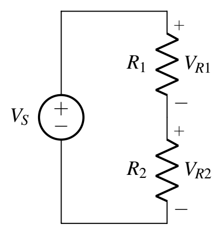
CSM 16A Designing Information Devices and Systems I
Spring 2021 Week 9

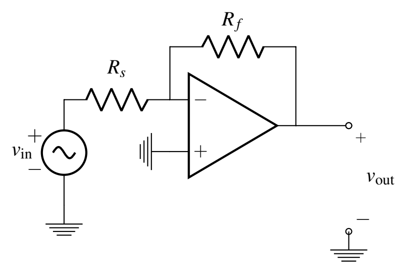
Reference: Op-Amp Example Circuits

Voltage Divider



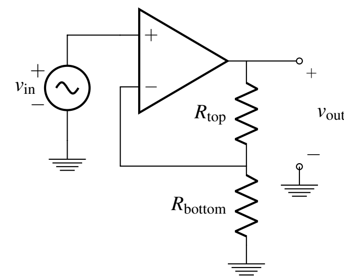
$$V_{R_2} = V_S \left(\frac{R_2}{R_1+R_2}\right)$$

Inverting Amplifier



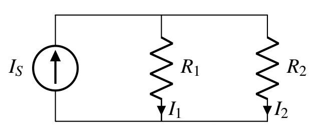
$$v_{out} = v_{in}\left(-\frac{R_f}{R_s}\right)$$

Noninverting Amplifier



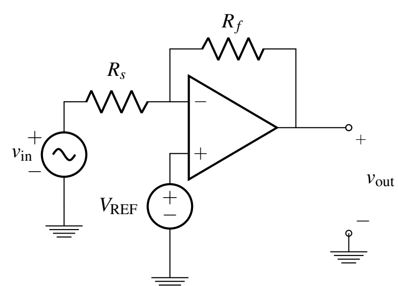
$$v_{out} = v_{in}\left(1+\frac{R_{top}}{R_{bottom}}\right)$$

Current Divider



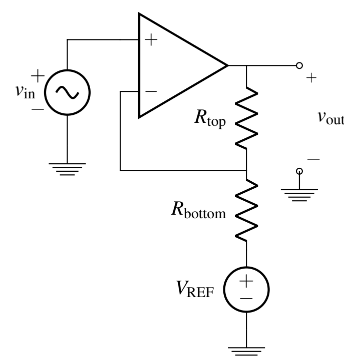
$$I_1 = I_S \left(\frac{R_2}{R_1+R_2}\right)$$

Inverting Amplifier with Reference



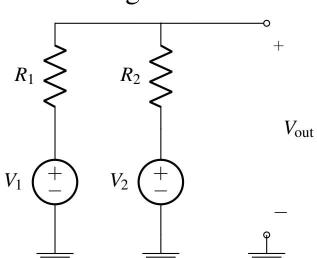
$$v_{out} = v_{in}\left(-\frac{R_f}{R_s}\right) + V_{REF}\left(\frac{R_f}{R_s}+1\right)$$

Noninverting Amplifier with Reference



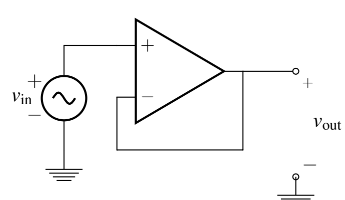
$$v_{out} = v_{in}\left(1+\frac{R_{top}}{R_{bottom}}\right) - V_{REF}\left(\frac{R_{top}}{R_{bottom}}\right)$$

Voltage Summer



$$V_{out} = V_1\left(\frac{R_2}{R_1+R_2}\right) + V_2\left(\frac{R_1}{R_1+R_2}\right)$$

Unity Gain Buffer



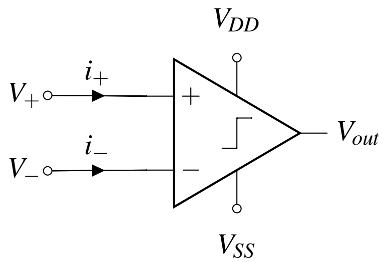
$$v_{out} = v_{in}$$

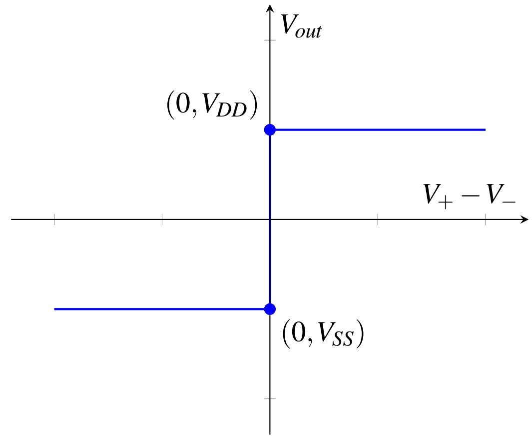
1. Comparators

Learning Goal: This problem will help to understand comparator properties and design circuits with comparators.

Relevant Notes: Note 17C goes over comparator properties.

Comparators are typically drawn like the figure on the left, and their internal workings can be represented by the figure on the right.

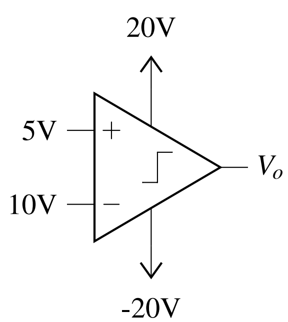




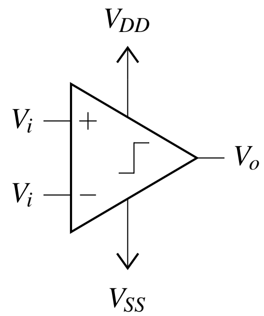
Here, V_+ and V_- are input voltages, V_{DD} and V_{SS} are what we call the "supply rails", and V_{out} is the output voltage. From the diagram and knowing that V_{out} cannot exceed the supply rail voltages, we have a relationship between the outputs and the inputs:

$$V_{out} = \begin{cases} V_{DD} & \text{, if} \quad V_+ > V_-) \\ V_{SS} & \text{, if} \quad V_+ < V_-) \\ \text{undefined} & \text{, if} \quad V_+ = V_-) \end{cases}$$

(a) Identify the output voltage V_o for the following comparator:

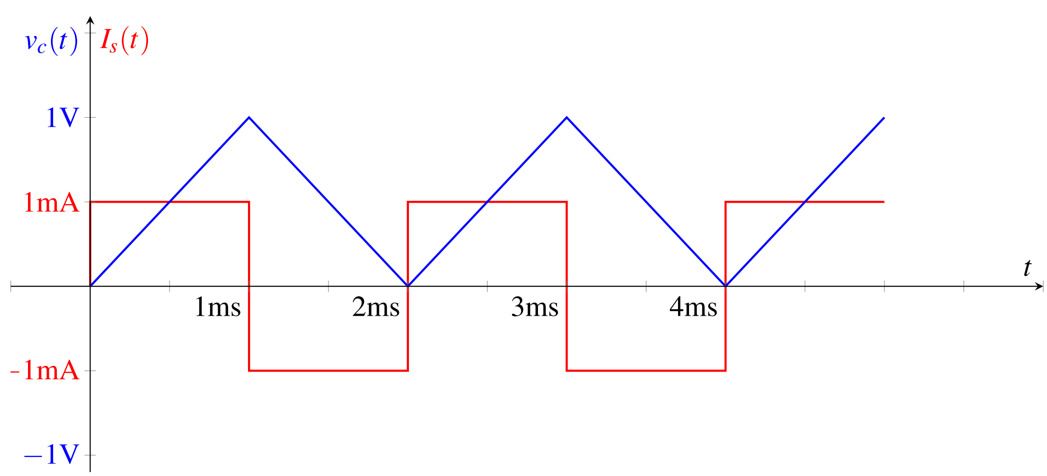


(b) Identify the output voltage V_o for the following comparator:



(c) Design a circuit such that $v_o = 2\text{V}$ if $v_c > 0.5\text{V}$ and $v_o = -1\text{V}$ if $v_c < 0.5\text{V}$. Draw your designed circuit.
You can use only up to 3 voltage sources, but other than that you can use whatever circuit components you want (ex. comparator, capacitor, resistors, etc.) and as many as you would like. Label the values of the voltage sources you use. Hint: Can we use the circuit components we talked about in last week's worksheet?

(d) Assume $I_s(t)$ and $v_c(t)$ are given in the following figure. Plot $v_o(t)$ vs. time for the circuit you designed in the last part.



(e) Redesign your circuit such that $v_o = -2\text{V}$ if $v_c > 0.5\text{V}$ and $v_o = 1\text{V}$ if $v_c < 0.5\text{V}$. Draw your redesigned circuit.

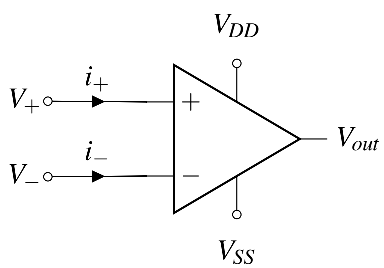
You can use as many voltage sources you want. Label the values of the voltage sources you use.

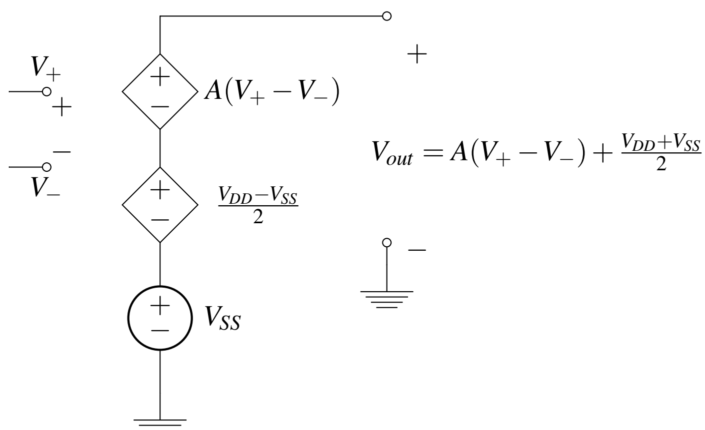
2. Operational Amplifiers

Learning Goal: This problem will help to understand op-amps in negative feedback and the operation of an inverting amplifier.

Relevant Notes: Note 18 goes over op-amp properties and derivation of circuit responses.

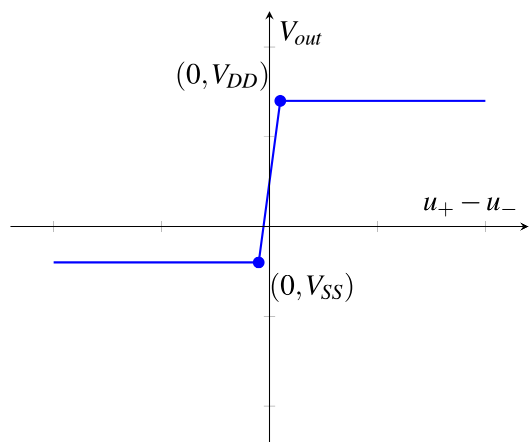
Operational amplifiers (op amps for short) are typically drawn like the figure on the left, and their internal workings can be represented by the figure on the right.





Here, V_+ and V_- are input voltages, V_{DD} and V_{SS} are what we call the "supply rails", and V_{out} is the output voltage. From the diagram and knowing that V_{out} cannot exceed the supply rail voltages, we have a relationship between the outputs and the inputs:

$$V_{out} = \begin{cases} V_{SS} & \text{, if} \quad A(V_+ - V_-) + \frac{V_{DD}+V_{SS}}{2} < V_{SS} \\ A(V_+ - V_-) + \frac{V_{DD}+V_{SS}}{2} & \text{, if} \quad V_{SS} \leq A(V_+ - V_-) + \frac{V_{DD}+V_{SS}}{2} \leq V_{DD} \\ V_{DD} & \text{, if} \quad V_{DD} < A(V_+ - V_-) + \frac{V_{DD}+V_{SS}}{2} \end{cases}$$

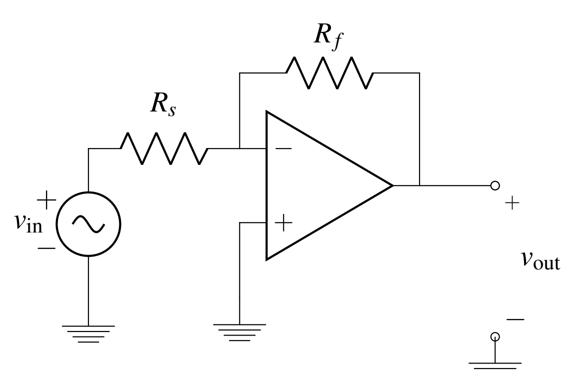


Typically gain A is quite large, meaning the the sloped region in the center is quite narrow.

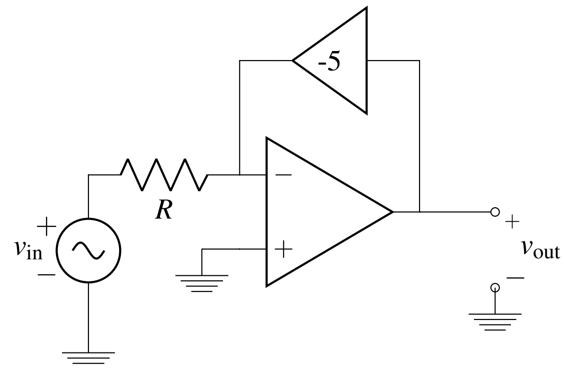
(a) Much of EE16A will have our analysis be restricted to ideal op-amps. However, it is important to know non-ideal behaviors. What are some main differences between ideal and non-ideal op-amps?

(b) If the gain of an operational amplifier/op amp is given by $A \to \infty$, so we can make some assumptions known as the "Golden Rules". What are the "Golden Rules" and when are they applicable?

(c) Determine if the following system is in negative feedback.

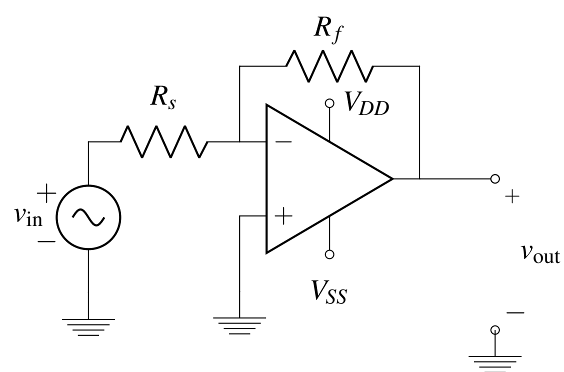


(d) Determine if the following system is in negative feedback.

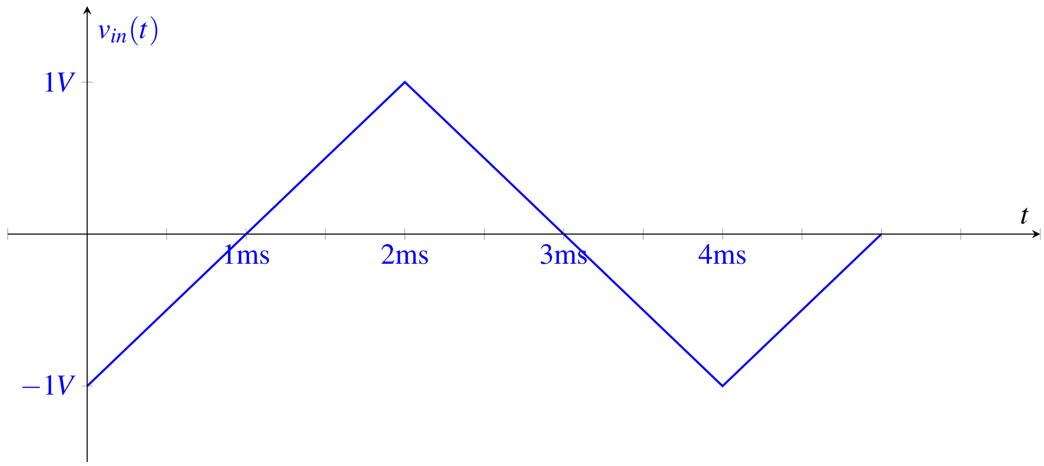


Note: The triangular block with the label "-5" in the figure above represents an amplifier with a factor of -5; In other words, it takes V_{out} as an input from the right side and outputs $-5V_{\text{out}}$ on the left side.

(e) Find the expression of v_{out} for the following circuit:



(f) Plot v_{out} vs. time for the following v_{in}. Assume $V_{DD} = 10\text{V}$, $V_{SS} = -10\text{V}$, $R_s = 100\Omega$, $R_f = 500\Omega$.



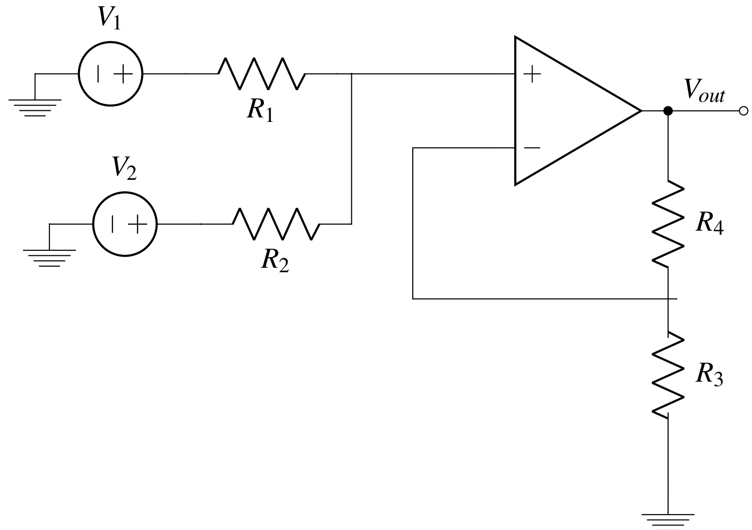
(g) What happens if R_f is changed to $R_f = 2000\Omega$. Plot v_{out} vs. time for the same v_{in}, where $V_{DD} = 10$V, $V_{SS} = -10$V, and $R_s = 100\Omega$.

3. Voltage Summers

Learning Goal: This problem uses basic circuit analysis techniques to find the response of a summer circuit.

Relevant Notes: **Note 19** goes different op-amp circuit topology and corresponding derivations.

(a) Calculate V_{out} in terms of V_1 and V_2. Assume that $R_1 = R_2$. Use superposition.



(b) What values should we select for R_1, R_2, R_3, and R_4 such that $V_{out} = V_1 + 2V_2$?

4. Multi-stage Amplifier

Learning Goal: The objective of this problem is to understand how multiple stages of op-amp circuits can be used to achieve a specific circuit gain.

Relevant Notes: **Note 19 Section 19.5** goes over inverting and non-inverting amplifiers.

(a) What is the range of values that we can scale V_{in} by when using a non-inverting op amp? (What are possible values for the gain?)

(b) What is the range of values that we can scale V_{in} by when using an inverting op amp? (What are the possible values for the gain?)

(c) Can you design a single inverting/ non-inverting amplifier with circuit gain $G = 0.5$? If not, what range of gain values is not reachable using a single inverting op amp or a single non-inverting op amp?

(d) How would you construct a circuit using inverting/ non-inverting amplifiers so that the overall circuit gain is $G = 0.5$?

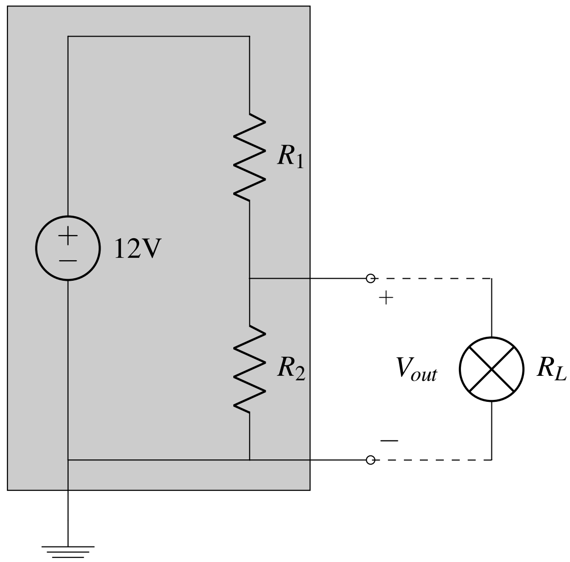
5. Op Amps as Buffers

Learning Goal: This problem helps understand the operating principle of an op-amp buffer and how it helps with loading.

Relevant Notes: **Note 19 Section 19.7** goes different op-amp circuit topology and corresponding derivations.

Now we will revisit a problem that you might have seen before, with our new knowledge of op-amps. We have access to a circuit inside a 'black box' as shown below, with two terminal coming out of it.

(a) We need a voltage of 6V power a light bulb with resistance R_L. Design R_1 and R_2 inside the black box so that the voltage across R_2 is exactly equal to this required voltage **when the bulb is not connected**; i.e. $V_{R_2} = V_{out} = 6$V.



(b) Now let us connect the bulb R_L across R_2. What is the voltage across R_1, R_2 and R_L when the bulb is connected when $R_L = R_2$? Use the values of R_1 and R_2 from the last part. Will the light bulb turn on? What happens if $R_L = 2R_2$?

(c) Using your knowledge of op-amps, how could you resolve this issue of V_{out} changing based on the value of R_L? Think about how you might use an op-amp buffer.

