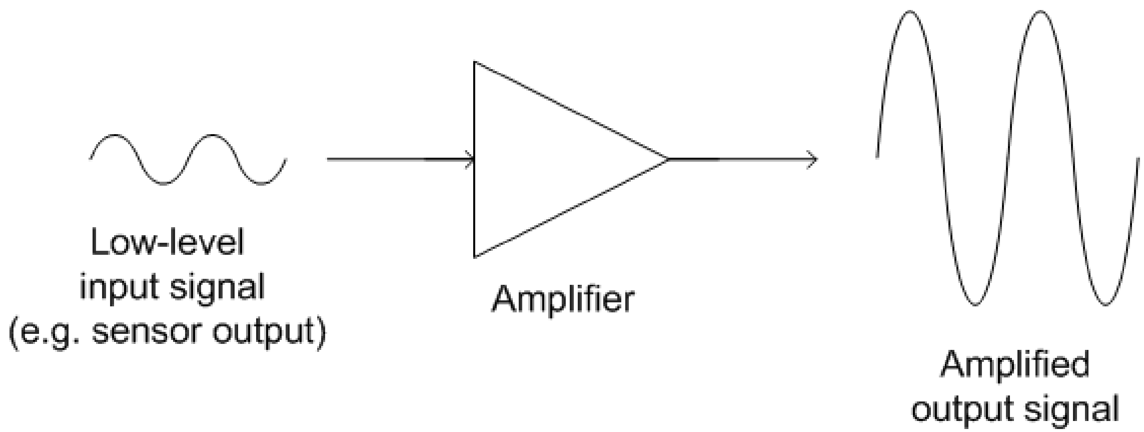
SECTION 4: OPERATIONAL AMPLIFIERS

ENGR 201 – Electrical Fundamentals I

Introduction

Amplification

- ***Amplification***
  - ***Multiplication*** of electrical signals
    - Voltage or current
    - Scaling factor: ***gain***
  - Performed by ***amplifiers***



Amplification – Why?

- Often want to ***increase the amplitude of small electrical signals***
  - Sensor outputs, e.g.:
    - Strain gauges
    - Pressure sensors
    - Flow meters
    - Temperature sensors
    - Photo-detectors, etc.
  - Wireless communication signals
  - Audio signals
- Larger signals are easier to measure
  - Utilize the full ***dynamic range*** of the measurement system
    - Higher accuracy

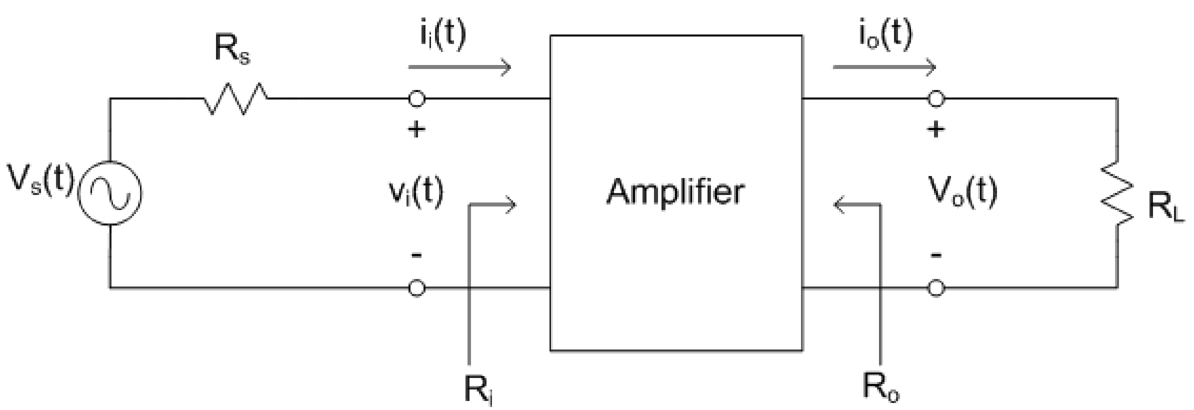
Amplification – Why?

- Amplifiers are also useful for ***impedance conversion***
  - Make a high-resistance source look like a low resistance
  - Make a low-resistance load look like a high resistance
  - ***Buffering*** a high- resistance source from a low-resistance load
- A single amplifier circuit can provide amplification and impedance conversion

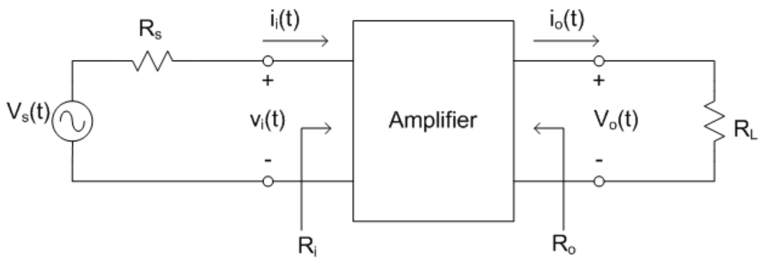
Amplifier Fundamentals

Amplifier Characteristics

- Key amplifier characteristics:
  - ***Gain***
    - May be designed for voltage, current, or power gain
  - ***Input resistance***
  - ***Output resistance***



Amplifier Characteristics - Gain



- ***Voltage gain***
  - Ratio of output to input voltage

$$A_V = \frac{v_o}{v_i}$$

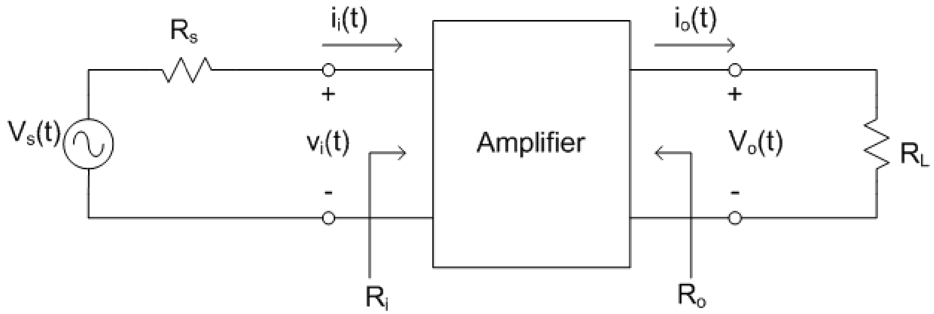
- ***Current gain***
  - Ratio of output to input current

$$A_i = \frac{i_o}{i_i}$$

- ***Power gain***
  - Ratio of output to input power

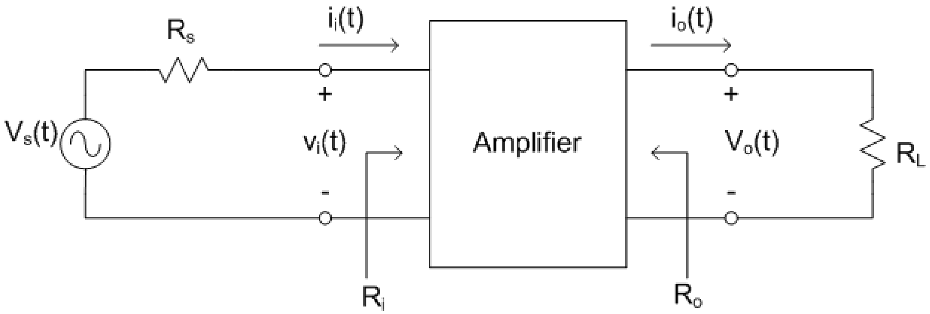
$$G = \frac{P_o}{P_i}$$

Amplifier Characteristics – Input Resistance



- ***Input resistance***, R_i
  - Equivalent resistance seen looking into the amplifier
- Amplifier ***loads*** the source
  - Source appears to be connected to a resistance of R_i
  - Possible voltage division between source resistance and input resistance

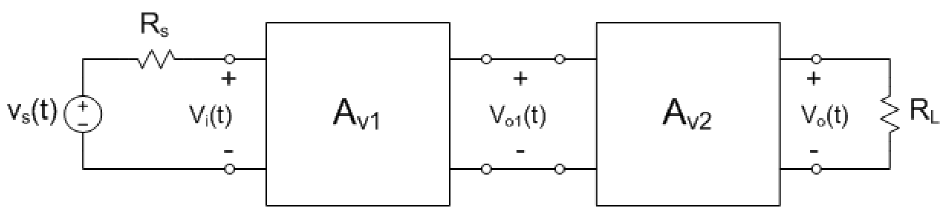
Amplifier Characteristics – Output Resistance



- ***Output resistance***, R_o
  - Thévenin equivalent resistance of the amplifier output
- From the perspective of the load, amplifier output is the source
  - Modeled as Thévenin equivalent circuit, with resistance, R_o
  - Possible voltage division between R_o and the load

Amplifier Characteristics – Cascaded Amplifiers

- Consider two amplifiers connected in ***cascade***



- Input to the second amplifier is the output from the first

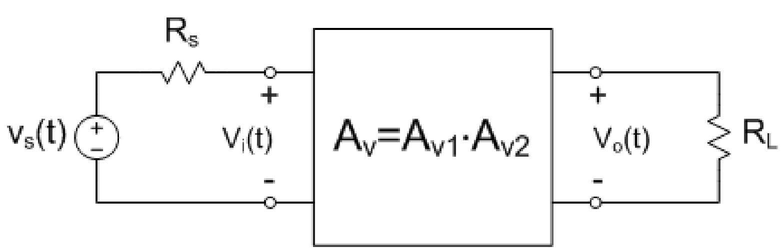
$$v_{o1}(t) = A_{v1} \cdot v_i(t)$$

- Output of the second amplifier is the output of the cascade

$$v_o(t) = A_{v2} \cdot v_{o1}(t) = A_{v1} \cdot A_{v2} \cdot v_i(t)$$

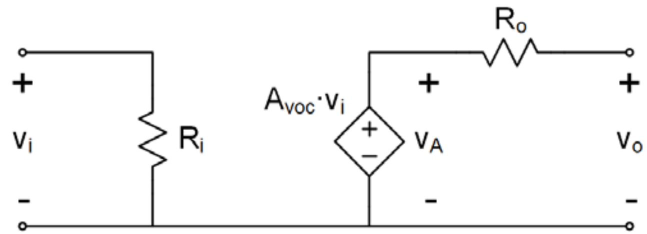
- Overall gain is the ***product*** of the individual gains

$$A_v = A_{v1} \cdot A_{v2}$$



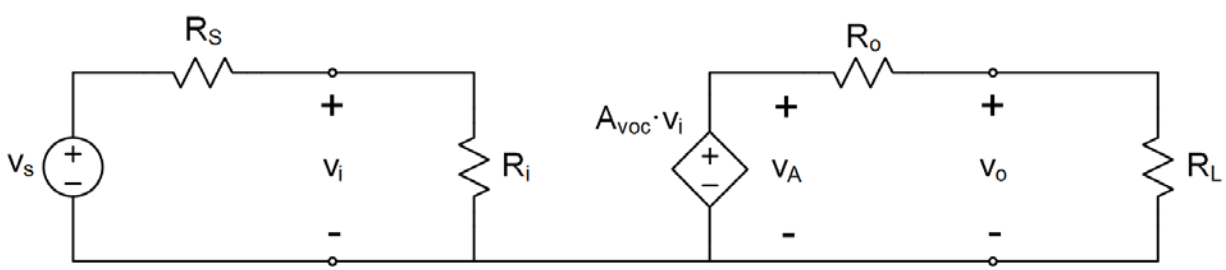
Amplifier – Equivalent Circuit

- Amplifier equivalent circuit:



- R_i: ***input resistance***
- R_o: ***output resistance***
- A_{voc}: ***open-circuit voltage gain***
  - Note that, in general, due to loading:

$$A_{voc} = \frac{v_A}{v_i} \neq A_v = \frac{v_o}{v_s}$$



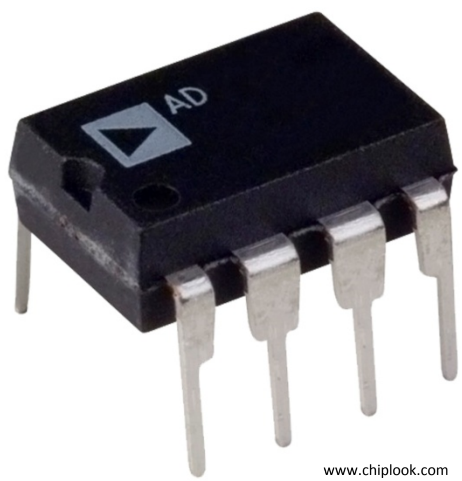
Opamp Fundamentals

Operational Amplifiers - Opamps

- How do we get the amplification we need?
- Different requirements for different applications
  - High gain/low gain – Inverting/non-inverting gain
  - Accuracy
  - Adjustability
- Building amplifiers out of transistors is difficult, inconvenient
- Chip makers could make unique integrated circuits (ICs) for all possible applications
  - Impractical, not economical
- Instead: ***operational amplifiers*** (***opamps***)
  - ***General-purpose*** amplifier ICs
  - Gain set by a few external components

Operational Amplifiers - Opamps

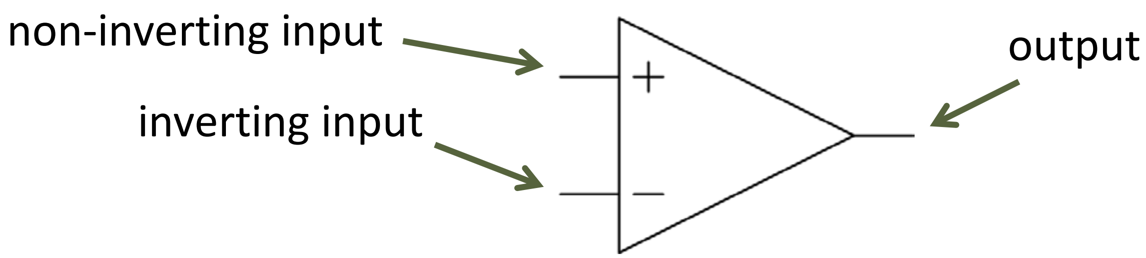
- High-gain amplifiers built from many transistors, resistors, and capacitors
- ***Integrated circuits*** (ICs)
  - All components fabricated on a single semiconductor (e.g. Si) chip
- Gain set by a few external resistors



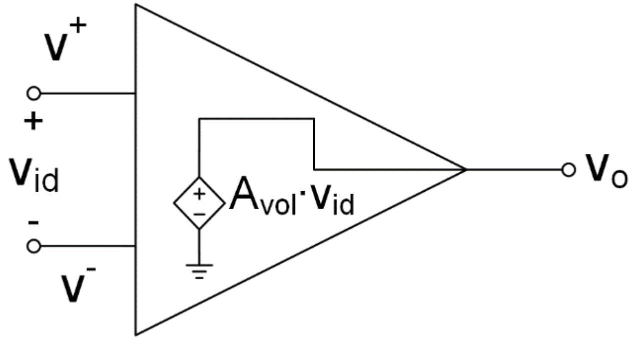
www.chiplook.com

Ideal Opamps

- Schematic symbol:



- Equivalent circuit:



- Open-loop voltage gain, A_{vol}
  - Gain of the opamp without feedback

- ***Differential input***, v_{id}
  - Difference between the two input voltages

$$v_{id} = v^+ - v^-$$

- ***Common-mode input***, v_{icm}

$$v_{icm} = \frac{(v^+ + v^-)}{2}$$

Ideal Opamp Characteristics

- Ideal opamp characteristics:
  1) ***Infinite input resistances*** – at v^+ and v^-
     - No current flows into either input terminal
  2) ***Infinite open-loop gain***
     - Any differential input will result in an infinite output
  3) **Zero output resistance**
     - Immune to the effect of loading

Infinite Gain

- Ideal opamps have infinite gain
  - How do we get a gain of 2 or 9 or -3?

Negative feedback

- By enclosing the opamp in a ***feedback loop*** we can create an amplifier with useable gain
- Before applying feedback to opamp circuits, we'll first introduce the concept of feedback

Introduction to Feedback

Feedback

- ***Feedback***
  - A process in which a portion of the output of some system is *fed back* to the input of that system
- ***Positive feedback***
  - The ***addition*** of a portion of the output to the input
  - Generally has a *destabilizing* effect
- ***Negative feedback***
  - The ***subtraction*** of portion of the output from the input
  - Generally has a *stabilizing* effect
  - All opamp *amplifiers* we will encounter in this course employ negative feedback

Feedback

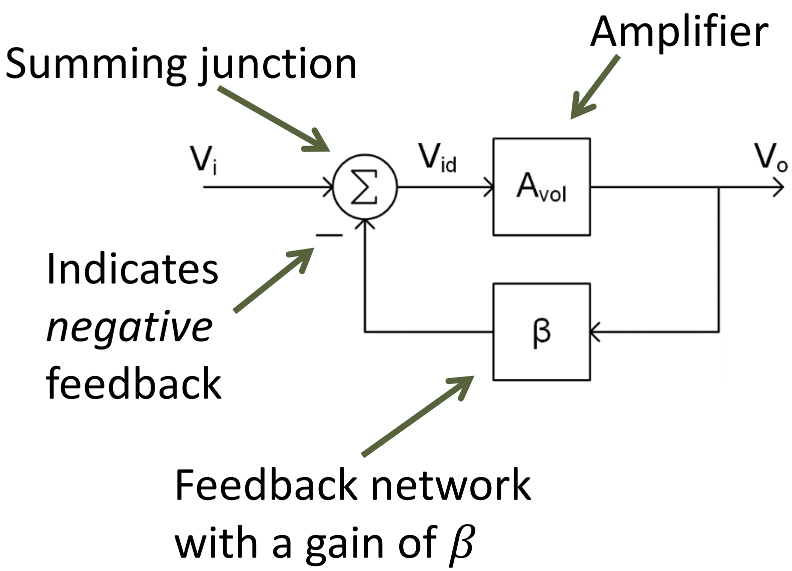
- Feedback is everywhere:
  - HVAC
  - Cruise control
  - Robotics
  - Amplifiers
  - Toilets
  - Ovens
  - Autonomous vehicles
  - Etc.

- A very important concept in many engineering fields, particularly ***controls*** and ***electronics***

Signal Flow Diagrams

- ***Signal flow diagrams***
  - Block diagrams
  - Show the flow of signals – energy, information, etc. – through a system
  - Used for all types of engineering systems: electrical, mechanical, etc.

- Amplifier, with open-loop gain A_{vol}, enclosed in a feedback loop:



- Amplifier is in a ***closed-loop*** configuration
- Feedback gain β, determines how much output is fed back
- Difference between input and feedback is amplifier input
- β determines overall gain
  - Closed-loop gain

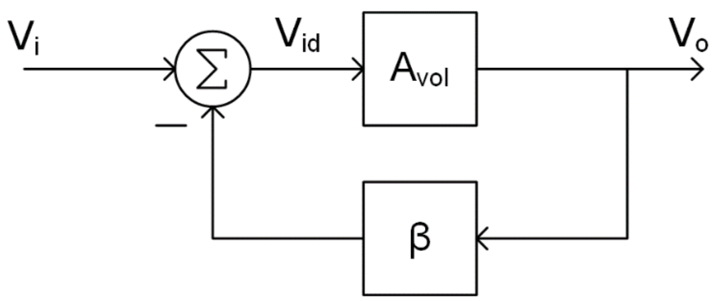
Closed-Loop Gain

- ***Open-loop gain***
  - Gain of amplifier without feedback

$$A_{vol} = \frac{v_o}{v_{id}}$$

- ***Closed-loop gain***
  - Gain of the closed-loop amplifier

$$A_{vcl} = \frac{v_o}{v_i}$$



- Calculating the closed-loop gain:

$$v_o = v_{id} \cdot A_{vol} = (v_i - \beta v_o)A_{vol}$$

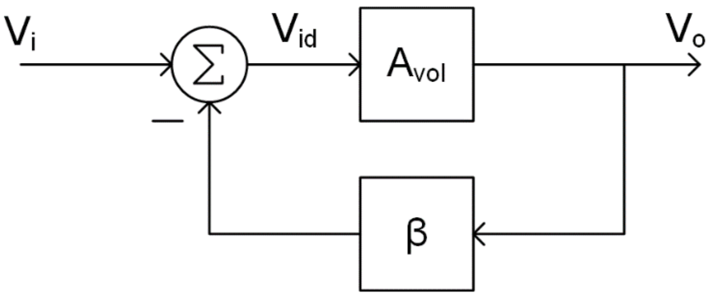
$$v_o + \beta \cdot v_o \cdot A_{vol} = v_i \cdot A_{vol}$$

$$v_o(1 + \beta \cdot A_{vol}) = v_i \cdot A_{vol}$$

$$\boxed{A_{vcl} = \frac{v_o}{v_i} = \frac{A_{vol}}{1 + \beta \cdot A_{vol}}}$$

Closed-Loop Gain

$$A_{vcl} = \frac{v_o}{v_i} = \frac{A_{vol}}{1 + \beta \cdot A_{vol}}$$



- Consider the case of ***infinite open-loop gain***
  - E.g., an ideal opamp

$$\lim_{A_{vol}\to\infty} A_{vcl} = \lim_{A_{vol}\to\infty} \frac{A_{vol}}{1 + \beta \cdot A_{vol}}$$

$$\lim_{A_{vol}\to\infty} A_{vcl} = \lim_{A_{vol}\to\infty} \frac{A_{vol}}{\beta \cdot A_{vol}} = \frac{1}{\beta}$$

- Feedback gain, alone, determines the closed-loop gain
  - For example, to get a gain of four, feed back one quarter of the output signal

Summing Point Constraint

- For $A_{vol} = \infty$, the differential input is

$$v_{id} = v_i - \beta v_o = v_i - \beta \frac{1}{\beta} v_i$$

$$v_{id} = v_i - v_i = 0$$

- A very important result, the ***summing-point constraint***:

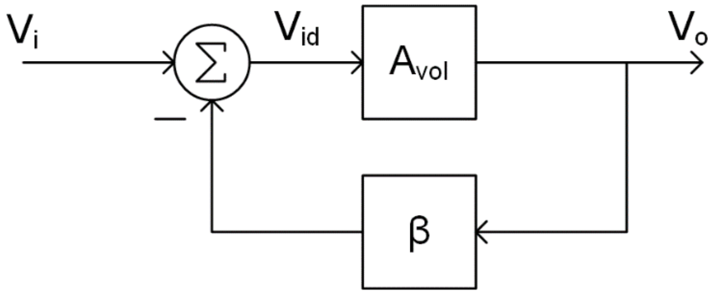
The input to an infinite-gain amplifier, enclosed in a negative feedback loop, is zero!

  - Any non-zero input would yield infinite output

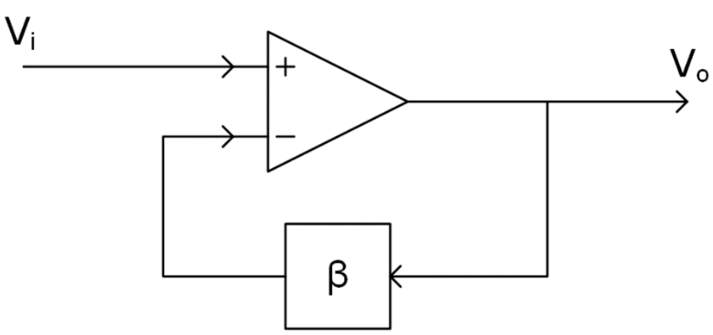
- Along with the properties of ideal opamps, the summing-point constraint will be essential for analyzing opamp circuits

Opamps as Feedback Systems

- ***Any amplifier*** enclosed in a negative feedback loop:
  - Output scaled by β and fed back
  - Feedback signal subtracted from the input at a summing junction
  - If $A_{vol} = \infty$, then $v_{id} = 0$



- ***Ideal opamp*** enclosed in a negative feedback loop:
  - Output scaled by β and fed back
  - Differential input is a built-in summing junction
  - $v_{id} = 0$, so $v^+ = v^-$
  - A ***virtual short*** between input terminals



Example Problems

An amplifier with a gain of 4 is used to amplify the output of a sensor. The amplifier has an input resistance of 1 kΩ and an output resistance of 100 Ω. The sensor has an open-circuit voltage of 1 V, and an output resistance of 50 Ω. The amplifier drives a 5 kΩ load. What is the amplifier's output voltage?

An amplifier is enclosed in a negative feedback loop with a feedback gain of 0.5. Determine the closed-loop gain for an amplifier with an open-loop gain of:

a) 10

b) 100E3

A 1 V input is applied to an opamp enclosed in a negative feedback loop with a feedback gain of 0.2. Determine the differential input voltage for an opamp with an open-loop gain of:

a) 10

b) 100E3

Opamp Amplifiers

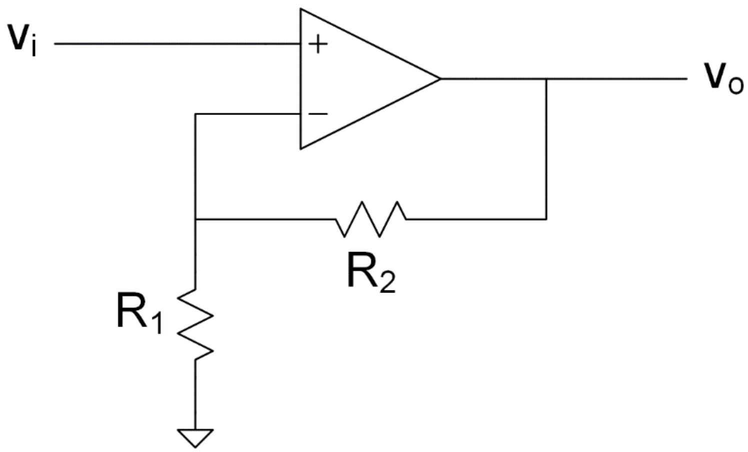
Analysis of Ideal Opamp Circuits

- Key properties for analysis of opamp circuits:
  1) Infinite input resistance – no input current
  2) Virtual short between inverting and non-inverting input terminals (as long as there is negative feedback)
  3) Infinite open-loop gain
- If there is negative feedback, 1 and 2 are sufficient

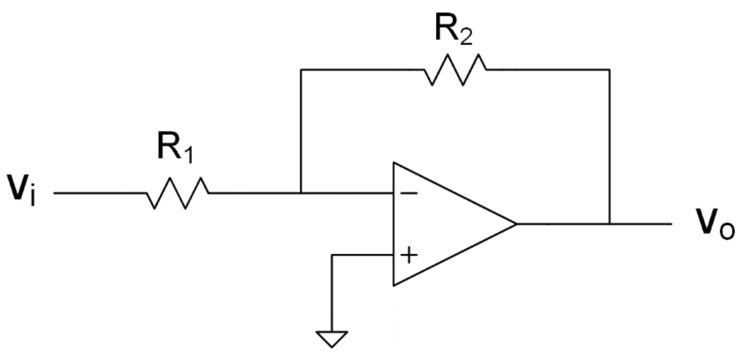
Opamp Amplifiers

- Two basic opamp amplifier configurations:

Non-inverting amplifier:



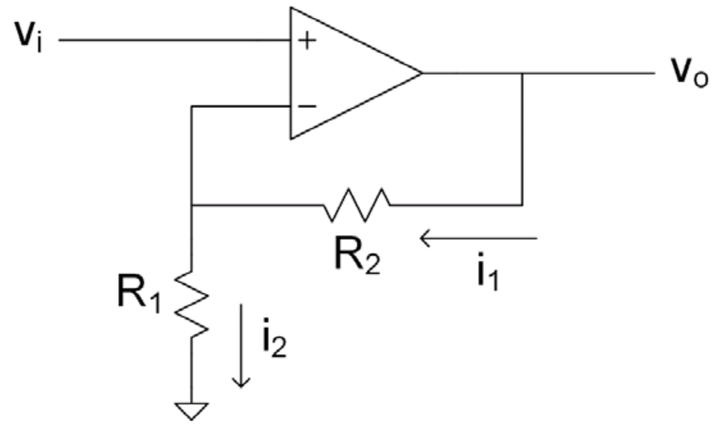
Inverting amplifier:



Non-Inverting Amplifier

Non-Inverting Amplifier – Gain

- ***Non-inverting amplifier*** gain:



- Negative feedback, so the ***summing-point constraint*** applies

$$v^- = v^+ = v_i$$

- ***Zero opamp input current***, so KCL at the inverting terminal gives:

$$i_1 = i_2$$

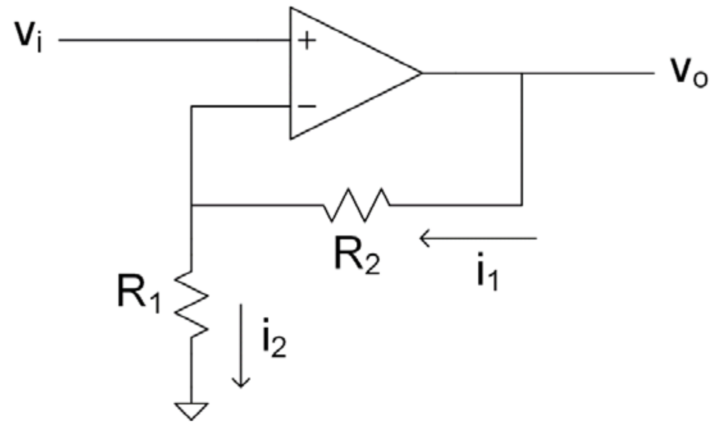
$$\frac{v_o - v^-}{R_2} = \frac{v^-}{R_1}$$

- Applying the summing-point constraint

$$\frac{v_o - v_i}{R_2} = \frac{v_i}{R_1}$$

Non-Inverting Amplifier – Gain

$$\frac{v_o - v_i}{R_2} = \frac{v_i}{R_1}$$



- Solving for the amplifier output

$$v_o = v_i\left(\frac{1}{R_1} + \frac{1}{R_2}\right)R_2$$

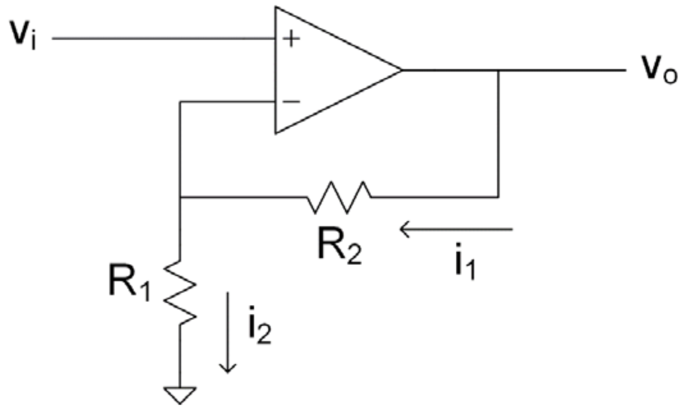
- Dividing both sides by v_i gives the non-inverting amplifier gain:

$$A_v = \frac{v_o}{v_i} = \frac{R_1 + R_2}{R_1}$$

- Note that this is the inverse of the feedback path gain

$$A_v = \frac{1}{\beta} = \frac{1}{\frac{R_1}{R_1 + R_2}}$$

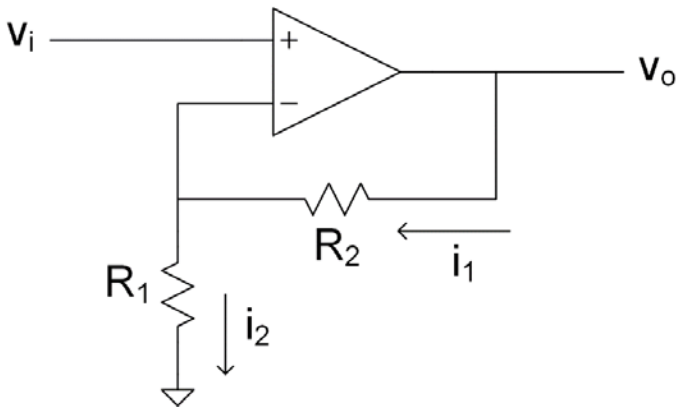
Non-Inverting Amplifier – Gain



$$A_v = \frac{v_o}{v_i} = \frac{R_1 + R_2}{R_1}$$

- Gain determined entirely by the relative value of two external resistors
  - Any gain value is possible
  - Resistor tolerance sets amplifier gain tolerance
- Gain is ***positive*** (non-inverting)
  - As input goes up, output goes up
- Gain can never be less than one
  - Unity gain for $R_2 = 0\ \Omega$

Non-Inverting Amplifier – R_i and R_o



- Input resistance, R_i:
  - Input connected directly to input terminal of ideal opamp

$$R_i = \infty$$

- Output resistance, R_o:
  - Output is the output from an ideal opamp

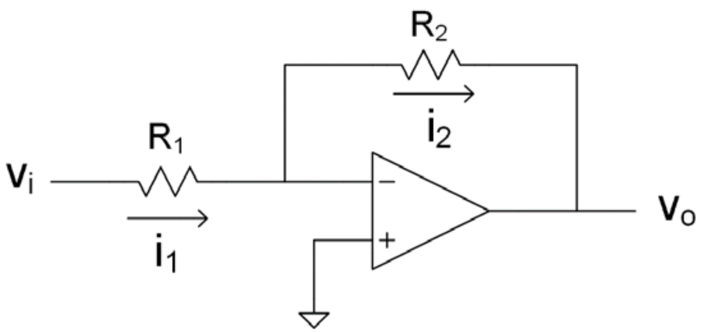
$$R_o = 0\ \Omega$$

Inverting Amplifier

Inverting Amplifier – Gain

- ***Inverting amplifier*** gain:
- Negative feedback, so the ***summing-point constraint*** applies

$$v^- = v^+ = 0$$



- ***Zero opamp input current***, so KCL at the inverting terminal gives:

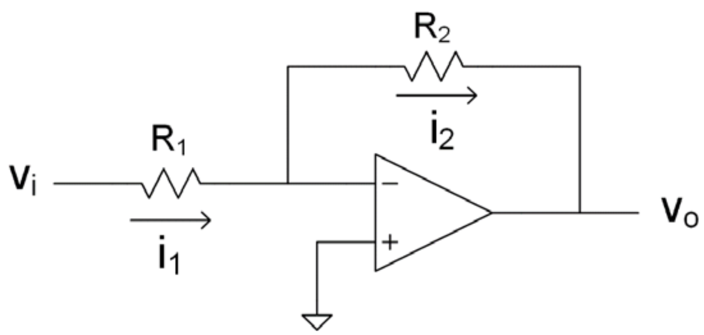
$$i_1 = i_2$$

$$\frac{v_i}{R_1} = \frac{-v_o}{R_2}$$

- Gain of the inverting amplifier:

$$A_v = \frac{v_o}{v_i} = -\frac{R_2}{R_1}$$

Inverting Amplifier – Gain



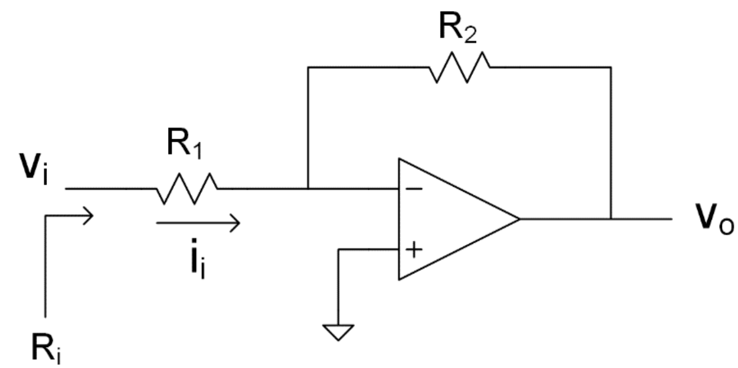
$$A_v = \frac{v_o}{v_i} = -\frac{R_2}{R_1}$$

- Again, gain determined entirely by external resistor values
- Gain is ***negative*** (inverting)
  - As input goes up, output goes down
- Gain can be any value
  - $A_v < 1$ for $R_1 > R_2$

Inverting Amplifier – R_i

- Input resistance, R_i:
  - Inverting terminal is a ***virtual ground***, so

$$i_i = \frac{v_i}{R_1}$$



- By definition, input resistance is

$$R_i = \frac{v_i}{i_i} = v_i \frac{R_1}{V_i}$$

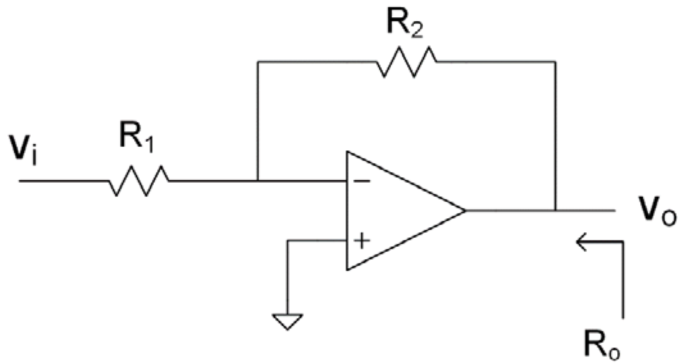
$$\boxed{R_i = R_1}$$

  - Input is a resistance, R_1, to (*virtual*) ground

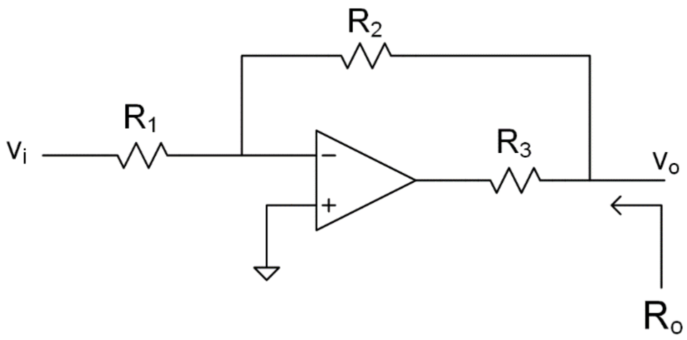
Inverting Amplifier – R_o

- Output resistance, R_o:
  - Output is the output of an ideal opamp, so

$$R_o = 0\ \Omega$$

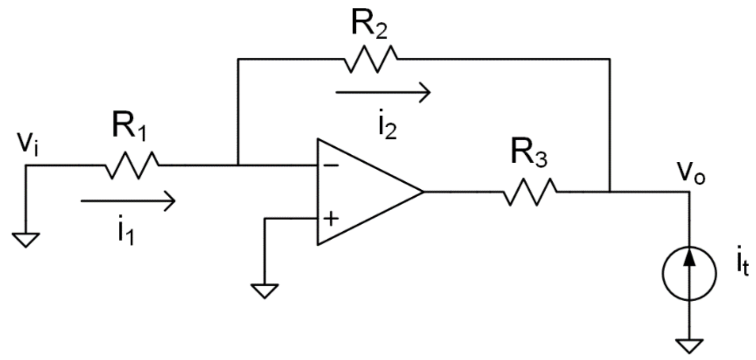


- Consider a non-ideal opamp with non-zero output resistance:
  - R_3 is driven by a ***dependent source***
    - Determining R_o is a bit trickier



Inverting Amplifier – R_o

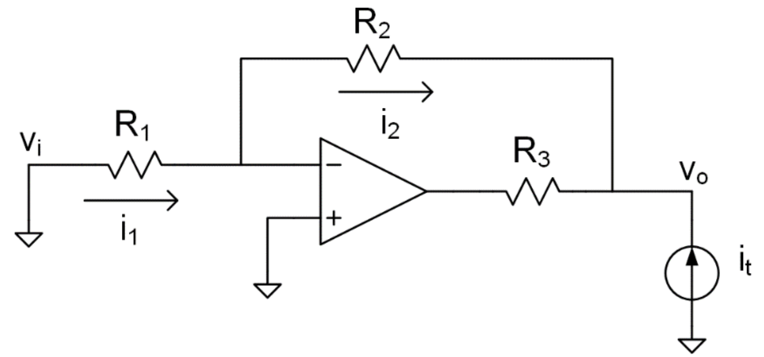
- To determine a terminal resistance in the presence of ***dependent*** sources:
  - Set all *independent* sources to zero
    - Here, ground the input, v_i
  - Apply a test current, i_t, to the terminal of interest
  - Analyze the circuit to determine the voltage at that terminal
  - Resistance at that terminal is given by



$$R_o = \frac{v_o}{i_t}$$

Inverting Amplifier – R_o

- Still a virtual ground at the inverting terminal, so



$$i_1 = i_2 = \frac{v_i}{R_1} = \frac{0\ V}{R_1} = 0$$

$$i_2 = -\frac{v_o}{R_1} = 0$$

$$v_o = 0$$

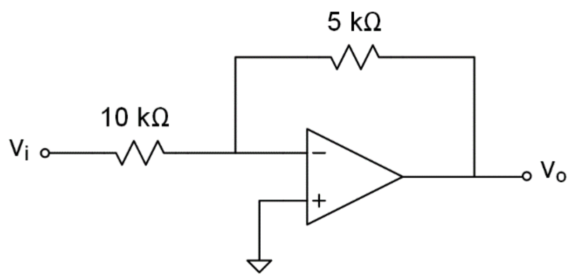
  - The output is zero, independent of i_t (and independent of R_3), so

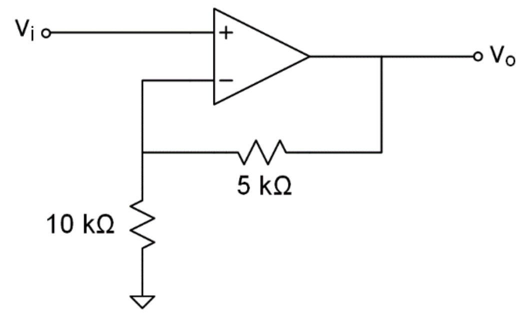
$$R_o = 0\ \Omega$$

- ***Feedback around an infinite gain amplifier forces the closed-loop output resistance to zero, even if the output resistance of the amplifier itself is non-zero***

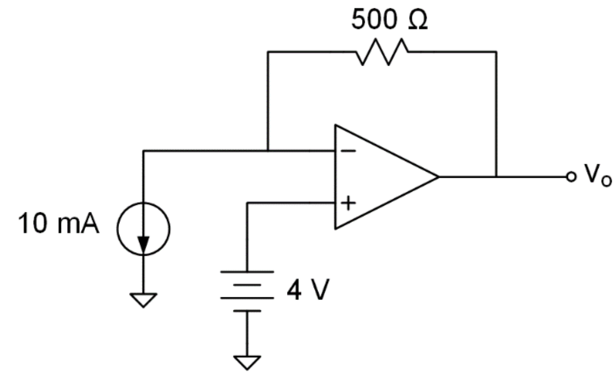
Example Problems

Determine the gain of the following circuits.

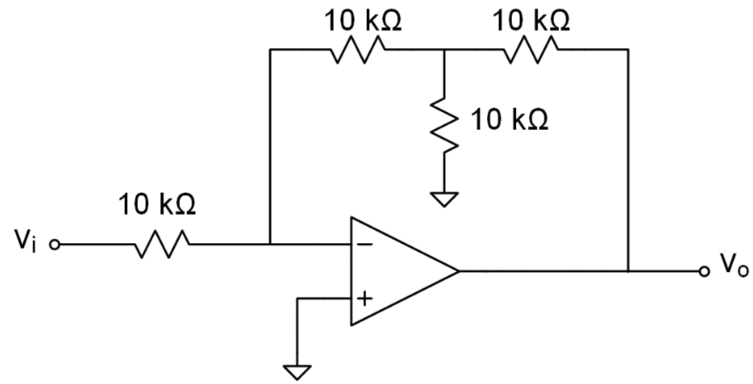


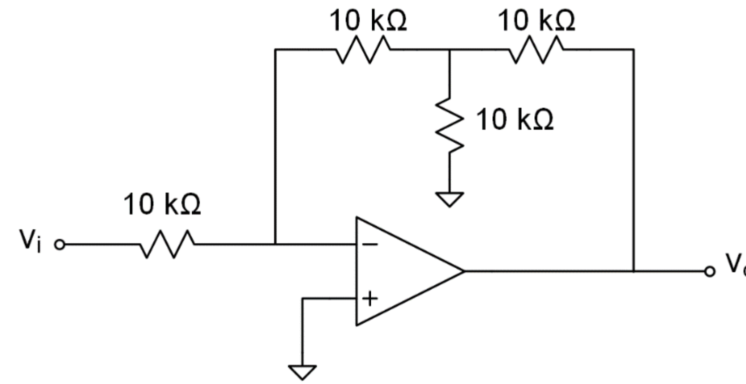


Determine the output voltage, V_o.

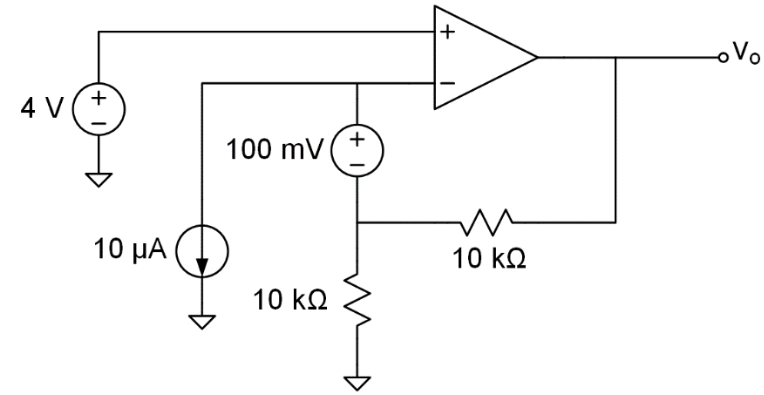


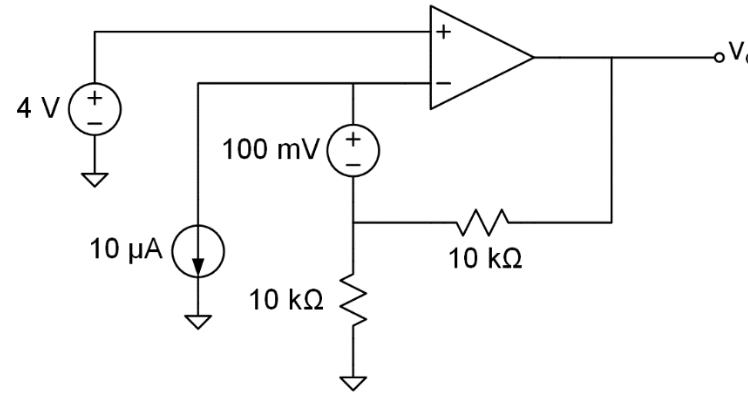
Determine the gain of th
following circuit.




10 kΩ
10 kΩ
10 kΩ
10 kΩ
Vi
Vo

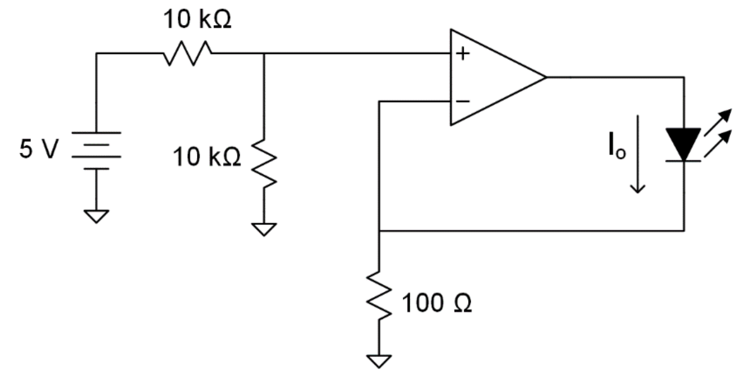
Determine the output voltage, V_o.





Vo
4 V
100 mV
10 µA
10 kΩ
10 kΩ

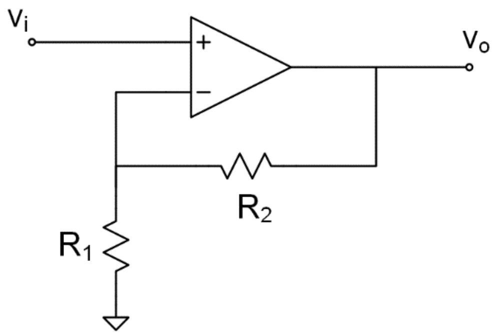
Determine the LED bias current, I_o.



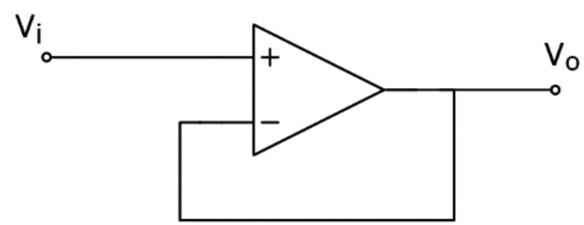
Unity-Gain Buffer

Unity-Gain Buffer

- Start with a non-inverting amplifier, and let the feedback path gain go to unity



$$\beta \rightarrow 1$$



- Inverting terminal is connected directly to the output

$$v^- = v_o$$

- Virtual short at the input terminals

$$v^- = v^+ = v_i = v_o$$

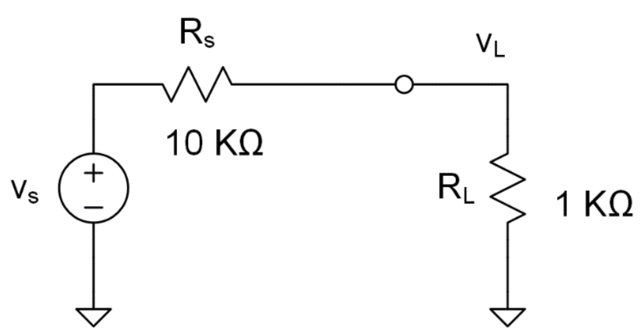
- Closed-loop gain is ***unity***

$$A_v = \frac{v_0}{v_i} = 1$$

Unity-Gain Buffer – Buffering

- What good is an amplifier with unity gain?
  - ***Impedance conversion***
  - A ***buffer*** between a high-resistance source and a lower-resistance load
  - Eliminates loading effects

- Consider the following scenario:
  - Sensor with $R_{th} = 10\ k\Omega$ drives a load of $R_L = 1\ k\Omega$



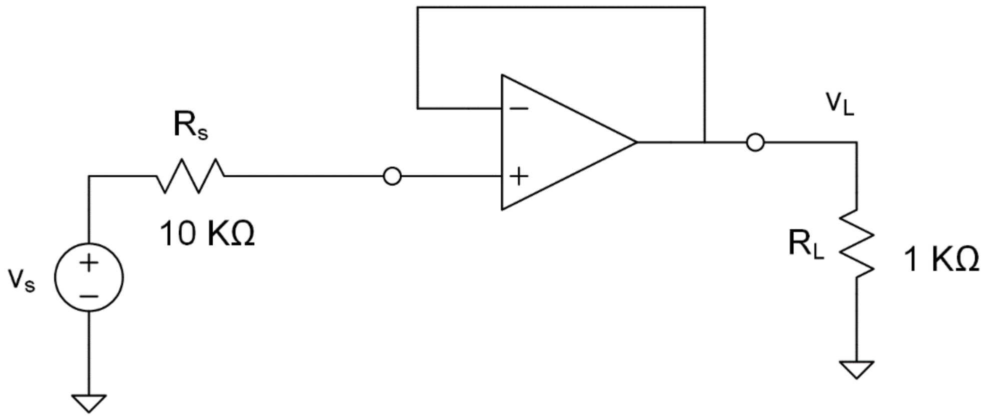
- Signal measured at the load is attenuated

$$v_L = v_s \frac{R_L}{R_s + R_L} = v_s \frac{1\ k\Omega}{11\ k\Omega}$$

$$v_L = \frac{1}{11} v_s$$

Unity-Gain Buffer – Buffering

- To prevent signal attenuation due to loading:
  - Add a unity-gain buffer between the source and the load
- Buffer input is the load for the source
  - $R_i = \infty$
- Buffer output is the source for the load
  - $R_o = 0\ \Omega$



- Now, full sensor signal appears across the load

$$v_L = v^+ = v_s$$

61

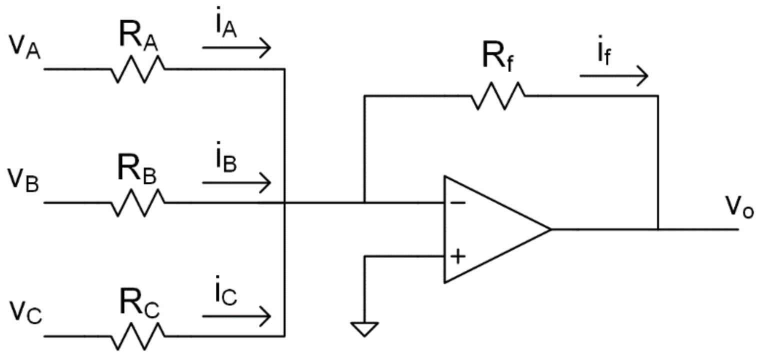
Summing & Difference Amplifiers

Summing Amplifier

- KCL at the inverting node:

$$i_A + i_B + i_C = i_f$$

$$\frac{v_A}{R_A} + \frac{v_B}{R_B} + \frac{v_C}{R_C} = -\frac{v_o}{R_F}$$



- Output is the (inverted) ***weighted sum*** of all of the inputs

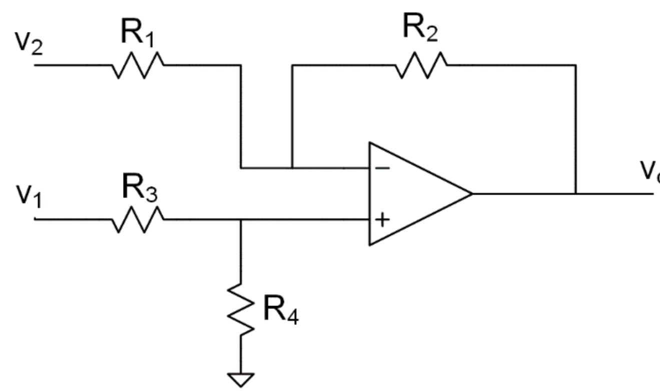
$$v_o = -R_F\left(\frac{v_A}{R_A} + \frac{v_B}{R_B} + \frac{v_C}{R_C}\right)$$

- For the special case of $R_A = R_B = R_C = R_i$:

$$v_o = -\frac{R_F}{R_i}(v_A + v_B + v_C)$$

Difference Amplifier

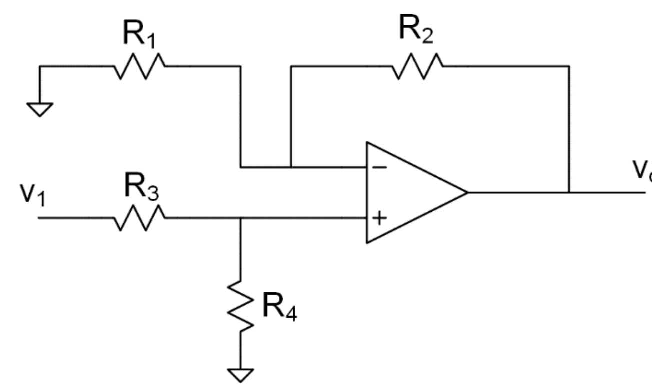
- This looks a bit like a combination of a non-inverting and an inverting amplifier
- Analyze by applying ***superposition***
- First, set $v_2 = 0$
  - A non-inverting amplifier with a voltage divider at the input



$$v_o\Big|_{v_1} = v^+ \frac{R_1 + R_2}{R_1}$$

$$v^+ = v_1 \frac{R_4}{R_3 + R_4}$$

$$v_o\Big|_{v_1} = v_1 \frac{R_4}{R_3 + R_4} \frac{R_1 + R_2}{R_1}$$



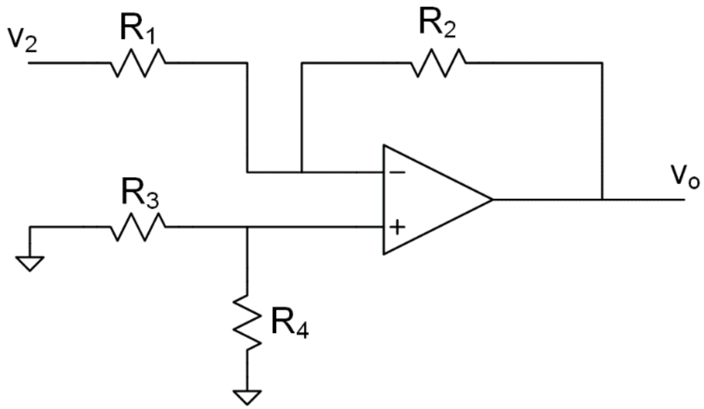
Difference Amplifier

- Next, set $v_1 = 0$
  - No current through R_3 and R_4

$$v^+ = 0\ V$$

  - An inverting amplifier

$$v_o\Big|_{v_2} = -v_2\frac{R_2}{R_1}$$



- Summing the contributions from each output:

$$v_o = v_o\Big|_{v_1} + v_o\Big|_{v_2}$$

$$\boxed{v_o = v_1\frac{R_4}{R_3+R_4}\frac{R_1+R_2}{R_1} - v_2\frac{R_2}{R_1}}$$

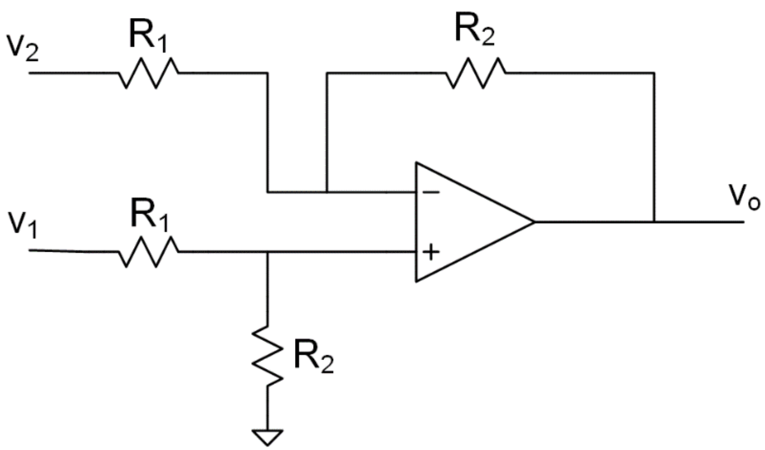
Difference Amplifier

- Restricting resistor values:
  - $R_3 = R_1$ and $R_4 = R_2$

$$v_o = v_1 \frac{R_2}{R_1 + R_2} \frac{R_1 + R_2}{R_1} - v_2 \frac{R_2}{R_1}$$

$$v_o = v_1 \frac{R_2}{R_1} - v_2 \frac{R_2}{R_1}$$

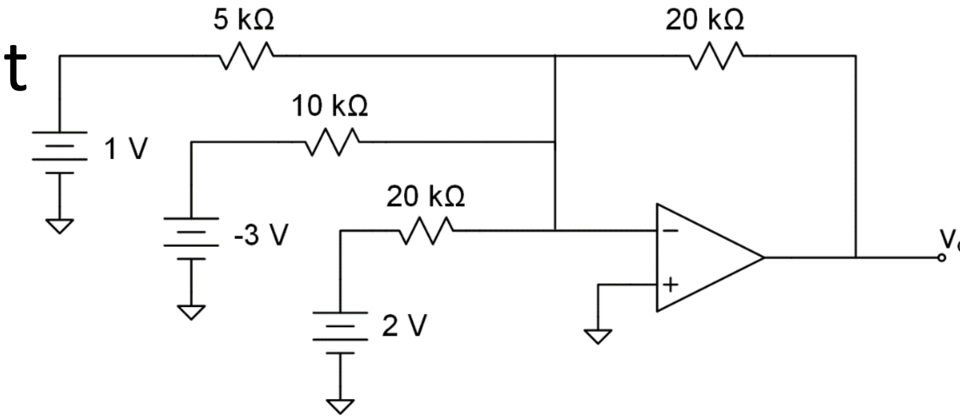
$$\boxed{v_o = \frac{R_2}{R_1}(v_1 - v_2)}$$



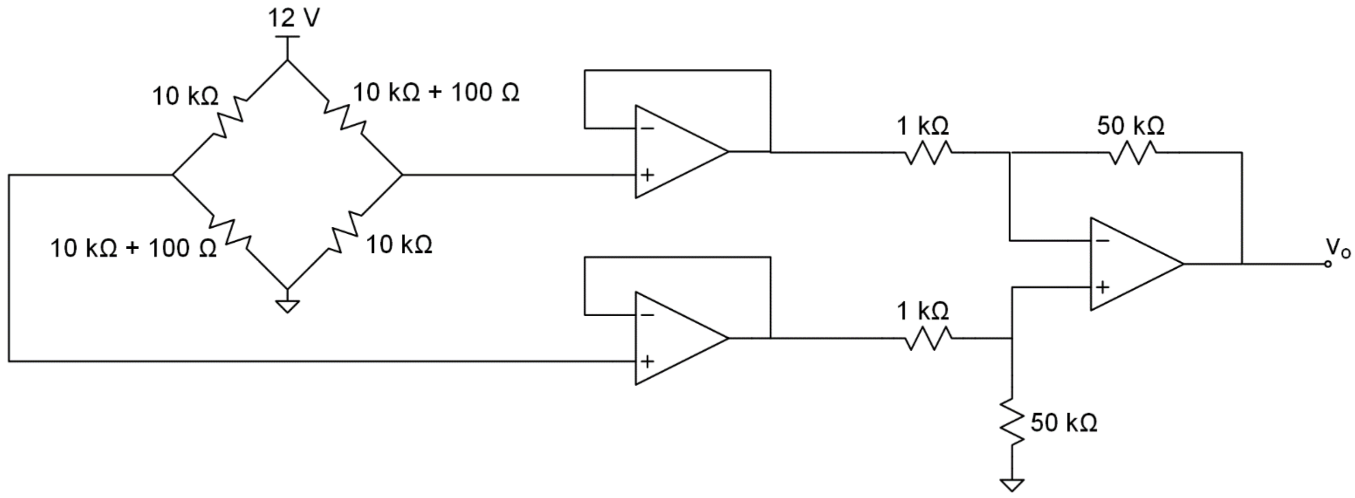
- Inverting and non-inverting amplifiers are special cases of the difference amplifier
  - Inverting amplifier: v_1 is grounded
  - Non-inverting amplifier: v_2 is grounded

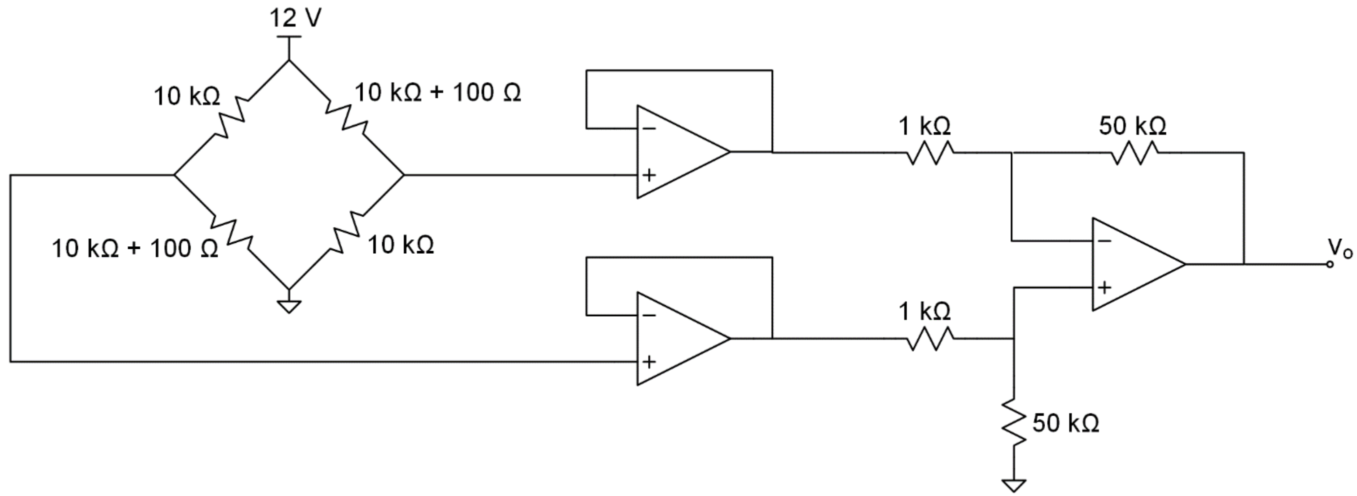
Example Problems

Determine the output voltage, V_o.



Determine the output voltage, V_o.





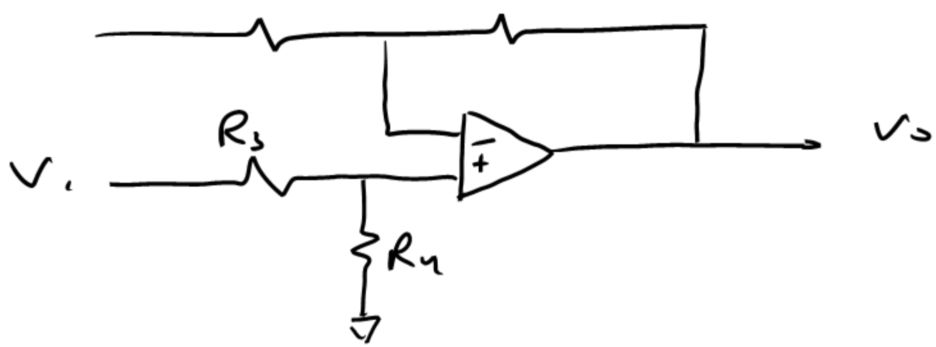
12 V
10 kΩ
10 kΩ + 100 Ω
10 kΩ + 100 Ω
10 kΩ
1 kΩ
50 kΩ
1 kΩ
50 kΩ
v_o

Design an opamp circuit to perform the following mathematical operation:

$$V_o = 3V_1 - 5V_2$$

Design an opamp circuit to perform the following mathematical operation:

$$V_o = 5V_1 - 3V_2$$



Comparators

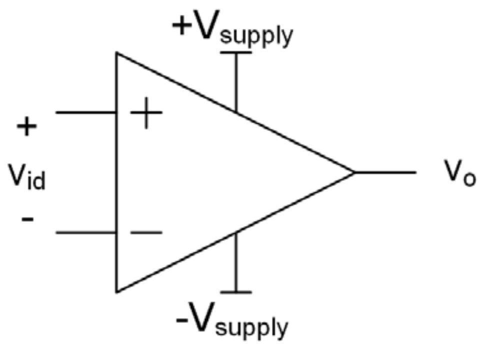
Open-Loop Opamp Behavior

- So far, we've looked at opamp ***amplifier*** circuits
  - ***Closed-loop*** configuration
  - ***Negative feedback***
  - Output remains within the opamp's ***linear*** output range

- We'll now consider using an opamp ***open-loop*** – without feedback – or with positive feedback
  - For ideal opamp, $A_{vol} = \infty$
  - For any non-zero input, $v_o \rightarrow \pm\infty$
  - But, v_o limits, or ***saturates***, somewhere near the supply voltages, $V_{o,max}$
  - In practice, the output of an open-loop opamp is always saturated at $\pm V_{o,max}$

Comparators

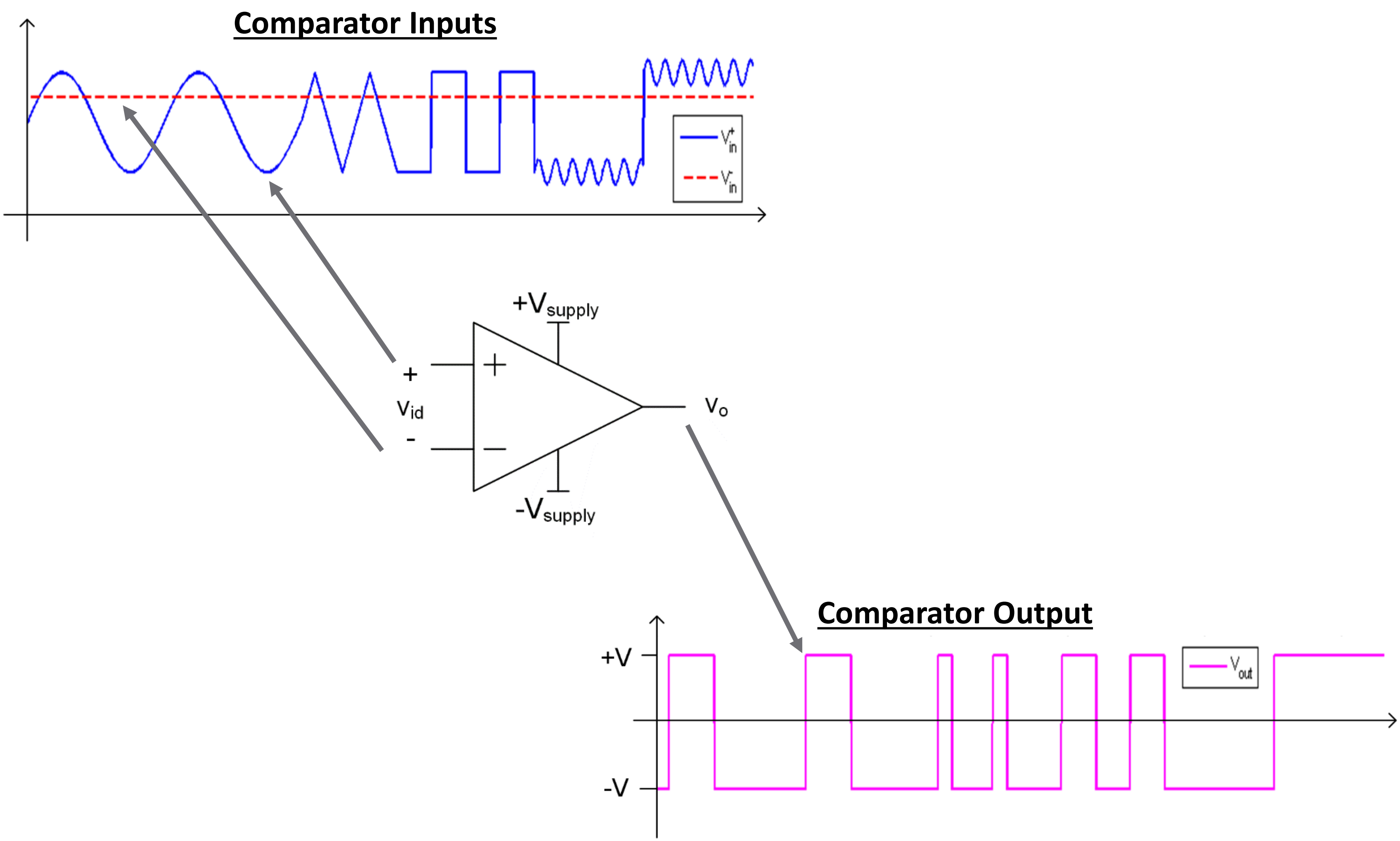
- Open-loop opamp's output determined by relative values of the two inputs, differential input



v^+, v^-	V_{id}	V_o
$v^+ > v^-$		
$v^+ < v^-$		

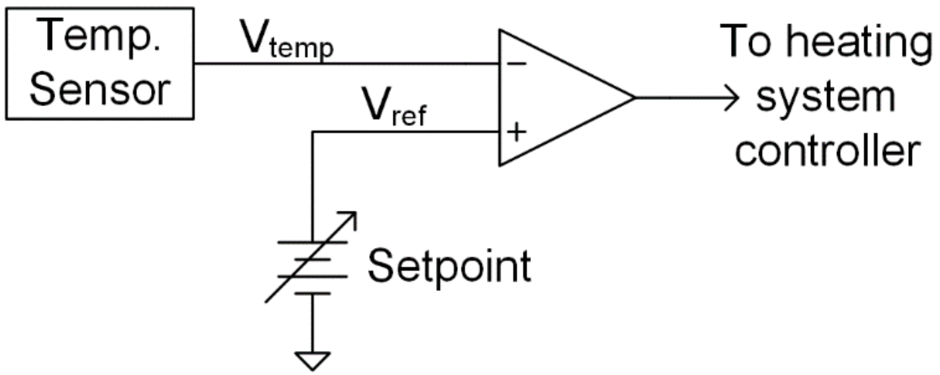
- An open-loop opamp acts as a ***comparator***
  - ***Compares*** the two input voltages
  - Sets the output based on which input is higher

Comparators



Comparators – Applications

- Simple comparator application: ***thermostat***
  - Inverting input connected to a temperature sensor
  - Non-inverting input connected to a variable reference voltage determined by the temperature setpoint

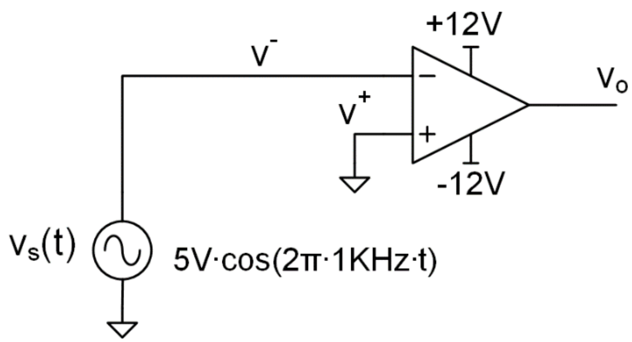


- If $T_{room} < T_{set}$
  - $V_{temp} < V_{ref}$
  - Output is high
  - Heat turns on
- If $T_{room} > T_{set}$
  - $V_{temp} > V_{ref}$
  - Output is low
  - Heat is off

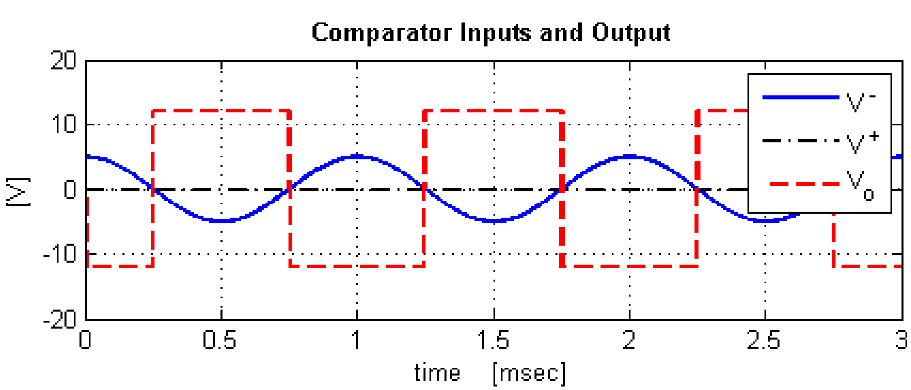
- Another example application: ***motion-sensing light***
  - One input from a motion sensor – variable analog voltage
  - Other input is a threshold voltage set by sensitivity setting
    - Want light to turn on for people and cars, not birds or insects

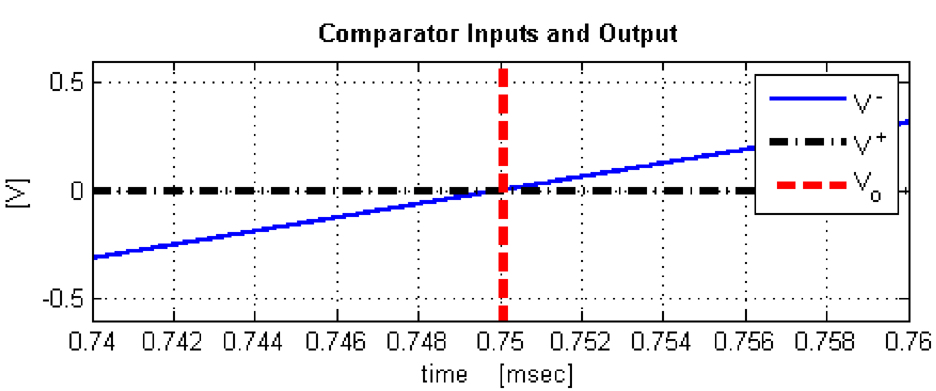
Comparators and Noise

- Consider the following comparator circuit:
  - Inverting input driven by sinusoidal voltage
  - Non-inverting input is ***threshold voltage*** – connected to ground ($0\ V$)



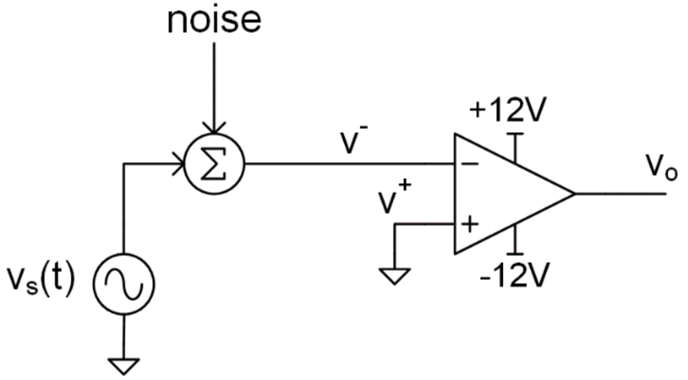
  - Output switches cleanly at each input threshold crossing

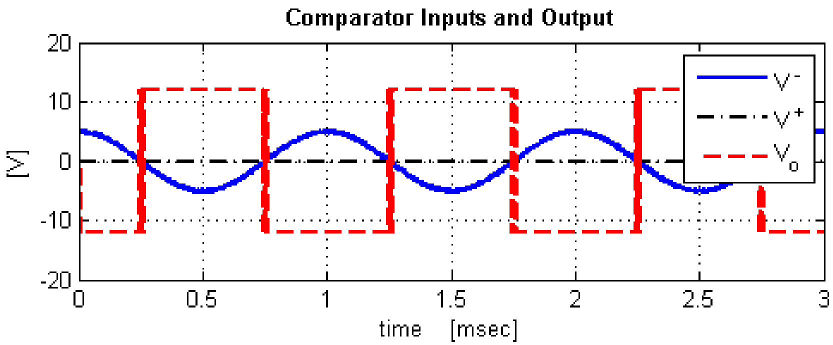


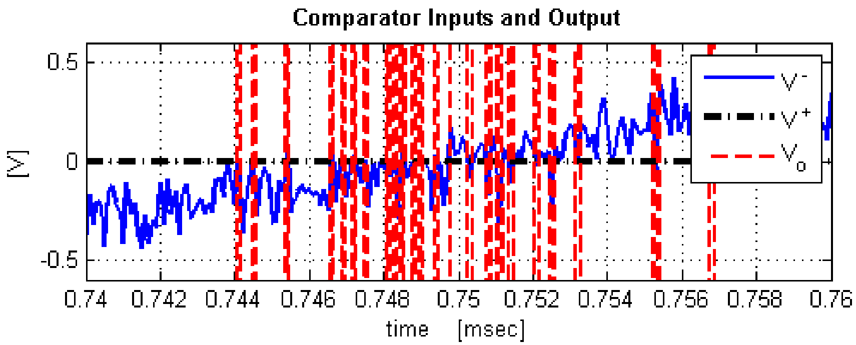


Comparators and Noise

- Now, the sinusoidal input is corrupted by noise
  - Multiple input threshold crossings each time $v_s(t)$ goes through $0\ V$
  - Multiple, unwanted, output transitions





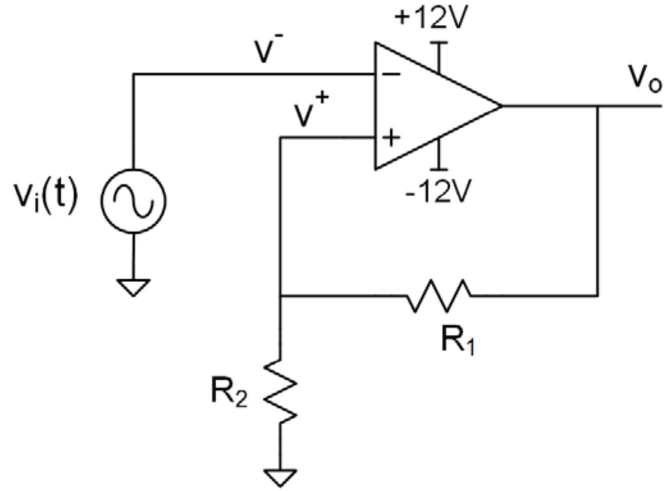


- Would like to be able to reject this noise at the input:
  - ***Schmitt trigger***

Hysteresis

Hysteresis – Schmitt Trigger

- Schmitt trigger employs ***hysteresis***
  - Characteristics of the circuit are dependent on its previous state
- Looks like a non-inverting amplifier, but it is not
  - ***Positive feedback***
- A comparator with a threshold voltage that depends on the output



$$v^{+} = v_o \frac{R_2}{R_1 + R_2} = \beta v_o$$

- Threshold voltage switches between two values as the output switches between $\pm V_{o,max}$

$$v^{+} = \pm \beta V_{o,max}$$

Schmitt Trigger – Hysteresis voltage

- Consider the case where the input is low

$$v_i < v^+$$

  - Output will be high

$$v_o = +V_{o,max}$$

- The input then increases and exceeds the threshold voltage

$$v_i > v^+$$

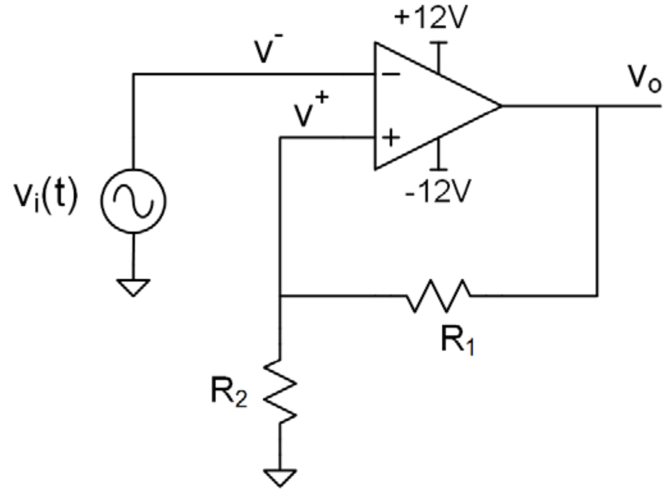
  - The output will then switch low

$$v_o \rightarrow -V_{o,max}$$

  - The threshold voltage will switch low

$$v^+ \rightarrow -\beta V_{o,max}$$

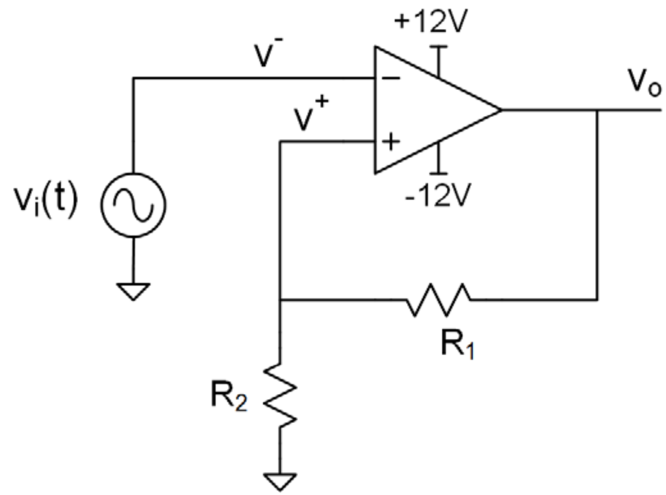
  - ***Threshold voltage switches away from the rising input***
- Similar thing is true for falling input



Schmitt Trigger – Hysteresis voltage

- Output, and threshold voltage, always ***switches away from the input signal*** at the first threshold crossing
- ***Hysteresis voltage***:
  - Magnitude of the threshold voltage change

$$V_{hyst} = 2\beta V_{o,max}$$

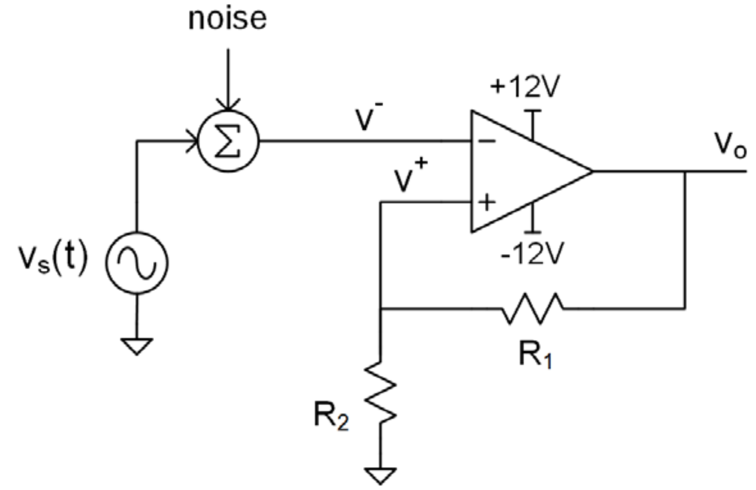


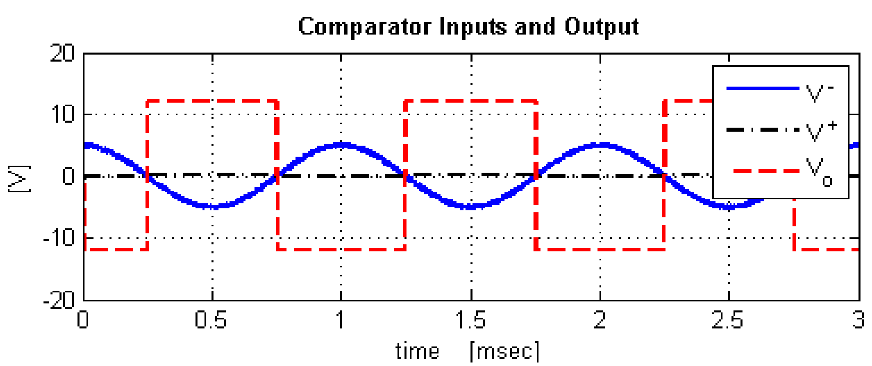
- Hysteresis voltage set for the amount of noise that is present
  - Threshold must switch far enough away from the noisy input that it will not be crossed multiple times by noise alone
  - V_{hyst} set greater than peak-to-peak noise on the input signal

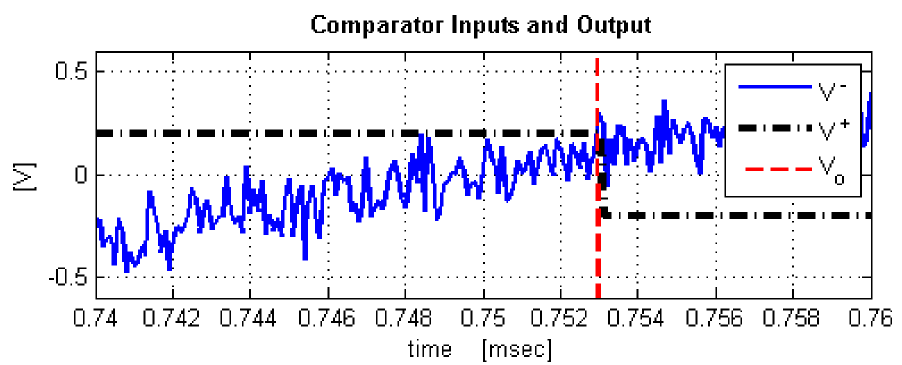
Comparators and Noise – Hysteresis

- Feedback gain, β, set to provide adequate hysteresis to reject the input noise
  - Noisy input crosses threshold
  - Threshold voltage switches away from the input by the hysteresis voltage

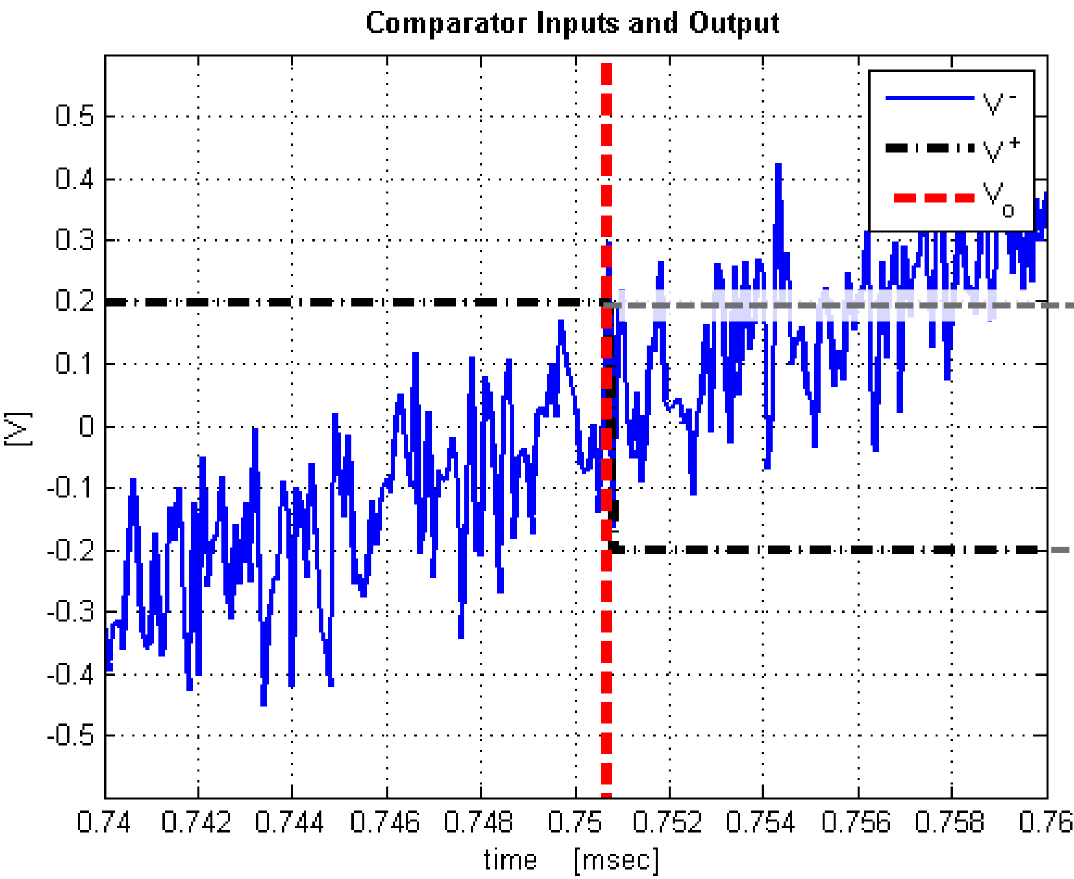
$$V_{hyst} > V_{n,pp}$$







Hysteresis Voltage



- ***Hysteresis voltage***
  - Full peak-to-peak swing of the threshold voltage

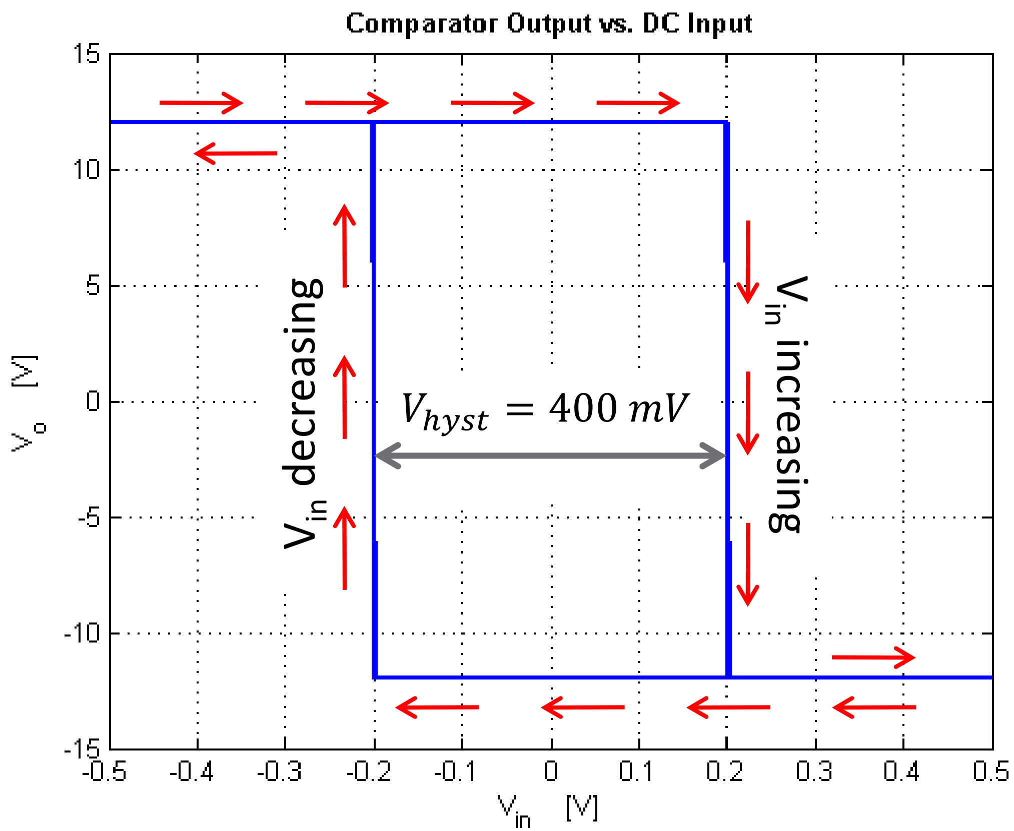
$$V_{hyst} = 400\ mV$$

  - Twice the magnitude of the feedback signal

$$V_{hyst} = 2\beta V_{o,max}$$

Hysteresis Voltage

- Can also measure V_{hyst} by performing a bidirectional DC sweep of the input
  - Low-to-high, then high-to-low



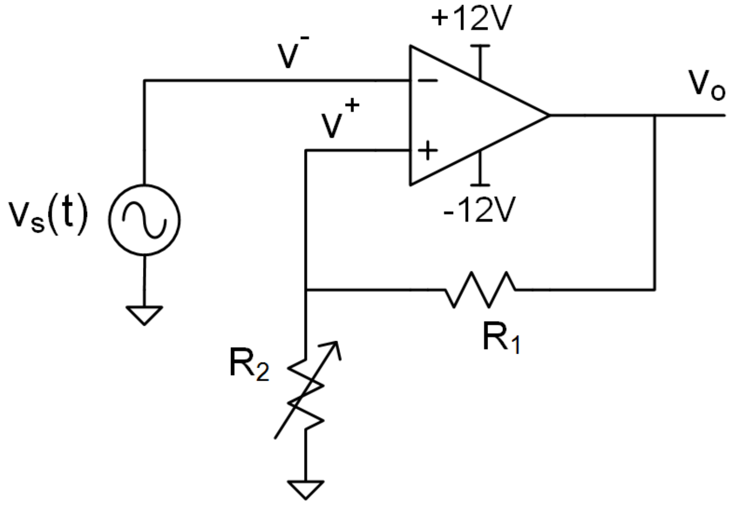
- Output traces a different path depending on direction of v_{in}
  - Vertical lines indicate threshold voltages
  - V_{hyst} given by difference between upper and lower thresholds

Adjustable Hysteresis

- If noise level is not known ahead of time
  - Use a potentiometer to get adjustable hysteresis

- R_2 adjustable from $0\ \Omega$ to $R_{2,max}$
- Hysteresis varies as R_2 varies

$$V_{hyst} = 2\frac{R_2}{R_1 + R_2}V_{o,max}$$



- Max hysteresis at $R_2 = R_{2,max}$

$$V_{hyst,max} = 2\frac{R_{2,max}}{R_1 + R_{2,max}}V_{o,max}$$

- Minimum hysteresis for $R_2 = 0\ \Omega$

$$V_{hyst,min} = 2\frac{0\ \Omega}{R_1 + 0\ \Omega}V_{o,max} = 0\ V$$

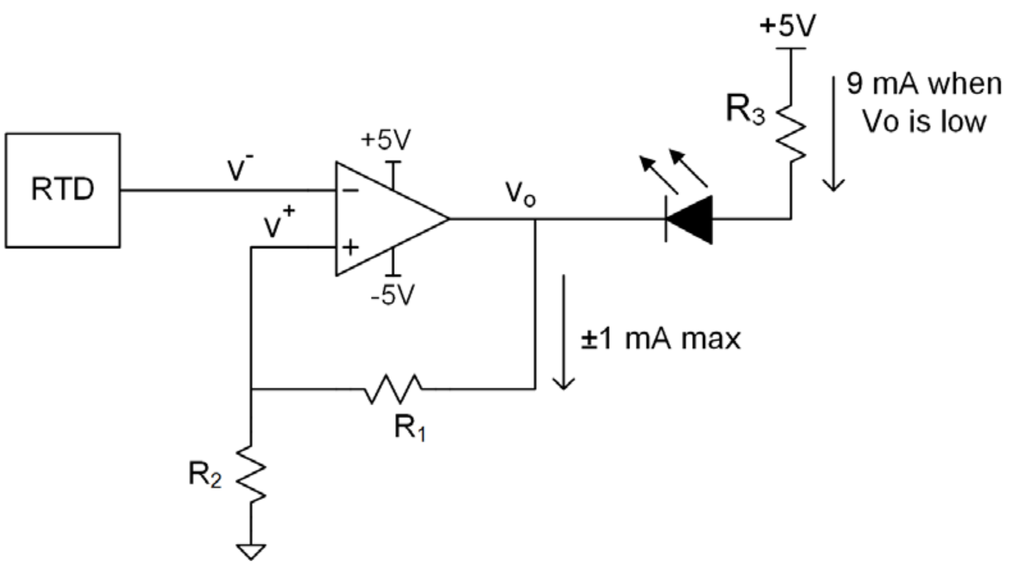
Schmitt Trigger – Example

- Consider the following scenario:
  - Test engine instrumented and running on a dynamometer
  - Want an engine temperature warning light (LED)
  - RTD (*resistive temperature detector* or *resistive thermal device*) installed to measure coolant temperature.
  - RTD is biased such that a $0\ V$ output corresponds to T_{max}
  - Noise: $V_{n,pp} \approx 100\ mV$
  - Opamp available for use as a comparator:
    - $V_{supply} = \pm 5\ V$
    - $V_{o,max} = \pm \left| V_{supply} - 500\ mV \right|$
    - $I_{o,max} = \pm 10\ mA$
  - $I_{LED} = 9\ mA$

Schmitt Trigger – Example

- When $T > T_{max}$
  - RTD output exceeds $0\ V$
  - Schmitt trigger output goes low: $v_o \rightarrow -4.5\ V$
  - LED turns on: $I_{LED} = 9\ mA$
  - Opamp output sinks LED current and feedback network current
  - Feedback network current must not exceed $1\ mA$

- Determine R_1 and R_2 to:
  - Set required hysteresis voltage
  - Limit feedback path current



Schmitt Trigger – Example

- Required hysteresis is *at least* the peak-to-peak noise voltage, $V_{n,pp} \approx 100\ mV$
  - Design for $V_{hyst} = 150\ mV$
  - The opamp saturates at $\pm 4.5\ V$, so

$$V_{hyst} = 2 \cdot 4.5\ V \frac{R_2}{R_1 + R_2} = 150\ mV$$

$$\frac{R_2}{R_1 + R_2} = \frac{150\ mV}{9\ V} = 16.67 \times 10^{-3}$$

- This specifies the ratio between the feedback resistors

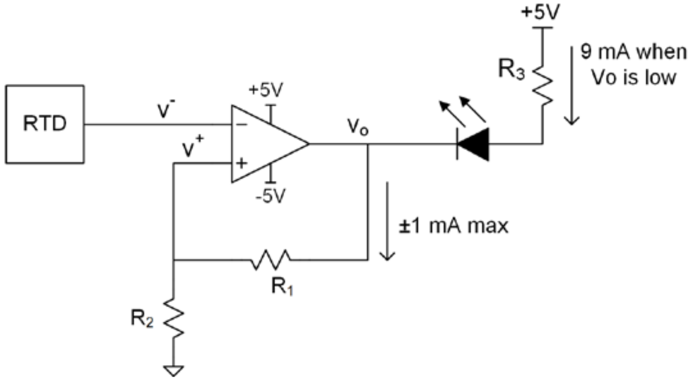
$$R_2 = 16.95 \times 10^{-3} \cdot R_1$$

- Absolute values will be selected to limit feedback path current

Schmitt Trigger – Example

- When the LED is on, the feedback path current flowing into the opamp output is

$$I_f = \frac{4.5\ V}{R_1 + R_2} < 1\ mA$$



- So, the total feedback path resistance is

$$R_1 + R_2 > 4.5\ k\Omega$$

- Select a standard value for the larger resistor

$$R_1 = 5.1\ k\Omega$$

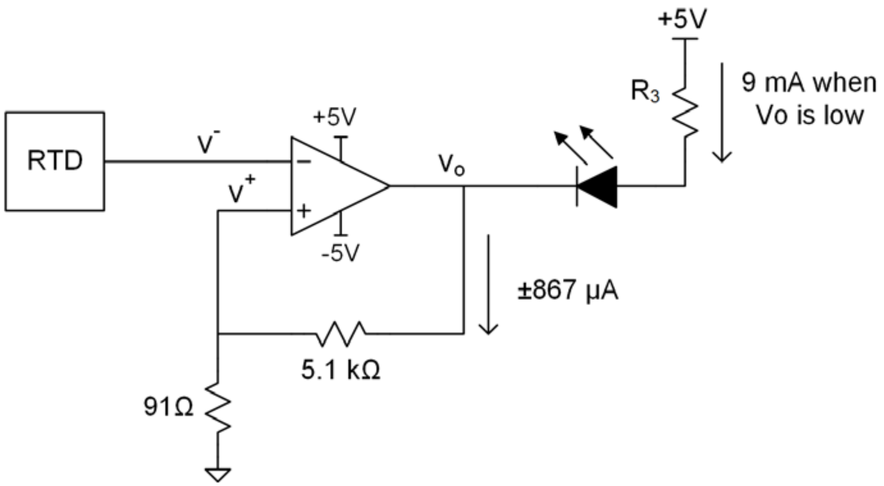
- Calculate R_2 using the previously derived ratio

$$R_2 = 16.95 \times 10^{-3} \cdot 5.1\ k\Omega = 86.4\ \Omega$$

- Select the next *larger* standard value: $R_2 = 91\ \Omega$
  - *Larger*, so as not to decrease V_{hyst}

Schmitt Trigger – Example

- The resulting circuit:



- Verifying hysteresis:

$$V_{hyst} = 9\,V \frac{91\,\Omega}{5.1\,k\Omega + 91\,\Omega}$$

$$V_{hyst} = 157\,mV$$

- Feedback path current:

$$I_f = \frac{4.5\,V}{5191\,\Omega} = 867\,\mu A$$