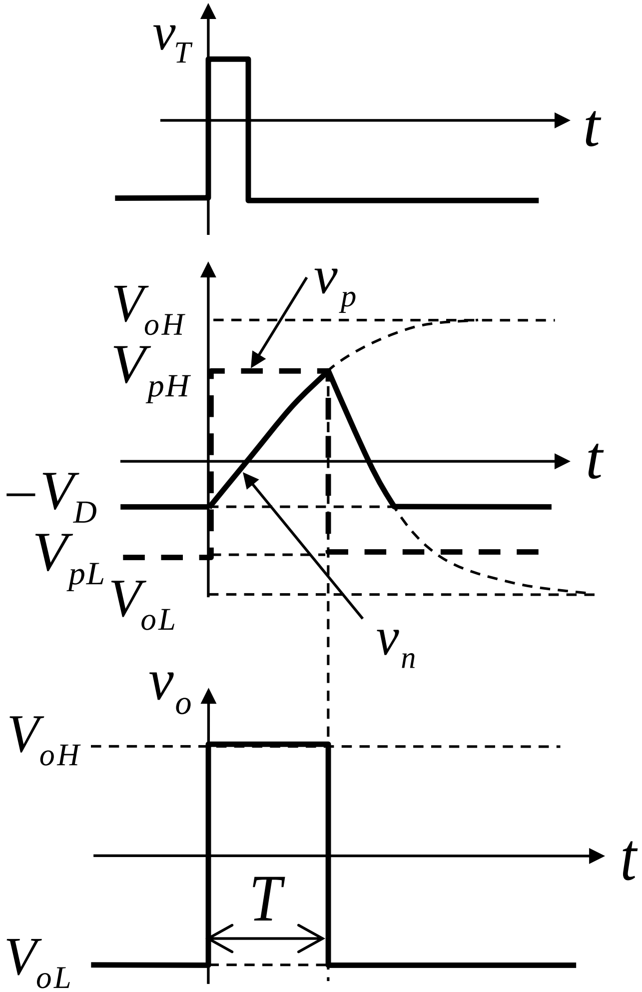
<u>Example 6:</u>

- What is the width of the pulse if V_{oH} = 5V, V_{oL} = -5V, V_D = 0.7V, R_1 =22kΩ, R_2 = 18kΩ, R_3 = 10kΩ and C=0.2μF?



Pulse Generator

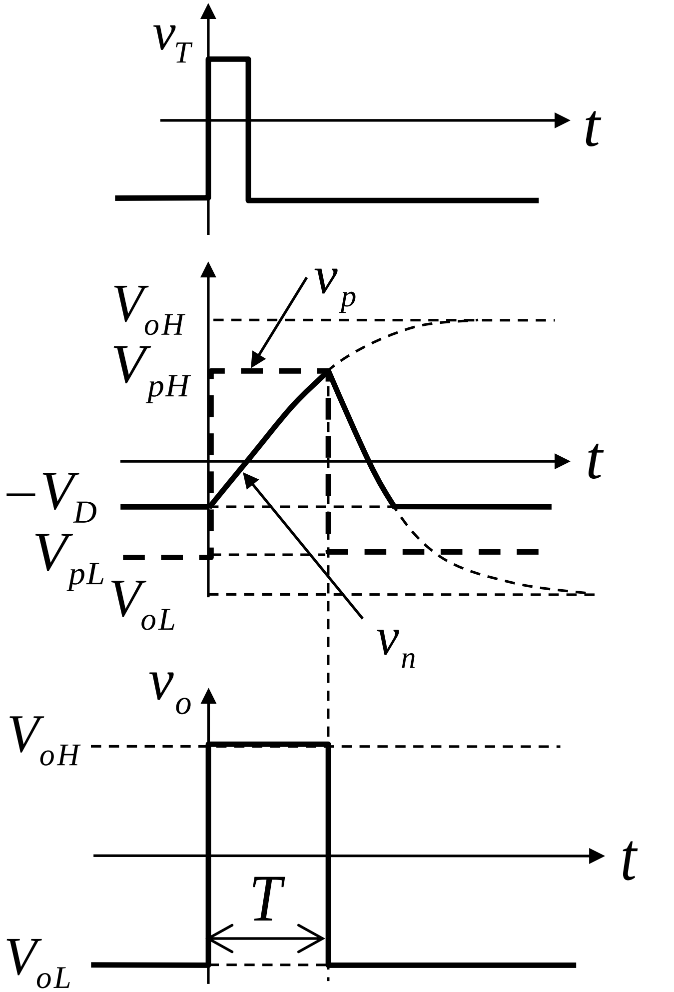
Example 6:



- Capacitor charge:

Pulse Generator

Example 6:



Pulse Generator

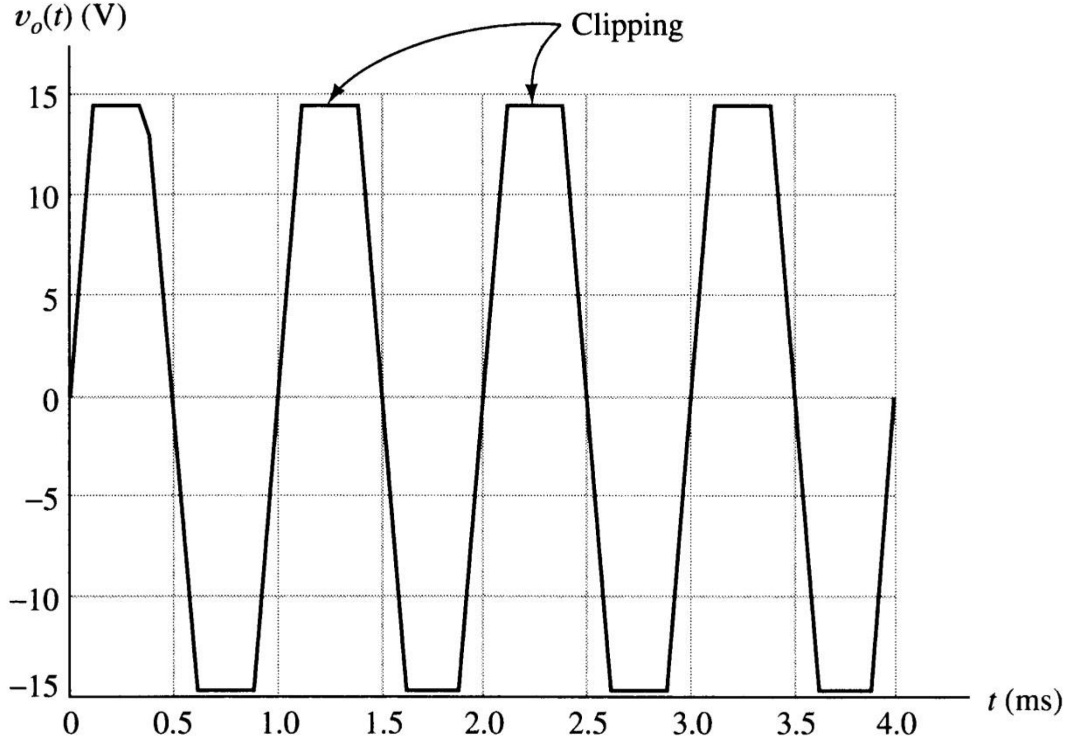
Example 6:

Op Amp Limitations

- Output voltage swing
- Slew rate
- Input bias currents and offset voltages

Output Voltage Swing

- Range of output voltage depends on the type of op amp, and the power supply voltages.
- Eg, if power supply voltages are ±15V:



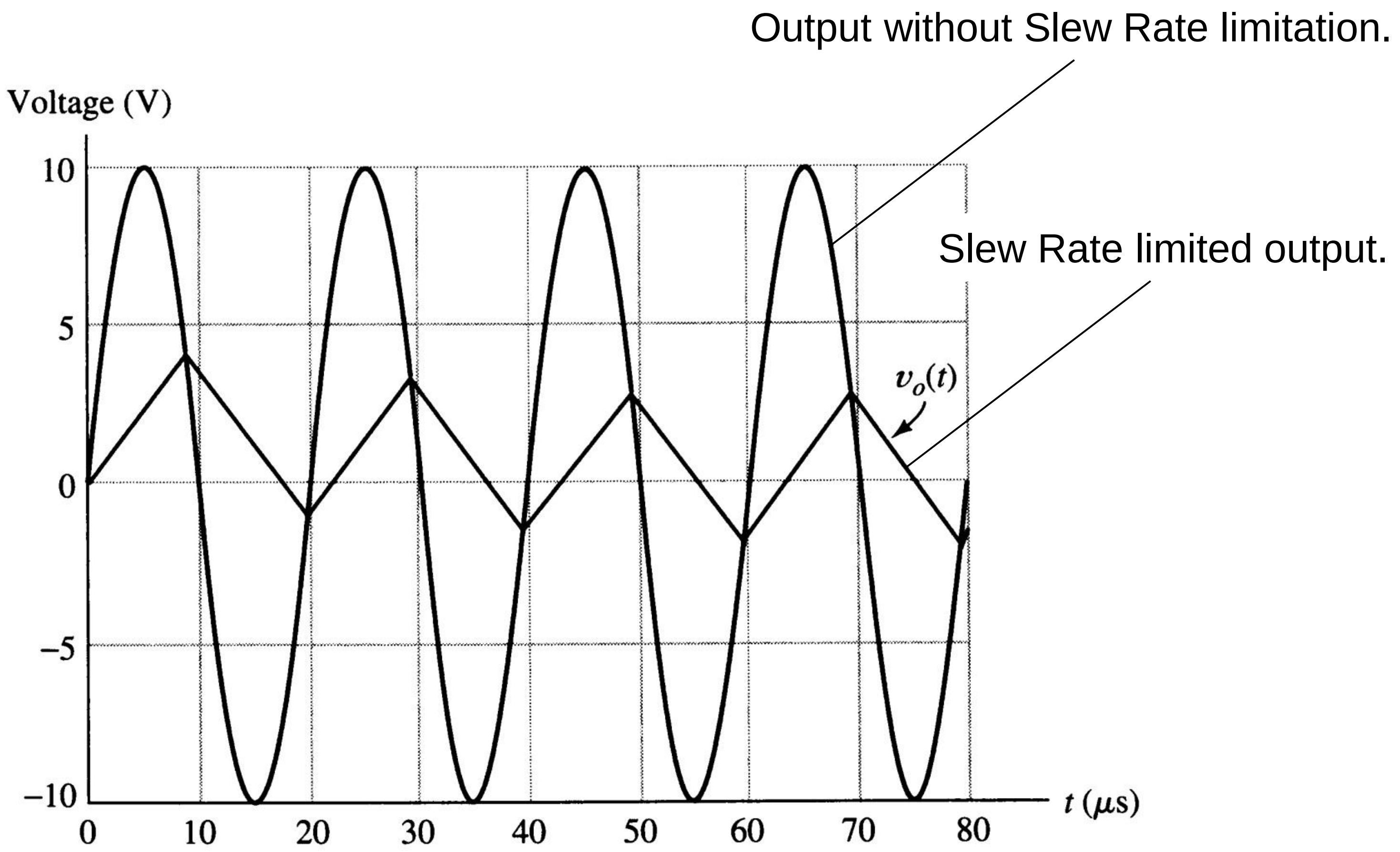
Hambley, p696.

Slew Rate

- Rate of change of the output voltage is limited.
- The slew rate (SR) is the maximum rate that the output of the op amp can change from most positive to most negative.
- Limits the maximum amplitude of signal that can be amplified without distortion.
- Typical values:

$$0.1\text{V}/\mu\text{s} \leq \text{SR} \leq 10\text{V}/\mu\text{s}$$

Slew Rate



Hambley, p697.

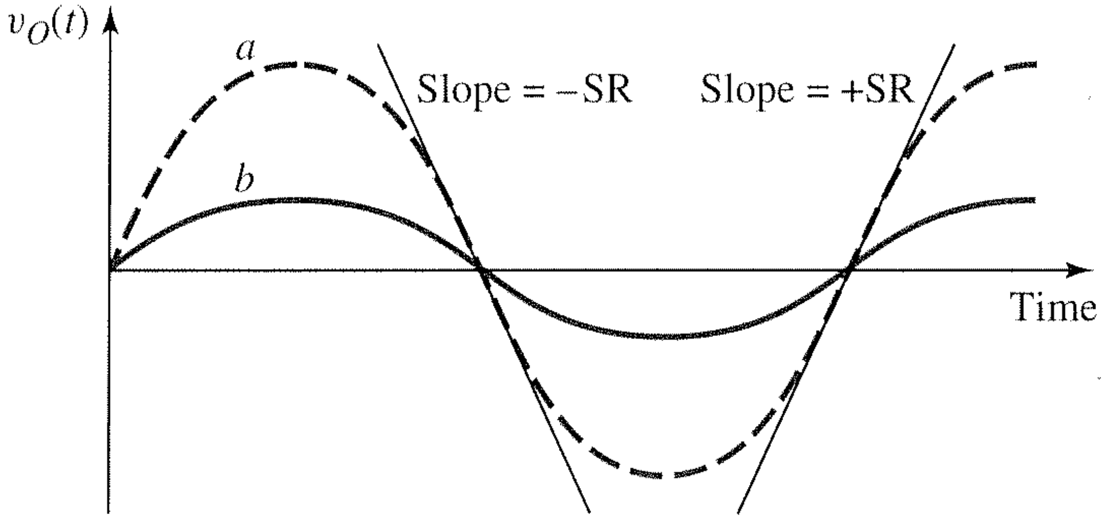
Slew Rate

- The ***Full Power Bandwidth*** (f_{FP}) is the frequency at which the op amp becomes slew rate limited.
- The Full Power Bandwidth is the maximum frequency at which the op amp can produce undistorted output with maximum amplitude.

$$f_{FP} = \frac{\mathrm{SR}}{2\pi V_{O(\max)}}$$

Slew Rate

- The Full Power Bandwidth can be considerably less than the small signal bandwidth.
- Small signals will be unaffected by slew rate as the rate of change is less than large signals.



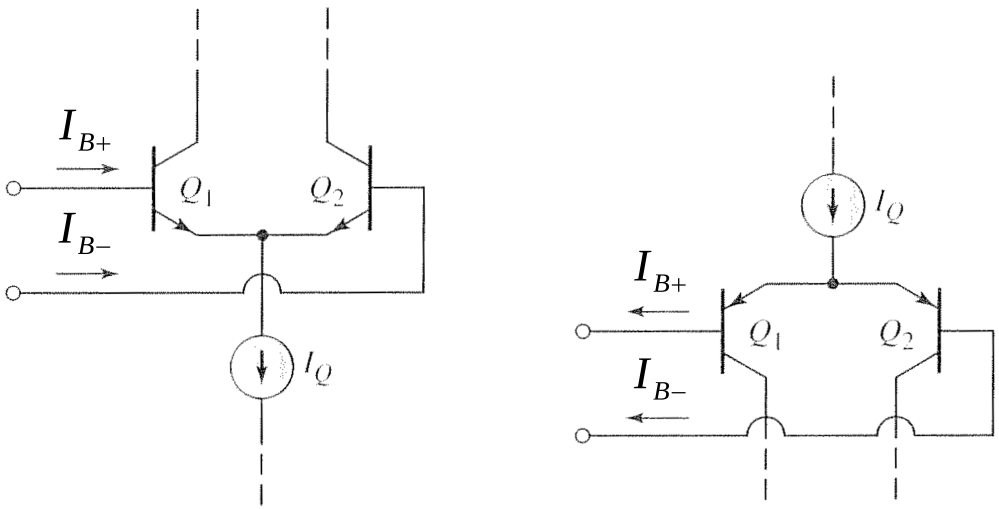
Slew Rate

Example

- An amplifier has a gain bandwidth product of f_T=1MHz, and closed loop gain of 10. The slew rate is 0.63V/μs, and the desired peak output voltage is 10V. Find the small signal bandwidth and the Full Power Bandwidth.

Offset Voltages and Currents

- Non-zero input currents:
  - I_{B+} is the DC current flowing into the non-inverting input.
  - I_{B-} is the DC current flowing into the inverting input.



(a) *npn* (b) *pnp*

Offset Voltages and Currents

- Average of the input DC currents is called the ***bias current***:

$$I_B = \frac{I_{B+} + I_{B-}}{2}$$

<u>Typical</u>

30nA for the 741 op amp

Offset Voltages and Currents

- If the input stage of the op amp is symmetrical, the bias currents will be equal.
- In practice, the DC currents are not equal, and the difference is called the ***offset current***:

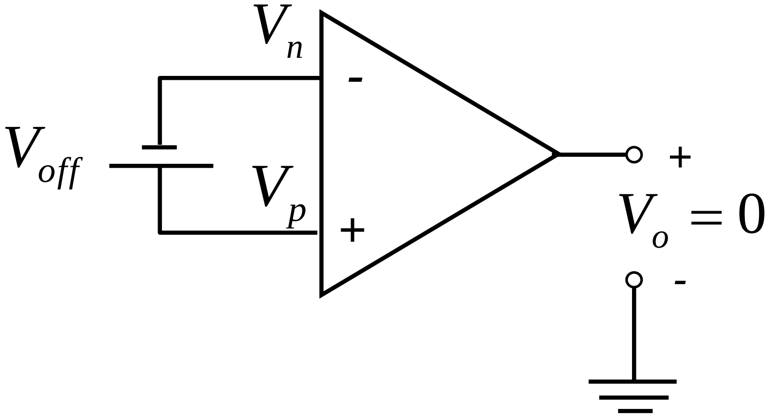
$$I_{off} = \left| I_{B+} - I_{B-} \right|$$

- typically about 20-50 % of the bias current.

Offset Voltages and Currents

- The output voltage might be non-zero for zero input voltage. The op amp behaves as if a small DC offset voltage V_{off} is in series with one of the input terminals.

- The ***offset voltage*** is defined as the input differential voltage that must be applied to the open loop op amp to produce a zero output voltage.

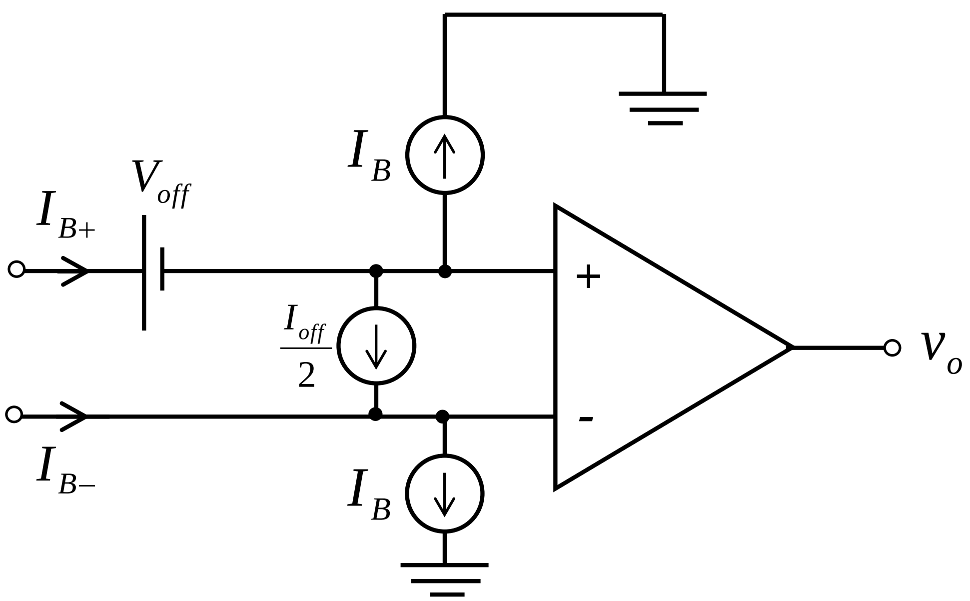


<u>Typically</u>

$$V_{off} \approx \pm 1\text{mV} \ \ \text{to} \ \ \pm 5\text{mV}$$

Offset Voltages and Currents

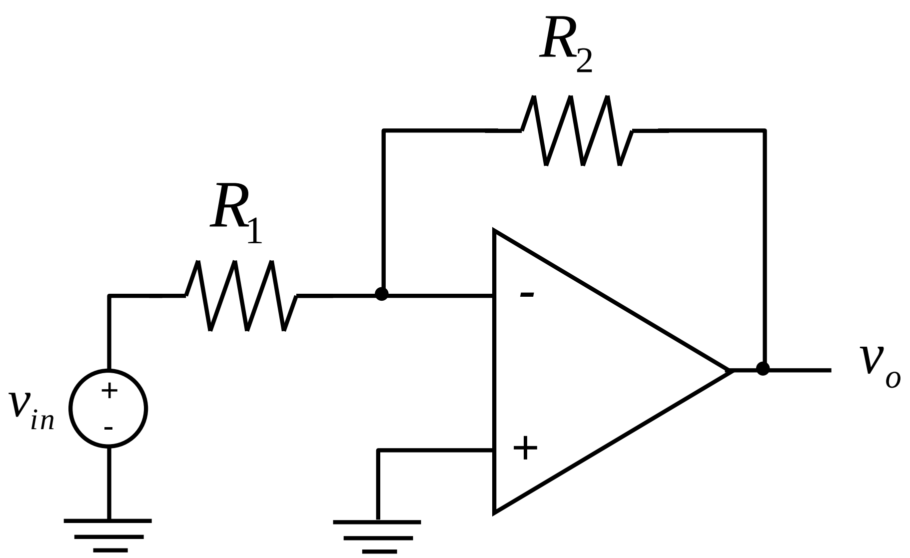
- bias current, offset current and offset voltage can be modelled as shown below:



Hambley, p699.

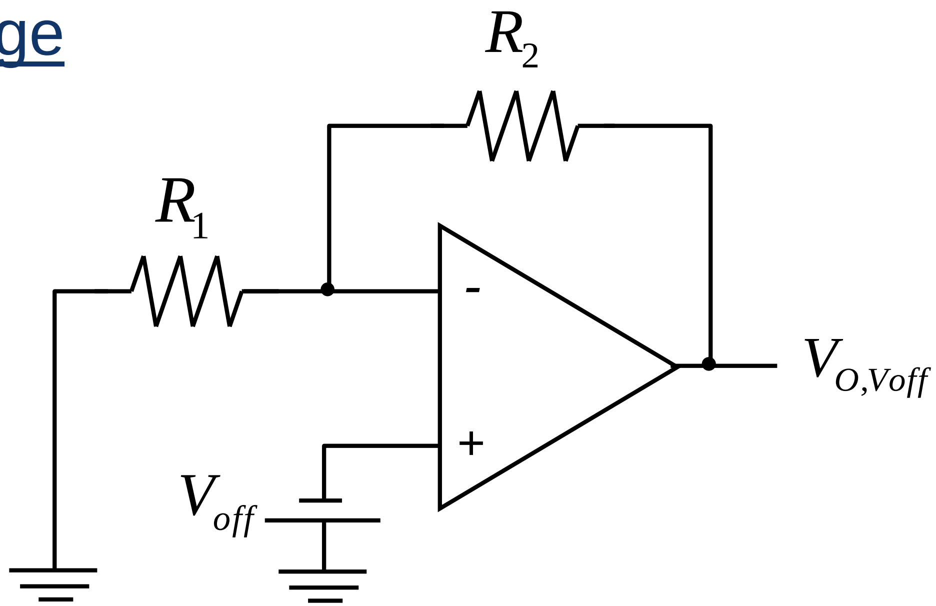
Effect of Offset Voltages and Currents

- For the the inverting amp below, determine offset voltage at the output due all DC offset sources:



Effect of Offset Voltages and Currents

Offset Voltage

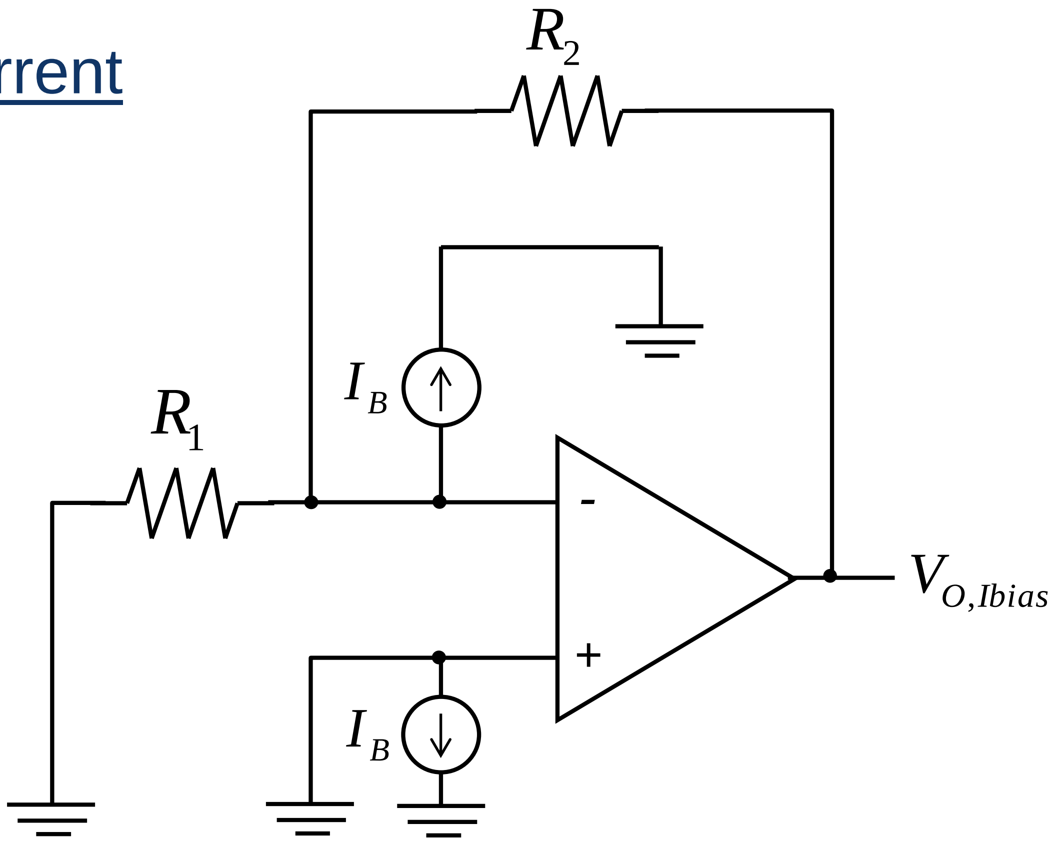


- Output offset voltage due to V_{off} :

$$V_{O,Voff} = -\left(1 + \frac{R_2}{R_1}\right)V_{off}$$

Effect of Offset Voltages and Currents

Bias Current



$$V_{O,Ibias} = R_2 I_B$$

Effect of Offset Voltages and Currents

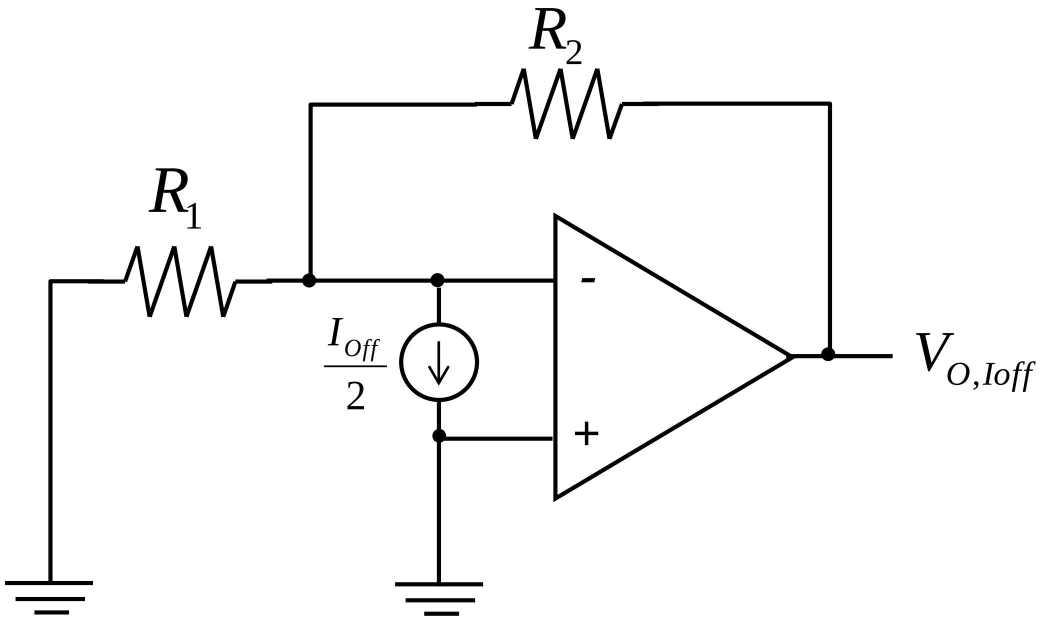
Bias Current

$$V_{in,Ibias} = I_B\left(R_1 // R_2\right) = I_B \frac{R_1 R_2}{R_1 + R_2}$$

$$V_{o,Ibias} = V_{in,Ibias}\left(1 + \frac{R_2}{R_1}\right) = I_B \frac{R_1 R_2}{R_1 + R_2}\left(\frac{R_1 + R_2}{R_1}\right) = R_2 I_B$$

Effect of Offset Voltages and Currents

Offset Current



$$V_{O,Ioff} = \frac{R_2 I_{off}}{2}$$

Effect of Offset Voltages and Currents

- Using the principle of superposition, the DC output voltage is the sum of all sources acting individually:

$$V_{O(Off)} = V_{O,Voff} + V_{O,Ibias} + V_{O,Ioff}$$

Effect of Offset Voltages and Currents

Example

- For a given op amp, the maximum bias current, offset current and input offset voltage are: 100nA, ±40nA, and ±2mV respectively. Find the worst case DC output of an inverting amp if R_1 = 10kΩ, R_2 = 100kΩ, and v_{in} = 0.

$$V_{O,Voff(\max)} = -\left(1+\frac{R_2}{R_1}\right)V_{Off} =$$

$$V_{O,Voff(\min)} = -\left(1+\frac{R_2}{R_1}\right)V_{Off} =$$

Effect of Offset Voltages and Currents

Example

$$V_{O,Ibias(\max)} = R_2 I_B =$$

$$V_{O,Ibias(\min)} = R_2 I_B =$$

$$V_{O,Ioff(\max)} = \frac{R_2 I_{Off}}{2} =$$

$$V_{O,Ioff(\min)} = \frac{R_2 I_{Off}}{2} =$$

Effect of Offset Voltages and Currents

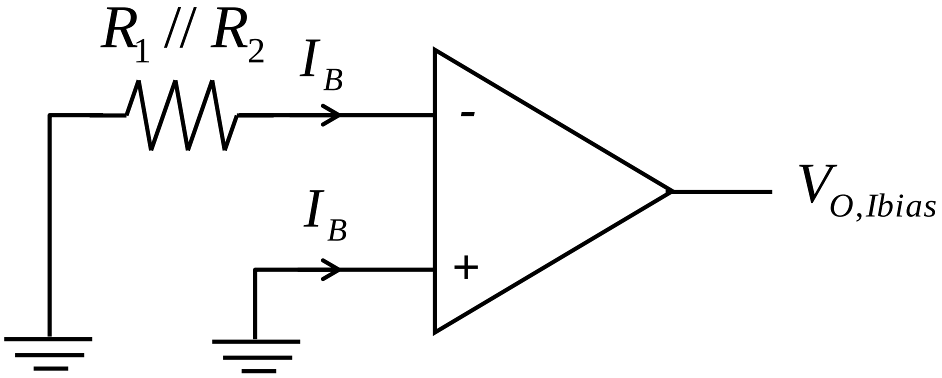
Example

$$V_{O\_Off(\max)} =$$

$$V_{O\_Off(\min)} =$$

- Output voltage offset ranges from -24mv to 34mV.

Reducing the Effect of Bias Current



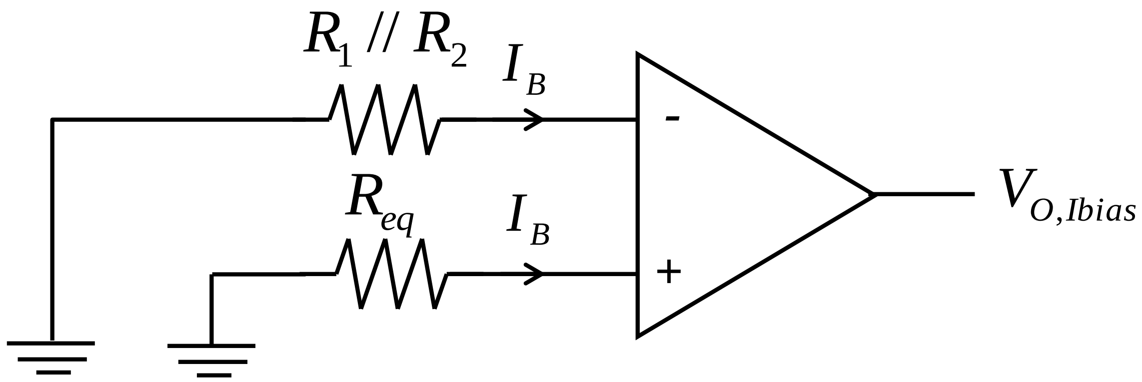
- Additional input offset voltage due to bias current:

$$V_{in,Ibias} = I_B\left(R_1 // R_2\right)$$

Reducing the Effect of Bias Current

<u>Reducing Effect of Input Bias Current</u>

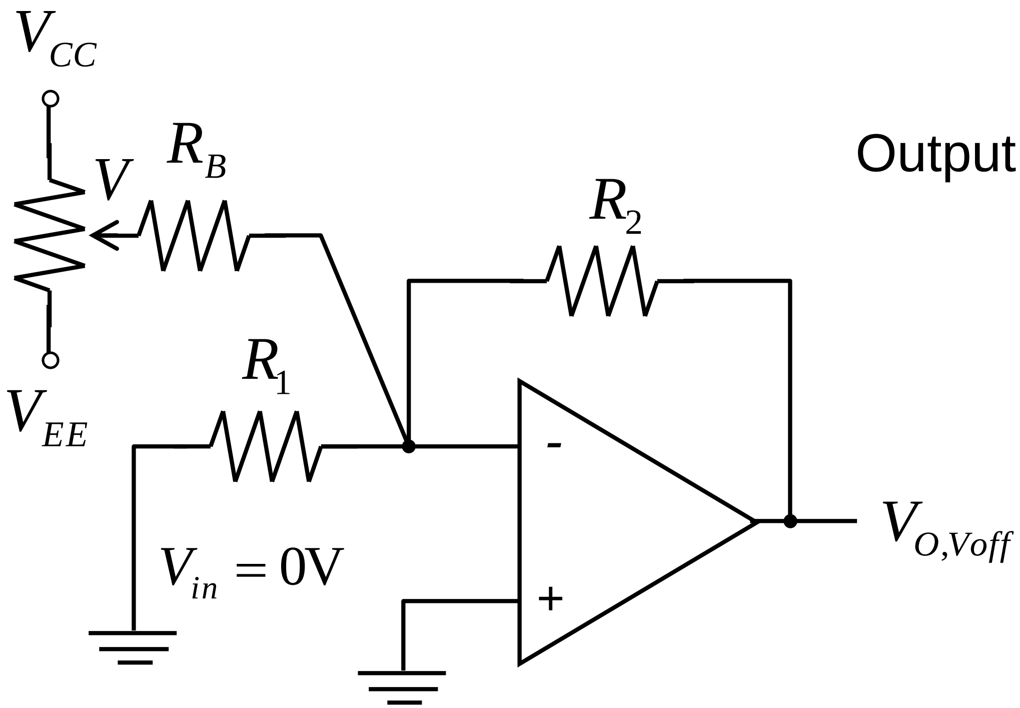
- Design the circuit so that the resistances looking out of the op amp inputs are equal to each other:



$$R_{eq} = R_1 \, // \, R_2$$

Compensating for Offset Voltage

- Can adjust the output offset voltage to zero using a potentiometer:

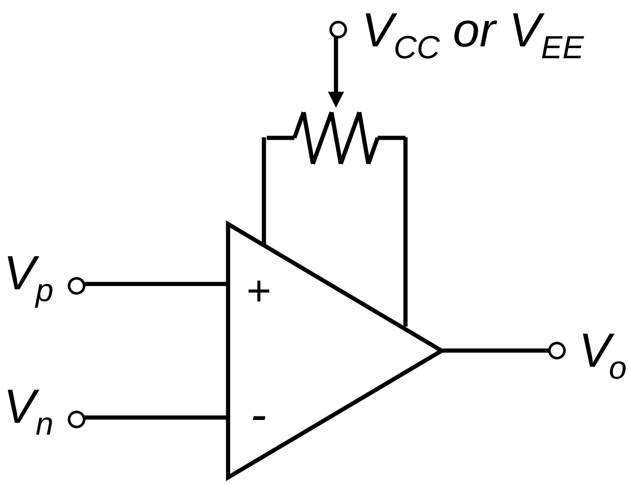


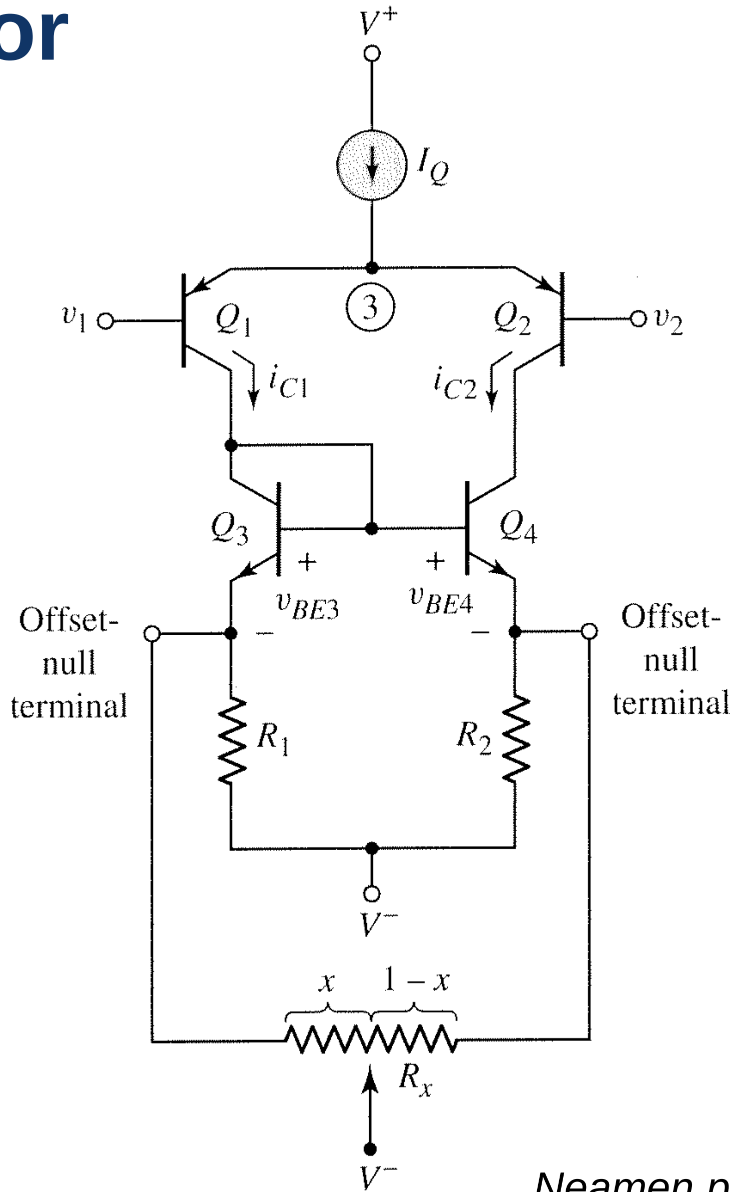
$$\text{Output adjustment} = \pm V\left(\frac{R_2}{R_B}\right)$$

- Set V_{in} to 0V and adjust the potentiometer until $V_{O,Voff} = 0$.

Compensating for Offset Voltage

- Can also use the offset null terminals of the op amp:





Neamen p1033

Compensating for Offset Voltage

- If the potentiometer is centred, then equal resistances are connected to each branch of the input diff-amp stage.
- If the potentiometer is off-centre, then unequal resistance is connected to each branch.
- This introduces an asymmetry in the circuit, and therefore an offset voltage. This offset voltage can be adjusted to compensate for the input offset voltage of the circuit.