

Block B Unit 2 Outline

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III. Op Amp Circuits (Part 2)

- Differential amplifier

IV. Op Amp in Real Life

V. Saturation

VI. Cascaded Amplifiers

III. Differential amplifier

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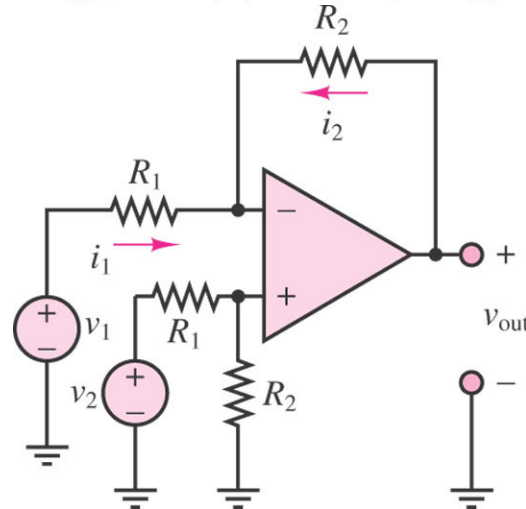


Figure 7 : Differential amplifier

- This circuit is very useful for building instruments that make fine measurements
- A differential amplifier is a device that amplifies the difference between two inputs but rejects any signals common to the two inputs

Analysis of differential amplifier I

- Apply KCL at inverting terminal
- Assuming no current into/out of op amp inverting input (v^-)

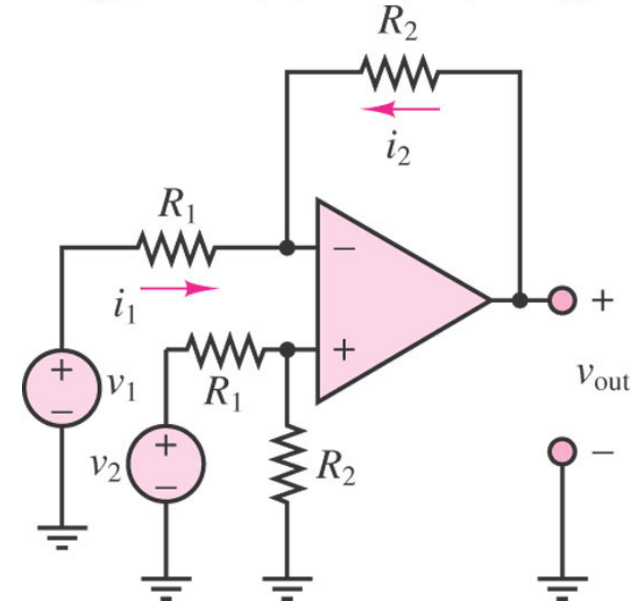
$$i_1 + i_2 = 0$$

$$\rightarrow \frac{v_1 - v^-}{R_1} + \frac{v_{out} - v^-}{R_2} = 0$$

$$\left(\frac{v_1}{R_1} + \frac{v_{out}}{R_2} \right) / \left(\frac{1}{R_1} + \frac{1}{R_2} \right) = v^-$$

$$\left(\frac{R_2}{R_1 + R_2} \right) v_1 + \left(\frac{R_1}{R_1 + R_2} \right) v_{out} = v^- \quad (1)$$

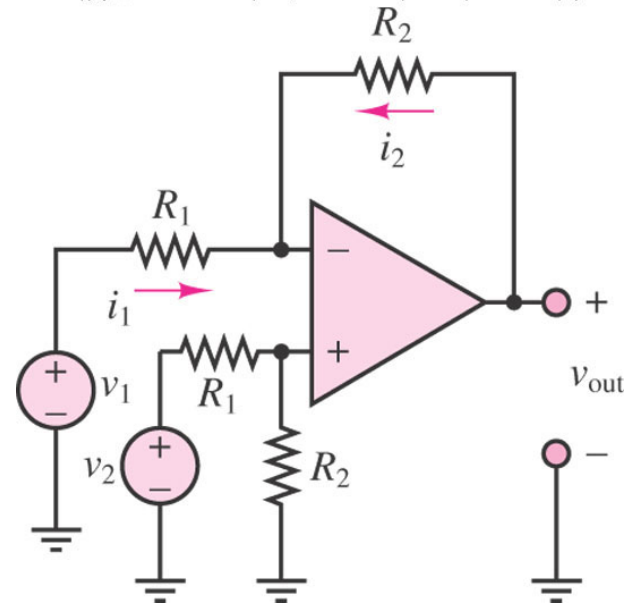
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Analysis of differential amplifier I

- At the non-inverting input (v^+) of op amp:
- Assuming no current into/out of non-inverting input of op amp
 - R_1 and R_2 appear in series
 - Apply voltage divider rule to R_1 and R_2 :

$$v^+ = \left(\frac{R_2}{R_1 + R_2} \right) v_2 \quad (2)$$



Operational amplifier internal circuit

- Finally, assume $v^- = v^+$ due to infinite open loop gain in negative feedback

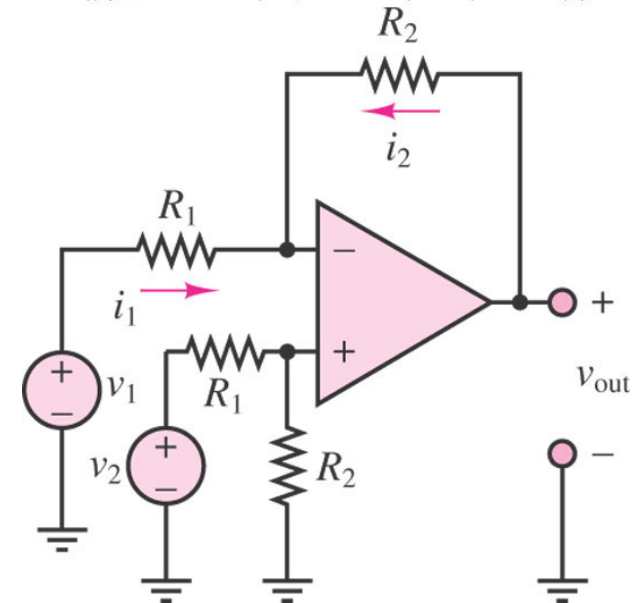
- Combine (1) and (2):

$$\left(\frac{R_2}{R_1 + R_2}\right)v_2 = \left(\frac{R_2}{R_1 + R_2}\right)v_1 + \left(\frac{R_1}{R_1 + R_2}\right)v_{out}$$

$$\left(\frac{R_1}{R_1 + R_2}\right)v_{out} = \left(\frac{R_2}{R_1 + R_2}\right)(v_2 - v_1)$$

$$v_{out} = \left(\frac{R_2}{R_1}\right)(v_2 - v_1)$$

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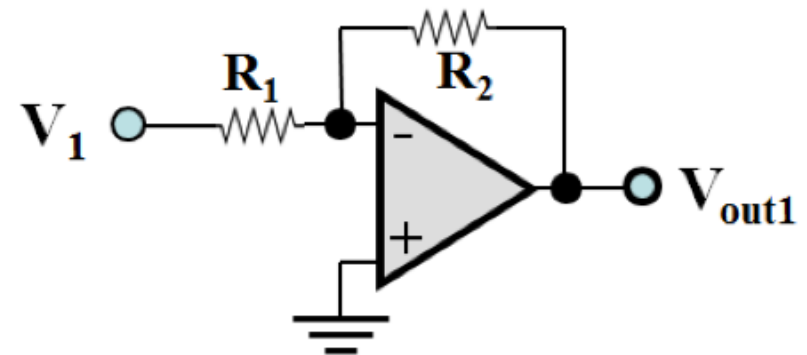
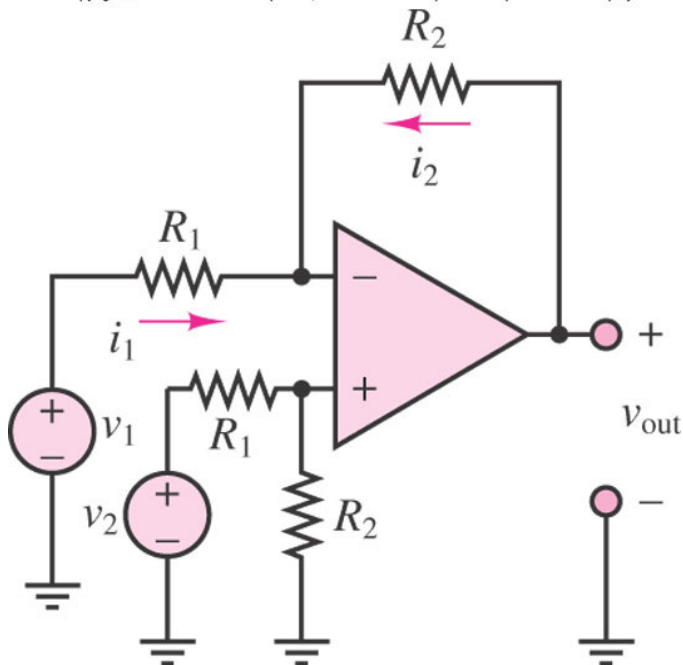
Note that the function of this op amp circuit is to take the difference between two input voltages and amplify them at the output.

Analysis of differential amplifier II

- Using superposition:

Short v_2

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- This is an inverting amp circuit
- Closed loop gain:

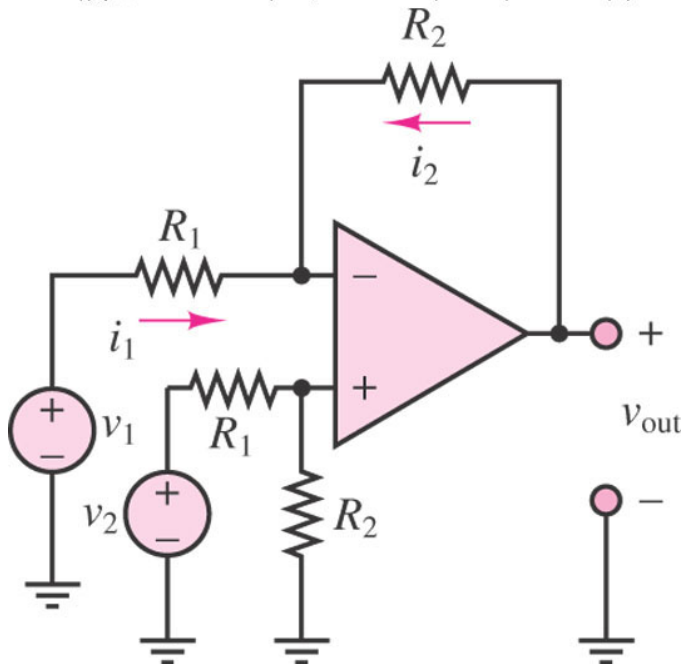
$$V_{out1} = -\frac{R_2}{R_1} V_1$$

Analysis of differential amplifier II

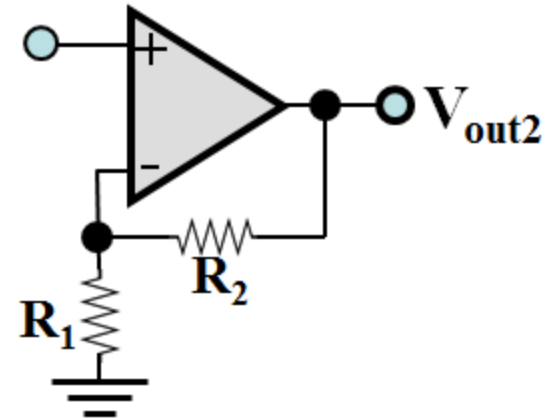
- Using superposition:

Short v_1

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$$\left[\frac{R_2}{R_1 + R_2} \right] V_2$$



- This is a non-inverting amp circuit
- Closed loop gain is $1 + (R_2/R_1)$ with input of $\left[\frac{R_2}{R_1 + R_2} \right] V_2$

$$\begin{aligned} V_{out2} &= \left(1 + \frac{R_2}{R_1} \right) \left(\frac{R_2}{R_1 + R_2} V_2 \right) \\ &= \frac{R_2}{R_1} v_2 \end{aligned}$$

Analysis of differential amplifier II

- Finally, add up the output voltages

$$\rightarrow V_{out} = V_{out1} + V_{out2}$$

$$V_{out1} = -\frac{R_2}{R_1} v_1$$

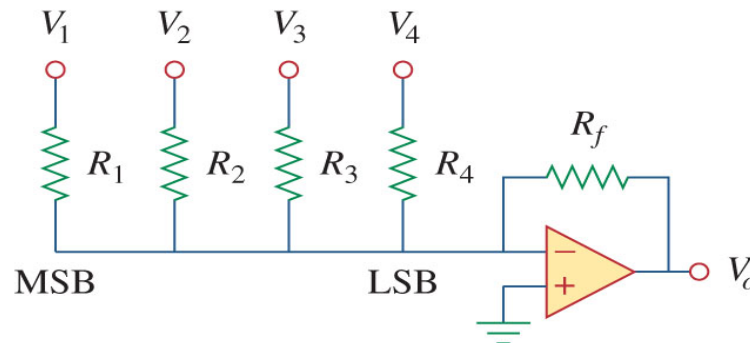
$$V_{out2} = \left(1 + \frac{R_2}{R_1}\right) \left(\frac{R_2}{R_1 + R_2} v_2\right)$$

$$= \frac{R_2}{R_1} v_2$$

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

Application: Digital-to-Analog Converter

- The following is circuit used for transforming digital signals into analog form, i.e. digital-to analog converter (DAC)
- The four-bit DAC is realized in the form of *binary weighted ladder* using the circuit below. The bits are weights according to the magnitude of R_f/R_n , where $R_f/R_1 > R_f/R_2 > R_f/R_3 > R_f/R_4$, such that each lesser bit has half the weight of the next higher bit



- Inputs V1 to V4 represent the most (MSB) to least significant bit (LSB)
- Inputs V1 to V4 can assume only a logic low (0 V) or a logic high (1 V) level

Digital-to-Analog Converter

- The previous circuit is an inverting summing amplifier

$$-V_o = \frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2 + \frac{R_f}{R_3} V_3 + \frac{R_f}{R_4} V_4$$

- Let $R_f = 10 \text{ k}\Omega$, $R_1 = 10 \text{ k}\Omega$, $R_2 = 20 \text{ k}\Omega$, $R_3 = 40 \text{ k}\Omega$, $R_4 = 80 \text{ k}\Omega$, the binary inputs of [0000], [0001], [0010], and [1111] will produce analog outputs of 0 V, 0.125 V, 0.25 V, and 1.875 V.

$$[V_1 V_2 V_3 V_4] = [0000] \\ -V_o =$$

$$[V_1 V_2 V_3 V_4] = [0001] \\ -V_o =$$

$$[V_1 V_2 V_3 V_4] = [0010] \\ -V_o =$$

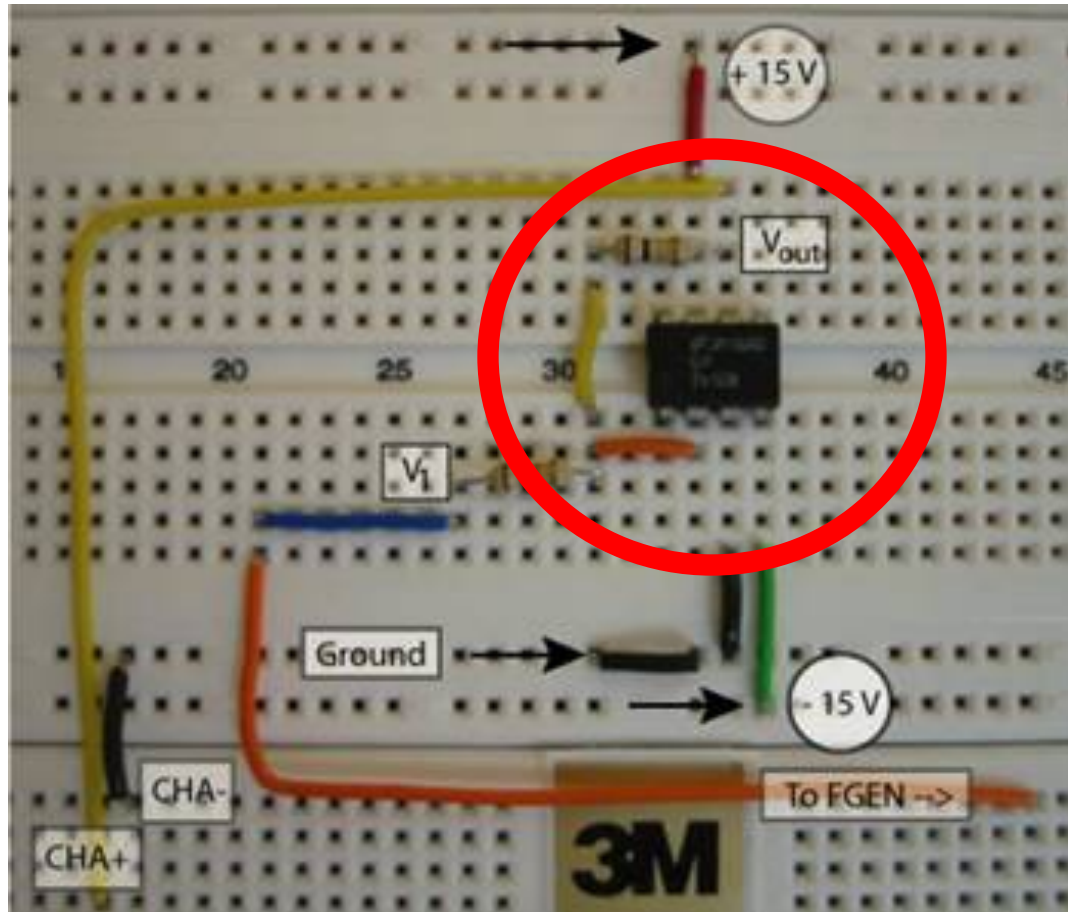
$$[V_1 V_2 V_3 V_4] = [1111] \\ -V_o =$$

Op amp wears different clothes



They come in different shapes and sizes

Op amp connects on breadboard



Op amp specification sheet



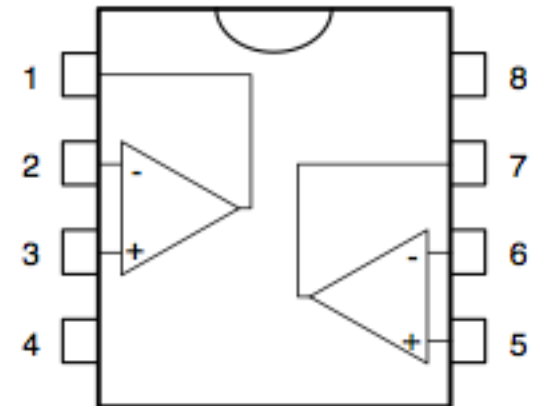
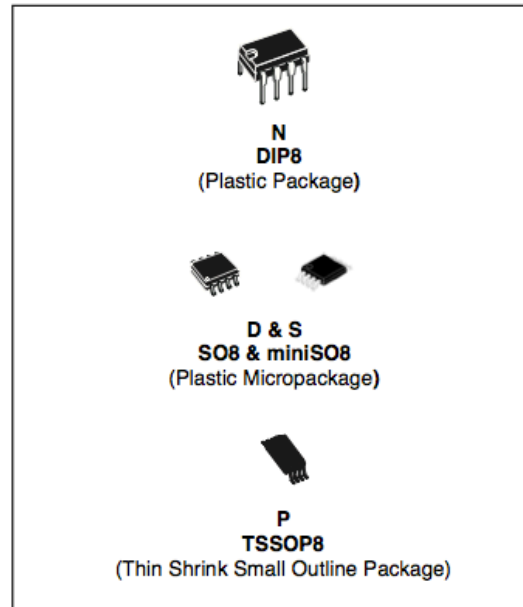
**LM158,A-LM258,A
LM358,A**

LOW POWER DUAL OPERATIONAL AMPLIFIERS

- INTERNALLY FREQUENCY COMPENSATED
- LARGE DC VOLTAGE GAIN: 100dB
- WIDE BANDWIDTH (unity gain): 1.1MHz (temperature compensated)
- VERY LOW SUPPLY CURRENT/OP (500 μ A) ESSENTIALLY INDEPENDENT OF SUPPLY VOLTAGE
- LOW INPUT BIAS CURRENT: 20nA (temperature compensated)
- LOW INPUT OFFSET VOLTAGE: 2mV
- LOW INPUT OFFSET CURRENT: 2nA
- INPUT COMMON-MODE VOLTAGE RANGE INCLUDES GROUND
- DIFFERENTIAL INPUT VOLTAGE RANGE EQUAL TO THE POWER SUPPLY VOLTAGE
- LARGE OUTPUT VOLTAGE SWING 0V TO ($V_{CC} - 1.5V$)

DESCRIPTION

These circuits consist of two independent, high gain, internally frequency compensated which were designed specifically to operate from a single power supply over a wide range of voltages. The low power supply drain is independent of the magnitude of the power supply voltage.



- 1 - Output 1
- 2 - Inverting input
- 3 - Non-inverting input
- 4 - V_{CC}^-
- 5 - Non-inverting input 2
- 6 - Inverting input 2
- 7 - Output 2
- 8 - V_{CC}^+

IV. Op amps in real life

- Op amps are actually electronic chips that are kept in a package. The various terminals of the op amp are then connected to different pins on the package.
- The figure below shows one example:

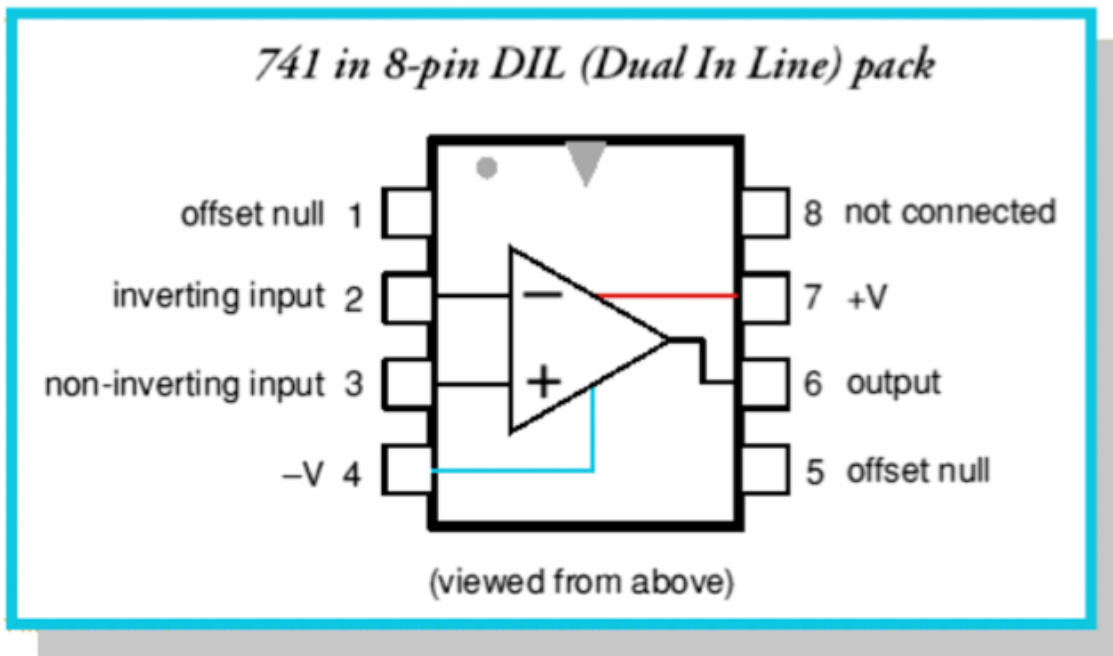


Figure 8: Symbol of an op amp

IV. Op amps in real life

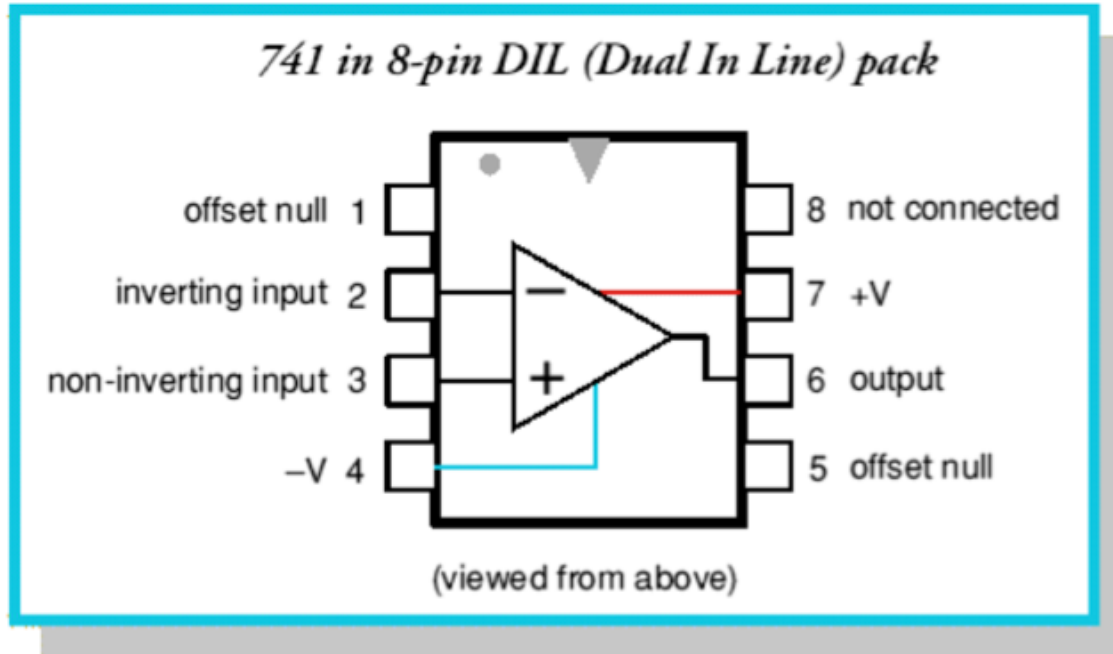


Figure 8: Symbol of an op amp

- One may see that the package has 8 pins, of which only 7 are used (1 pin has no connection – pin 8). To build the circuits mentioned so far, we only need to consider 5 of the pins.
- The pins -V and +V each refer to the negative and the positive supply. For the op amp to work, power needs to be supplied to the -V and +V pins.

Power Supply

- The following figure shows an inverting amplifier with the power supply connections included
- You might realize that we did not consider the power supply pins when deriving expressions for v_{out}

$$G = \frac{V_{out}}{V_S} = -\frac{R_F}{R_S}$$

- In practice, we need to supply power otherwise the op amp will not work and will not get these expressions of V_{out} .
- So what then is the effect of the power supply pins apart from giving power to the op amp for it work?

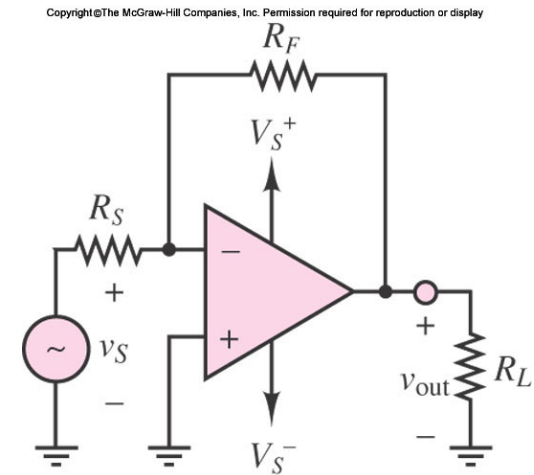


Figure 9: Inverting op amp with power supply

V. Saturation

- From the expression of $V_{\text{out}}/V_{\text{in}}$, you cannot see whether there is a limit on the maximum V_{out} . In a real op amp, V_{out} cannot exceed either of the supply voltages
- Hence if $V_{\text{S}+}$ is 15V and $V_{\text{S}-}$ is -15V, then V_{out} cannot be higher than 15V. It also cannot be lower than -15V

Example on saturation

- You have built an inverting op amp with gain of 10 and you use power supply of 15V to the op amp

Case 1: $V_s = 2V$

If we multiply 2V by -10, V_{out} should be -20V. This is lower than the negative supply. So V_{out} will be -15V. In the labs, you will find that the minimum V_{out} does not even reach V_s^- .

Case 2: $V_s = -2V$

If we multiply -2V by -10, V_{out} should be +20V. This is higher than the positive supply. Thus V_{out} will be +15V. In the labs, you will find that the maximum V_{out} does not even reach V_s^+ .

Example on saturation

Case 3: $V_s = 2 \sin(2000t)$ V

When V_{out} reaches V_{s+} or V_{s-} , the output gets chopped off.

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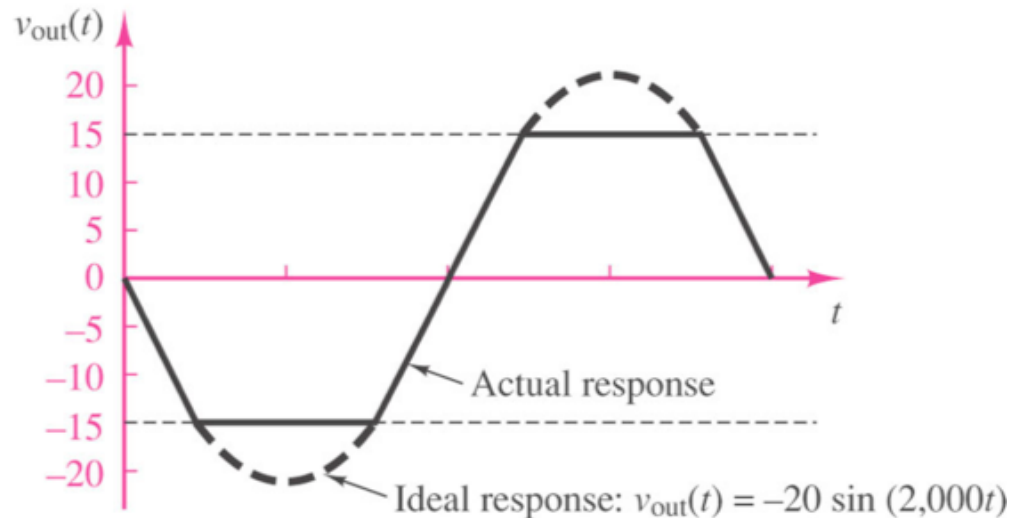


Figure 10. Saturated output

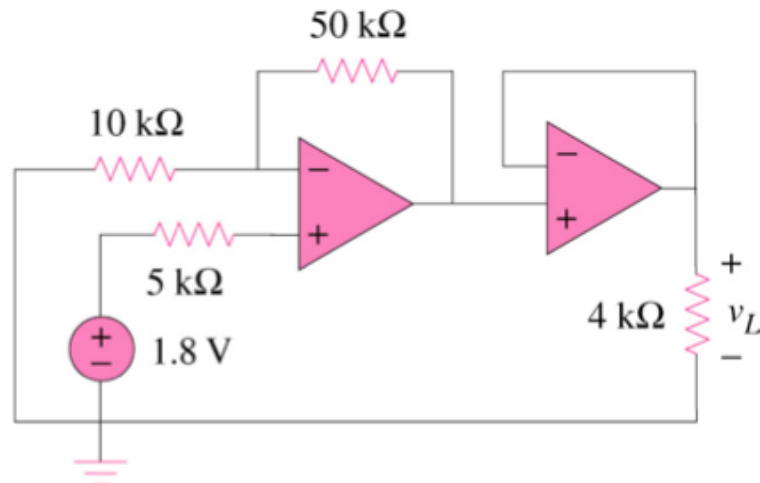
Op amps are only capable of amplifying signals within the range of their supply voltages.

The output cannot exceed the supply voltages while the input is also capped by the supply voltages.

VI. Cascaded amplifiers 1

Identify the types of amplifiers in the circuit below. Find v_L .

Answer: $v_L = 10.8\text{V}$



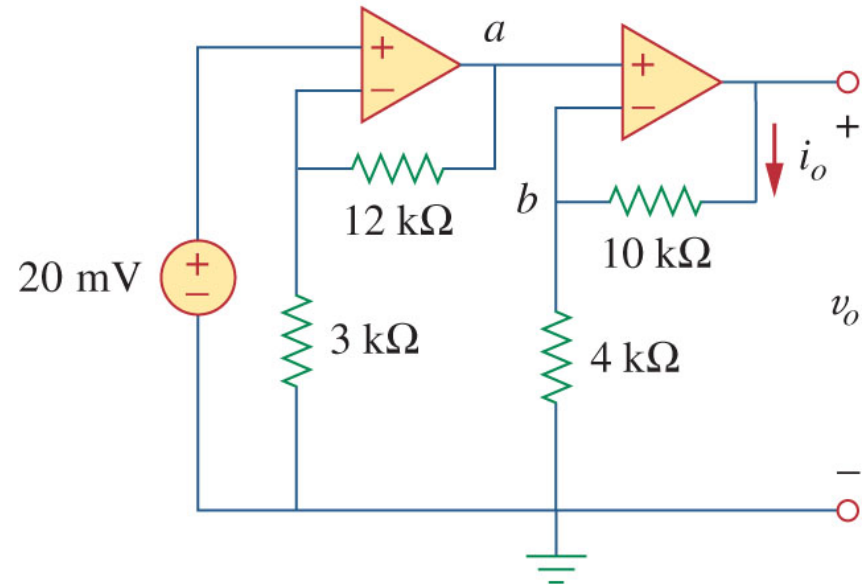
First stage: Non-inverting amp
Second stage: Source follower

Cascaded amplifiers 2

Find v_o and i_o in the circuit.

$(v_o = 350 \text{ mV}, i_o = 25 \text{ } \mu\text{A})$

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Summary

- (1) Remember the 3 characteristics of an ideal op amp
- (2) The output voltage is limited by the power supply
- (3) Op amps can be cascaded and combined