EECE251

Circuit Analysis I

Set 5: Operational Amplifiers

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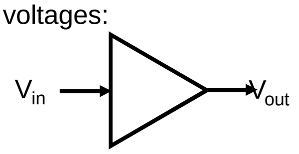
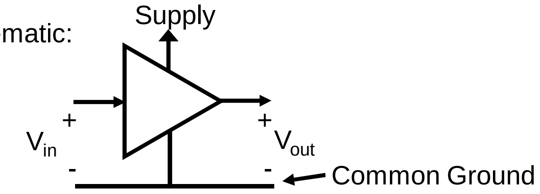
Amplifiers

- There are various types of amplifiers.
- Perhaps the most common type is a voltage amplifier (usually referred to simply as an amplfier!) where both input and output of the amplifier are voltages:

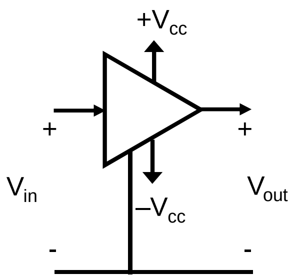


- A bit more realistic schematic:



Amplifiers

- Typically, amplifiers have two supplies: One is positive ($+V_{cc}$) and one is negative ($-V_{cc}$).



Common Reference (Ground)

Saturation

- A practical limitation for amplifiers (at least the ones that we will see in this course) is that the magnitude of their output voltage cannot exceed the supply, that is:

$$-V_{cc} \leq V_{out} \leq +V_{cc}$$

- If the output wants to go beyond the supplies (for example when the input is positive and large) then it will be clipped at $+V_{cc}$:

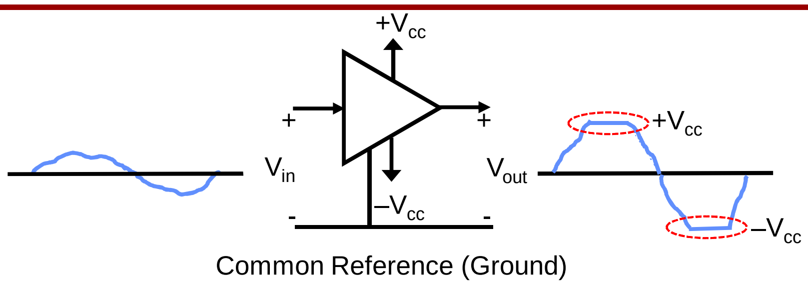
$$V_{out} = +V_{cc}$$

- If the output is so negative then it will be limited by $-V_{cc}$:

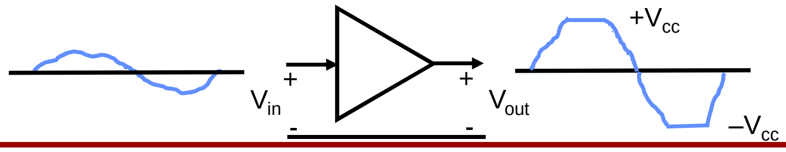
$$V_{out} = -V_{cc}$$

- In these cases we say that the amplifier is saturated

Saturation

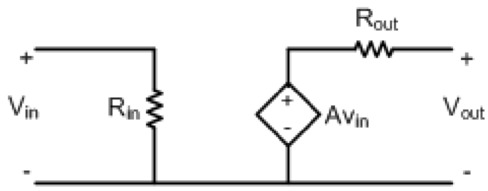


- Often for simplifying the drawings, the supplies and ground connections of the amplifiers will not be explicitly shown



Equivalent Model of a (Voltage) Amplifier

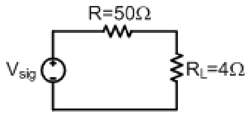
- A voltage amplifier can be modeled with voltage-controlled voltage source:



$$V_{out} = AV_{in}$$

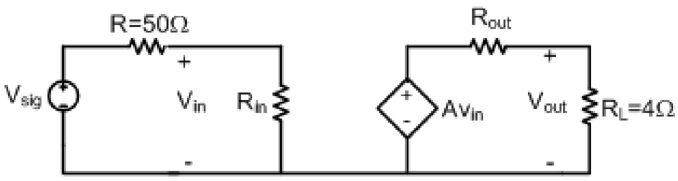
Ideal Amplifier

- What do you think the input and output resistance of an ideal amplifier should be?
- Let's look at a example:
- Let's assume you have a signal source with a 50Ω resistance (its Thevenin equivalent is the signal voltage source in series with a 50Ω) and a load of 4Ω.
- What happens if we naively connect the output of the signal source to the load?

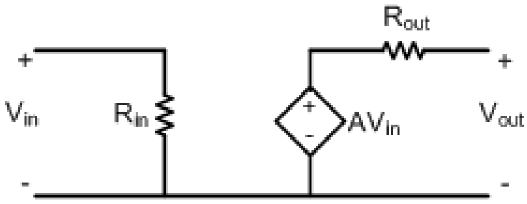


Ideal Amplifier

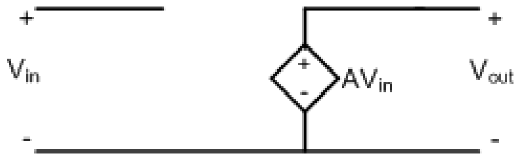
- What if we insert an amplifier between the source and the load.
- In order to maximize the signal at the output can you guess what should be the values for R_{in} and R_{out}?



Ideal Amplifier

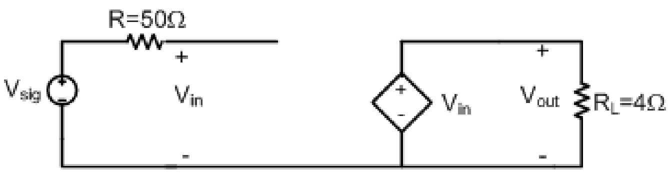


$$R_{in} \rightarrow \infty \text{ and } R_{out} \rightarrow 0$$



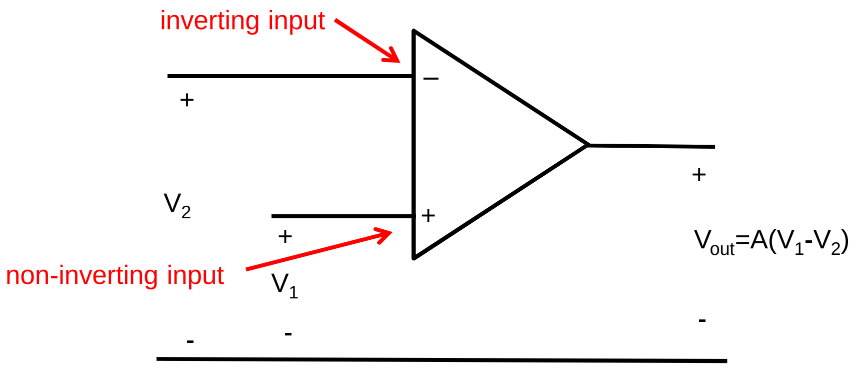
Buffer

- An amplifier with the gain of one is typically referred to as "buffer".
- Buffers are very useful when one wants to "drive" a low resistance with a signal source that has a large series resistance.

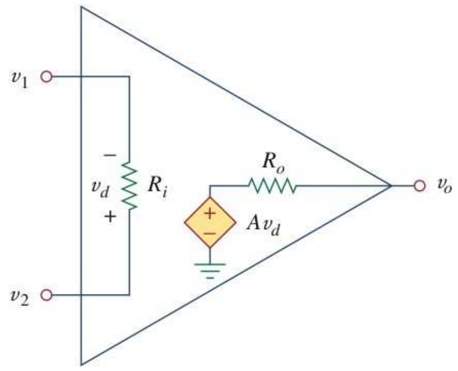


Differential Amplifier

- An amplifier that has two inputs and amplifies the potential difference between its input nodes (that is, it amplifies the difference between the voltages of its two inputs)



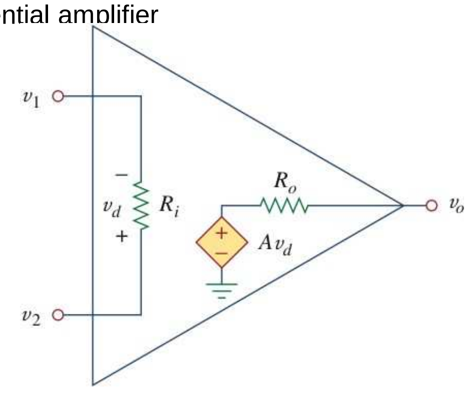
Equivalent Model for a Differential Amplifier



$$v_d = v_2 - v_1 \text{ and } v_o = Av_d = A(v_2 - v_1)$$

Differential Amplifier

For ideal differential amplifier



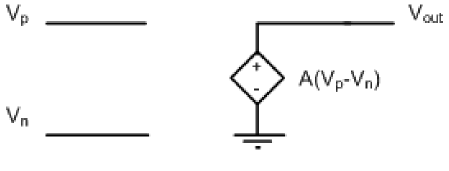
$$R_i \to \infty \;\; and \;\; R_o \to 0$$

Operational Amplifier

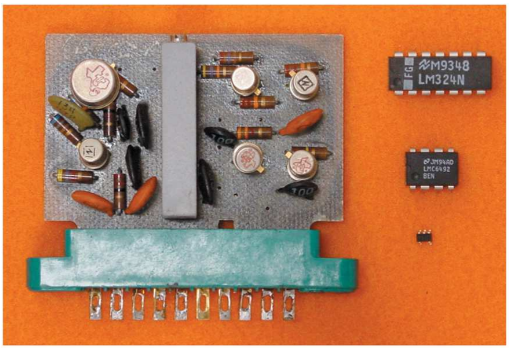
- Operational amplifier (or op amp for short) is a differential amplifier whose gain is very large.
- Ideal op amp is an ideal differential amplifier with infinite gain!

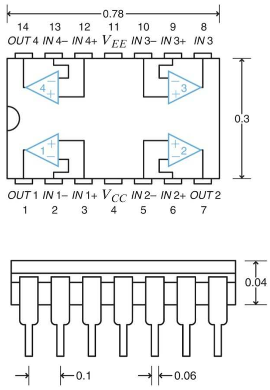
$$With\ R_i \to \infty \;\; and \;\; R_o \to 0$$

$$and\ A \to \infty$$

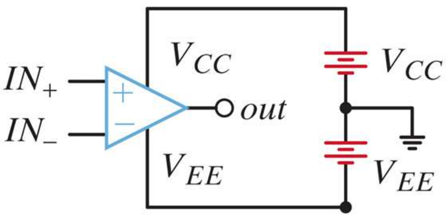


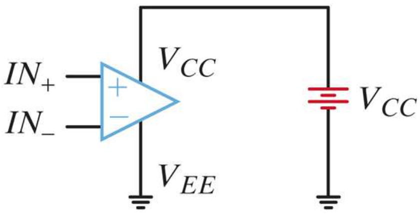
Operational Amplifiers





Operational Amplifiers



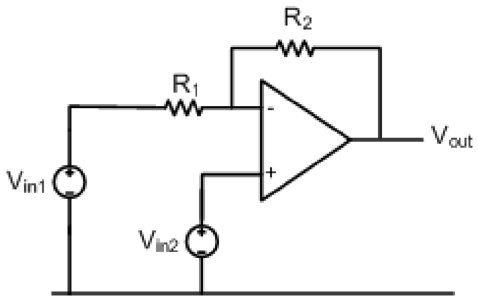


Operational Amplifiers (Op Amps)

- In light of their large gain, op amps are usually used in a negative feedback configuration where their output is somehow (usually through a passive component) is connected to their negative (inverting) input.
- If there is no feedback, what do you expect the output will be?
- In practice, If $V_p > V_n$ then the output will be saturated to the positive supply. Why?
- And, if $V_p < V_n$ then the output will be saturated to the negative supply

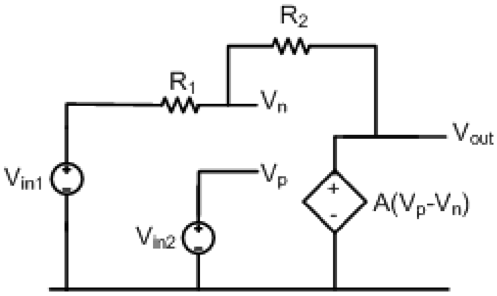
Op Amp

- What is the relationship between V_p and V_n in an op amp with negative feedback?



Op Amp

- What is the relationship between V_p and V_n in an op amp with negative feedback?



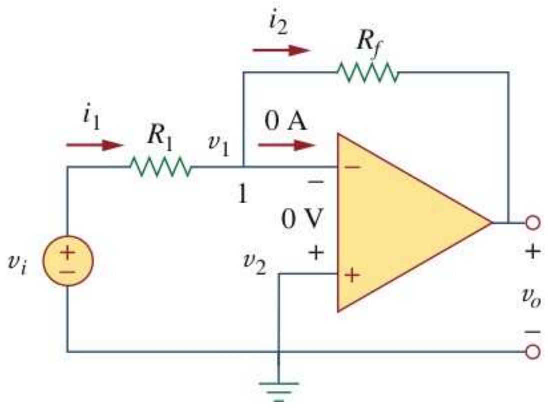
Op Amps

- Op amps were designed to performed mathematical operations such as subtraction, addition, multiplication, division, integration, and differentiation (therefore the name operational amplifier!).
- So let's have a look at how we can perform these operations using op amps.
- Note that in all these cases we should make sure that we have a negative feedback. Why?

Op Amps

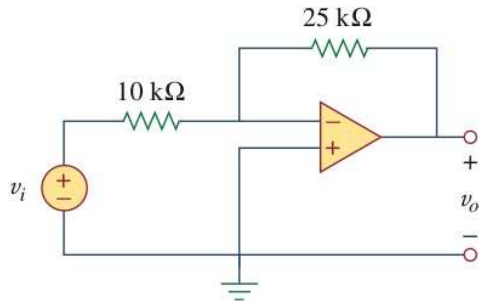
- Strategy to analyze op-amp circuits (assuming ideal op amps):
  - Check to see if there is a negative feedback
    - If so, then use: Vp=Vn. If there is no negative feedback then we can't assume anything about Vp and Vn.
  - Input currents In and Ip are both zero.
  - Apply nodal analysis
  - Solve nodal equations to express output voltage in terms of input signals.

Inverting Amplifier



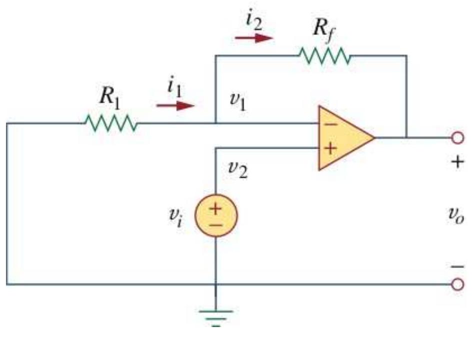
Example

- What is the gain of this circuit, that is, what is v_o/v_i?
- If v_i=0.5V what is the output voltage? What is the current in the 10kΩ resistor?



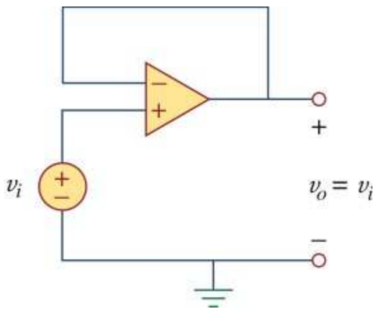
Non-inverting Amplifier

- Find the gain (v_o/v_i) of the following circuit?



Buffer

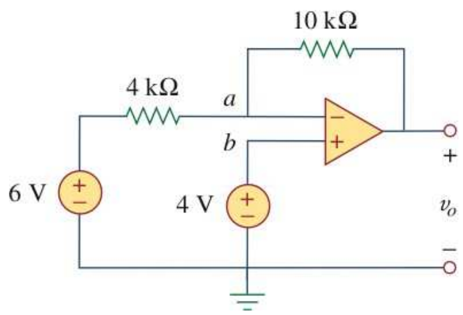
- Also known as *voltage follower* or *unity gain amplifier*



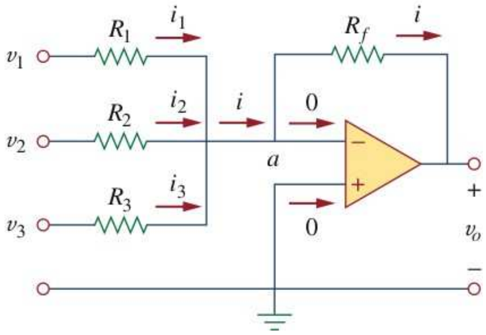
- What is the use of such amplifier?

Example

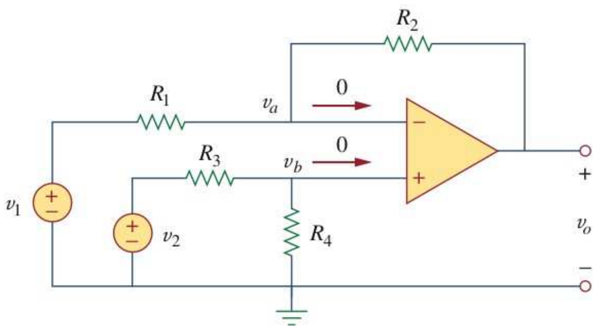
- In the following circuit, find the output voltage.



Summing Amplifier



Difference Amplifier

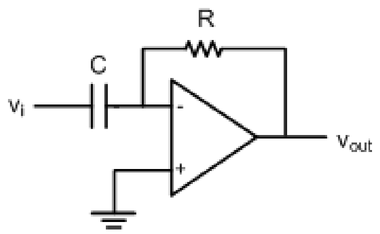


Example

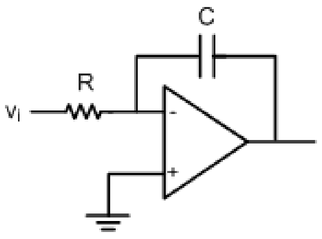
- Design an op amp circuit with inputs v_1 and v_2 such that

$$v_o = -2v_1 + 1.5v_2$$

Differentiator



Integrator

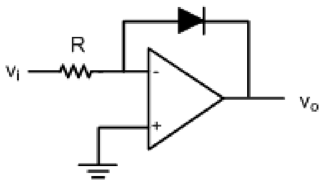


Logarithm!

- Let's assume that for a diode (a component that we will see later) we have

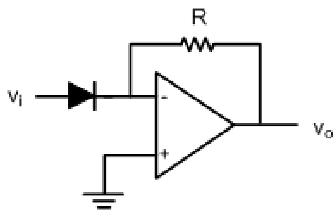
$$i_D \approx I_s e^{\frac{v_D}{V_T}}$$

- In the following circuit, find the relationship between v_o and v_i .



Exponential

- In the following circuit, find the relationship between v_o and v_i .



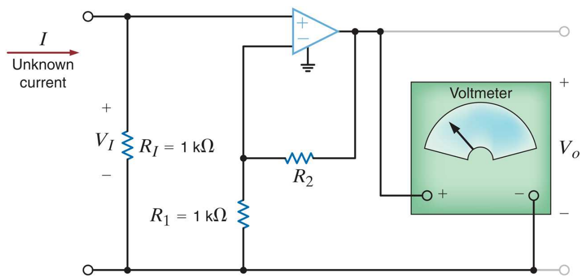
Multiplication and Division

- Can you think of a circuit that can be used to multiply two voltages?

- How about a circuit that can be used to divide two voltages?

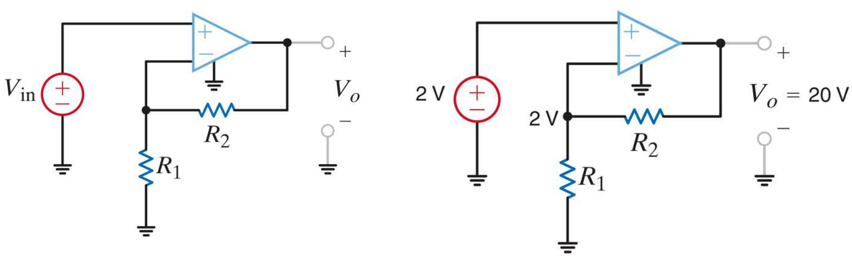
Example

- The following circuit is an electronic ammeter. It operates as follows: the unknown current, I, through R_I produces a voltage, V_I. V_I is amplified by the op-amp to produce a voltage, V_o, which is proportional to I. The output voltage is measured with a simple voltmeter. We want to find the value of R_2 such that 10 V appears at V_o for each milliamp of unknown current.



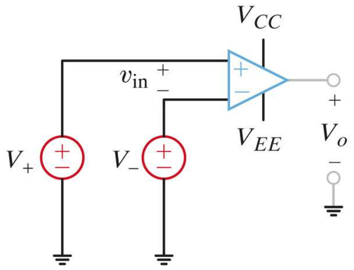
Example

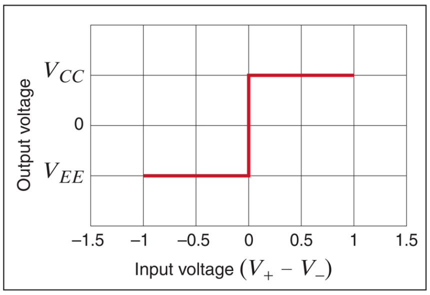
- There is a requirement to design a noninverting op-amp configuration with two resistors under the following conditions: the gain must be +10, the input range is ±2 V, and the total power consumed by the resistors must be less than 100 mW.



Comparators

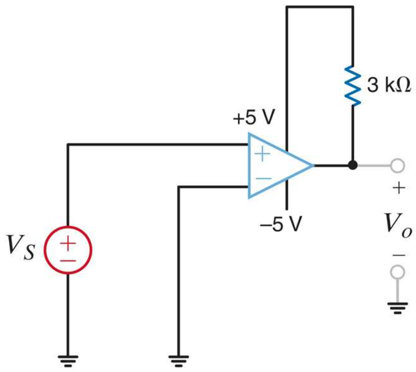
- A comparator, a variant of the op-amp, is designed to compare the non-inverting and inverting input voltages. When the non-inverting input voltage is greater, the output goes as high as possible, at or near V_{CC}. On the other hand, if the inverting input voltage is greater, the output goes as low as possible, at or near V_{EE}.

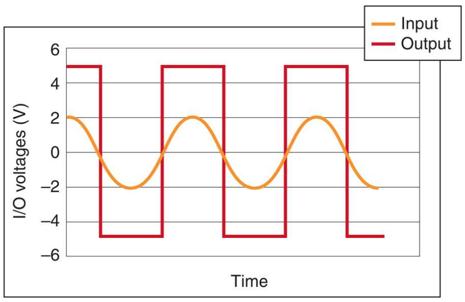




Comparators

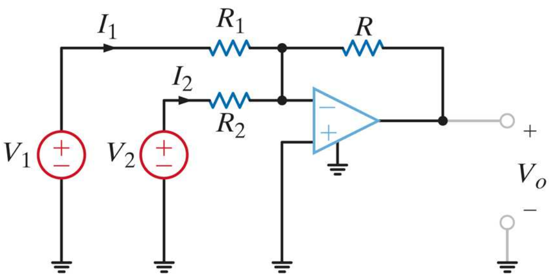
- A common comparator application is the zero-crossing detector, as shown here:





Design Example

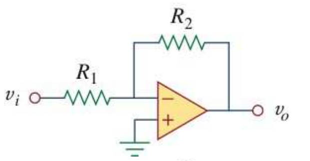
- We wish to design a weighted-summer circuit that will produce the output The design specifications call for use of one op-amp and no more than three resistors. Furthermore, we wish to minimize power while using resistors no larger than 10 kΩ.



Summary

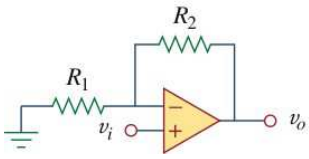
- Inverting amplifier

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



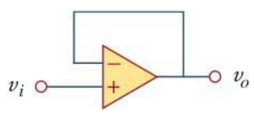
- Non-inverting amplifier

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



- Buffer (voltage follower)

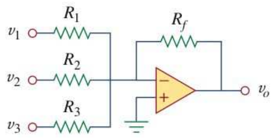
$$v_o = v_i$$



Summary

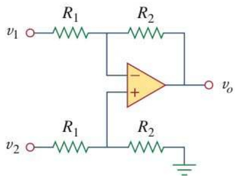
- Summer (adder)

$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$$



- Difference Amplifier

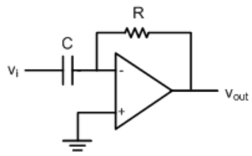
$$v_o = \frac{R_2}{R_1}(v_2 - v_1)$$



Summary

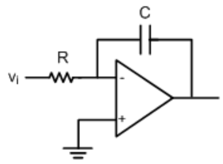
- Differentiator

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



- Integrator

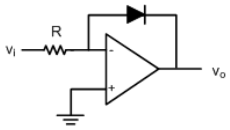
$$v_o = -\frac{1}{RC}\int v_i dt$$



Summary

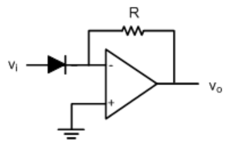
- Taking natural logarithm

$$v_o = -V_T\, ln\left(\frac{v_i}{R \cdot I_s}\right)$$



- Raising to the power of e

$$v_o = -R \cdot I_s e^{\frac{v_i}{V_T}}$$



Instrumentation Amplifier