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 Amplifiers

Jasmine Banks (2020)

Recommended Readings:

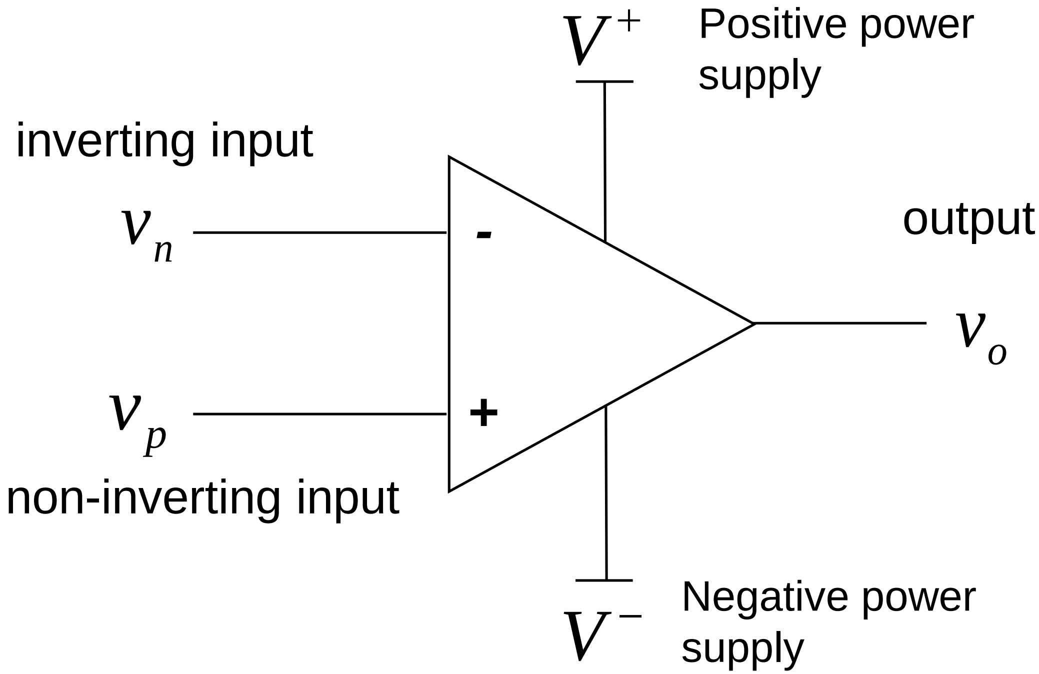
Hambley: Chapter 14, Horowitz and Hill: Chapter 4

Operational Amplifiers

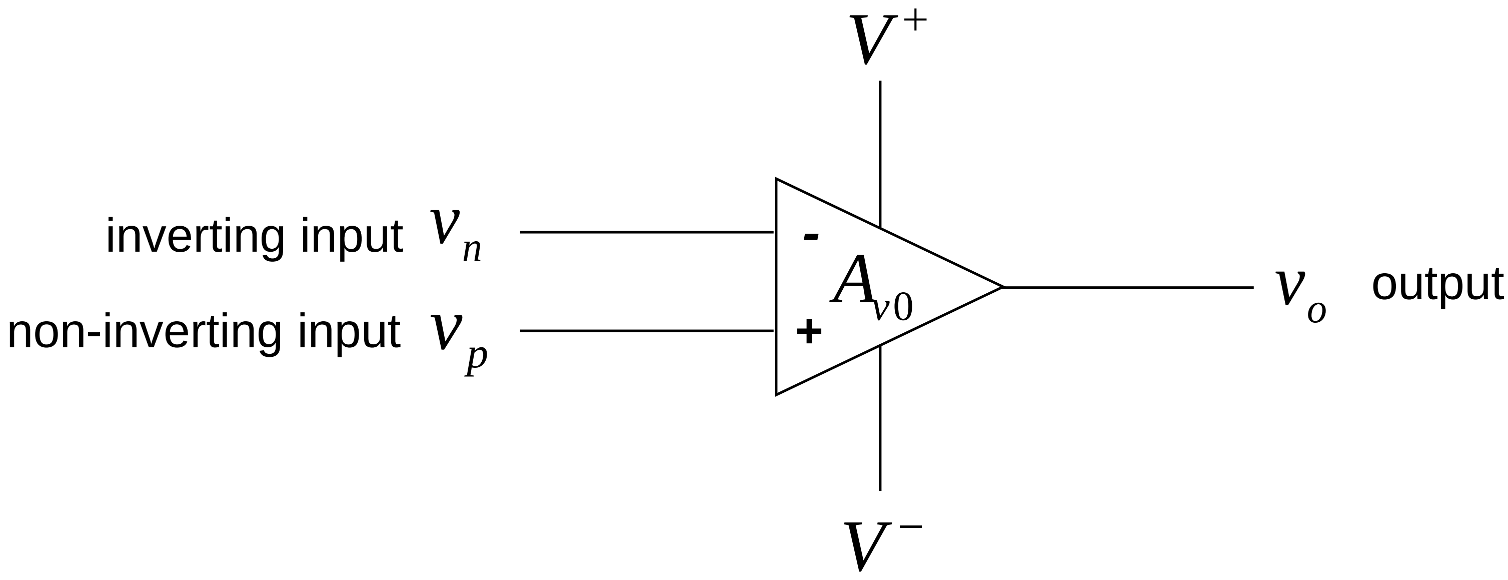
- An *operational amplifier* or *op amp* consists of ~20–30 transistors (BJTs or FETs), and a few resistors and capacitors, on a single IC.
- Op-amps have a wide range of general purpose applications.
- The term "Operational Amplifier" comes from the original application of the device in circuits to perform mathematical operations such as addition, subtraction, differentiation and integration.

Operational Amplifiers

- Terminals:



Operational Amplifiers



- differential input voltage:

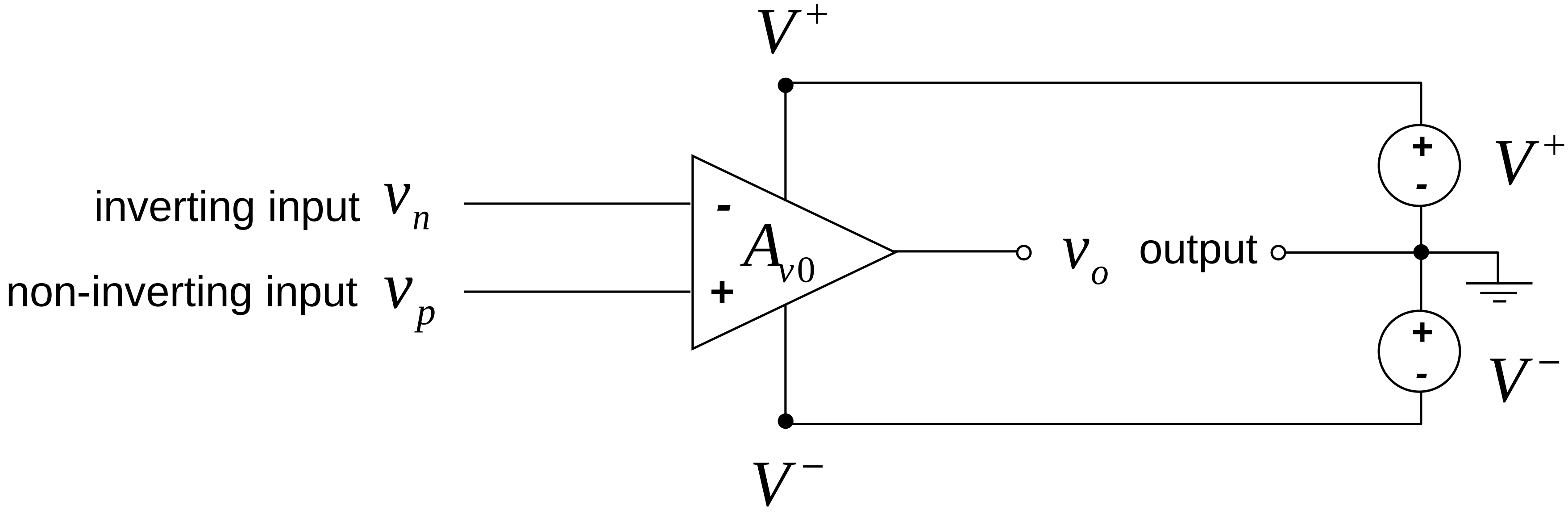
$$v_d = v_p - v_n$$

- output voltage:

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

where A_{v0} = open loop voltage gain
(typically 10^5 – 10^8 V/V at DC – ideally infinite)

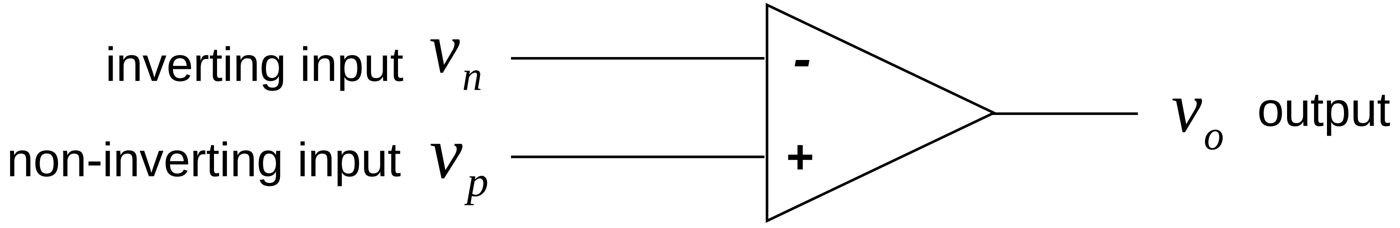
Operational Amplifiers



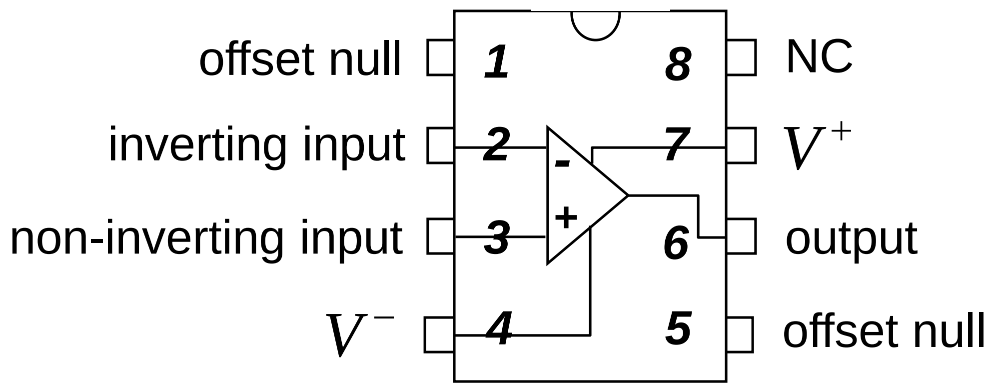
- Operational amplifiers are *active* devices.
- An op amp requires a DC power supply (V^+ and V^-), to bias internal transistors.

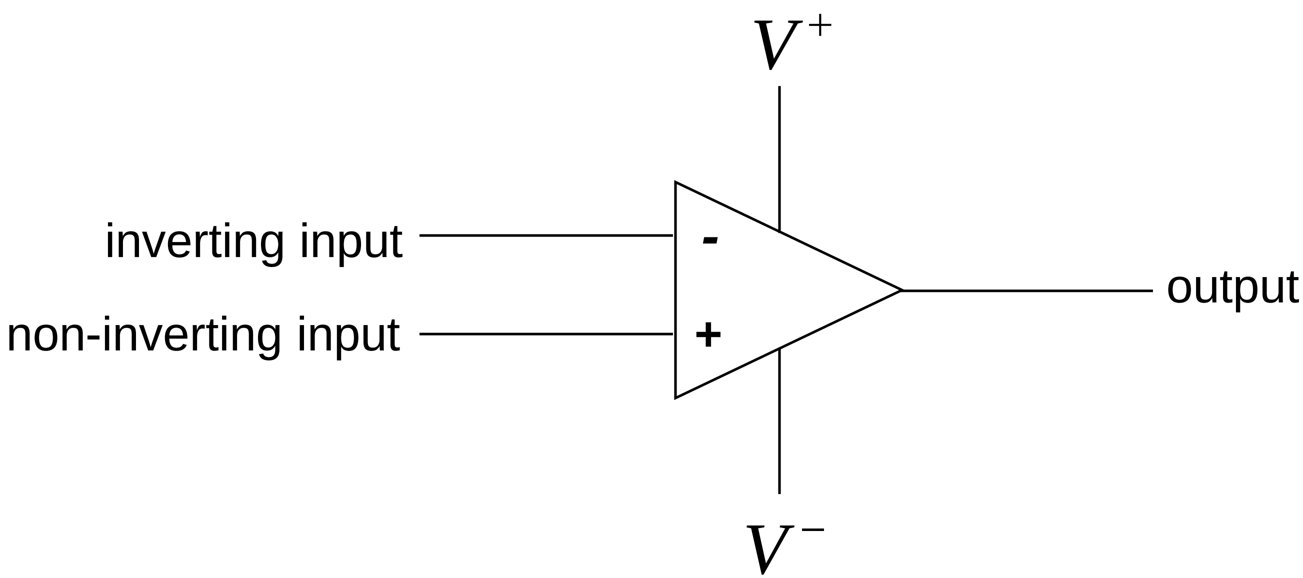
Operational Amplifiers

- Power supply connections are often not explicitly shown in circuit diagrams, to reduce clutter. However, we must remember that the power supply terminals are always connected in a real circuit.



Operational Amplifiers

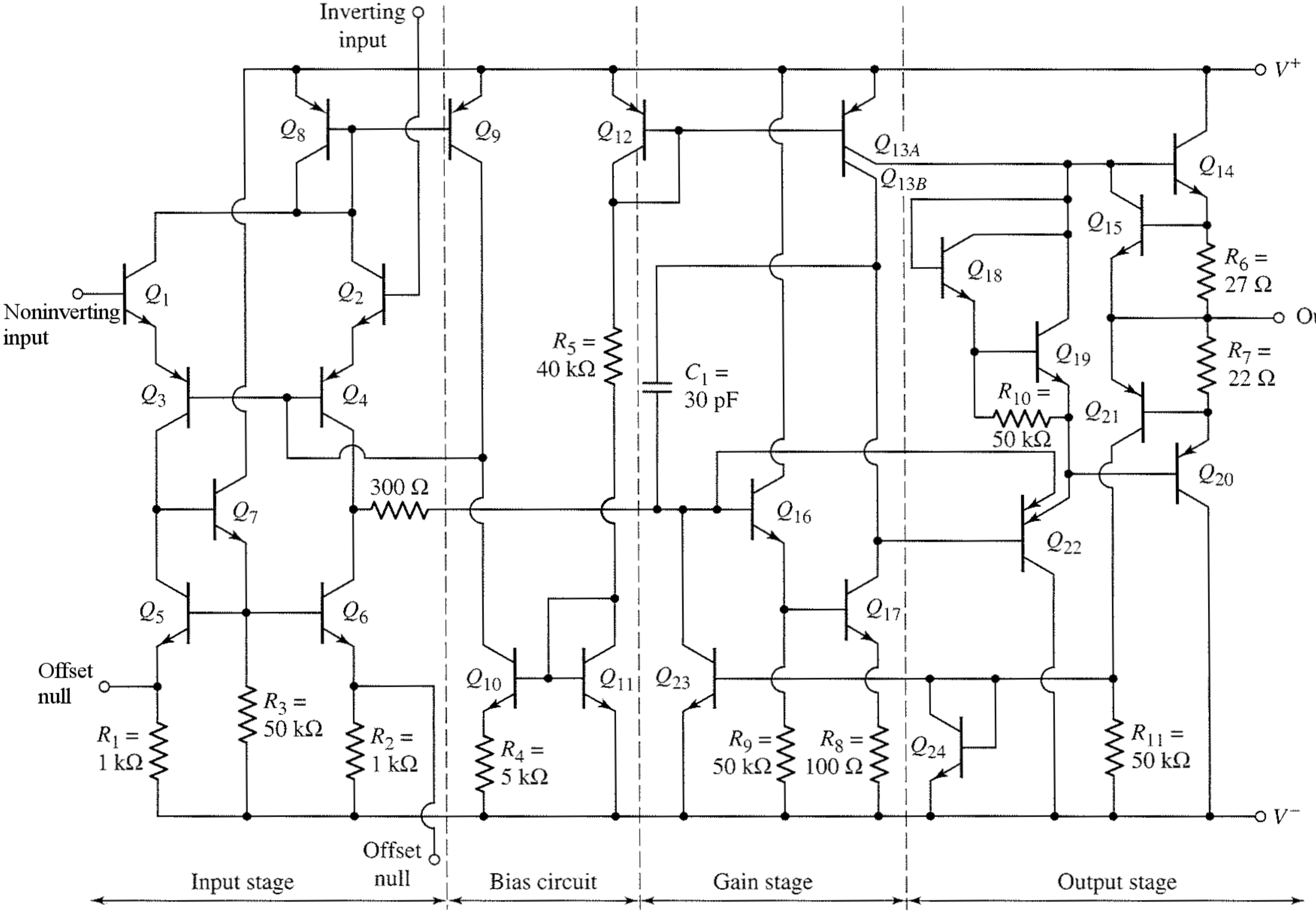




Operational Amplifiers

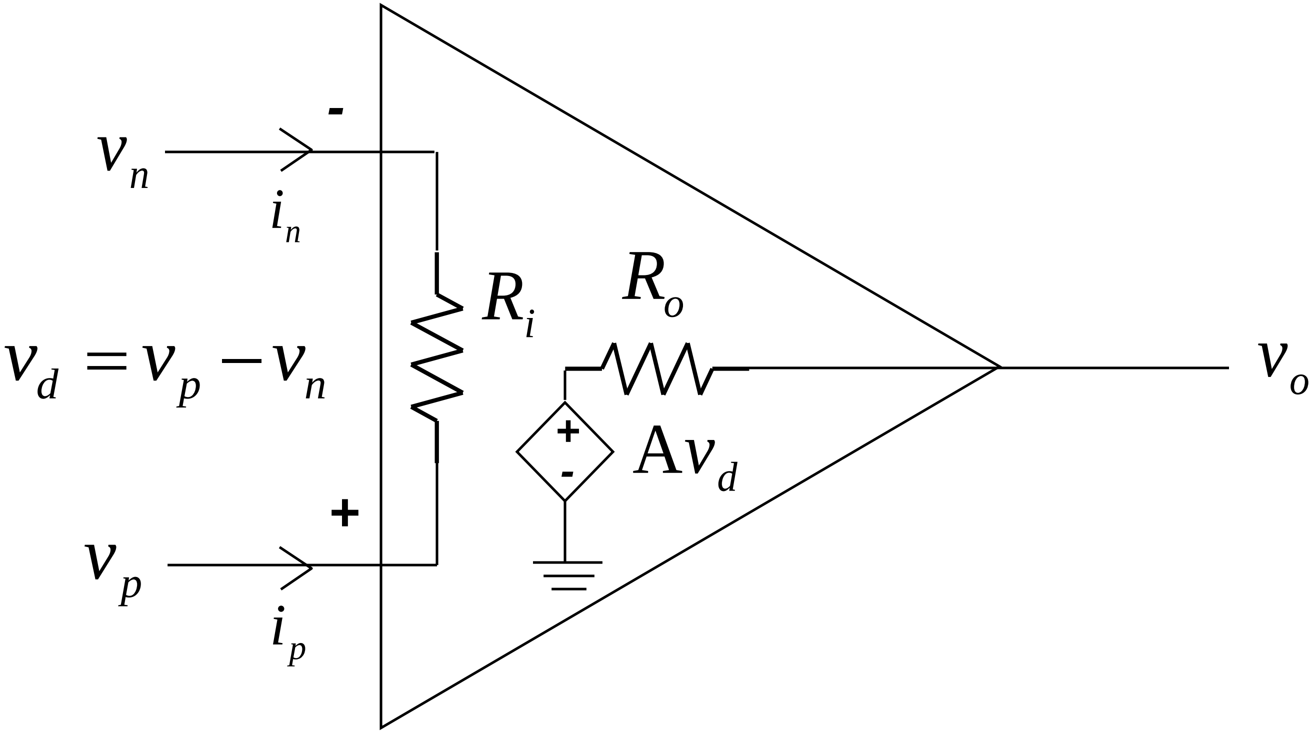
- Although we can think of an op amp as a single electronic device, internally it can consist of ~20-30 transistors (see μA741 circuit on the next page)

Operational Amplifiers



Schematic of the 741 Op Amp (Neamen, 3rd edition, p947).

Op Amp Equivalent Circuit

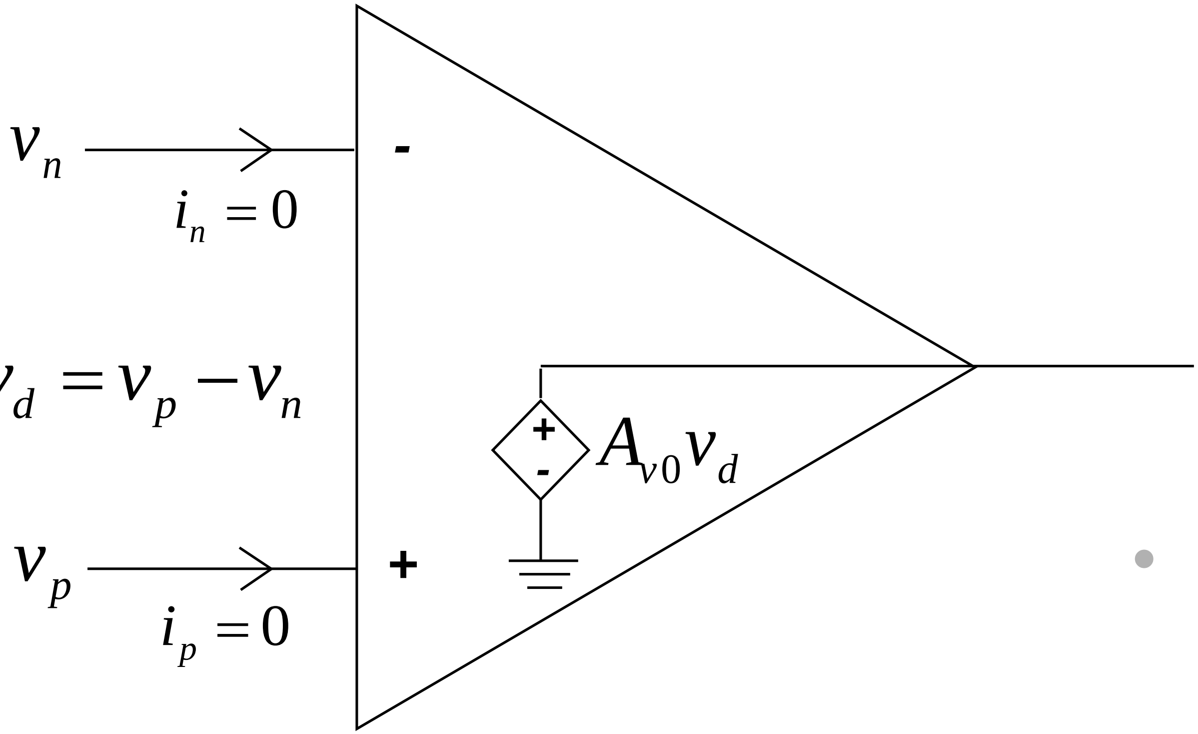


R_i = input resistance (typically 10^5 – $10^{13}\Omega$)

R_o = output resistance (typically 10 – 100Ω)

In and ip are small (μA for BJT or pA for FET op amps)

Ideal Op Amp



$$v_d = v_p - v_n$$

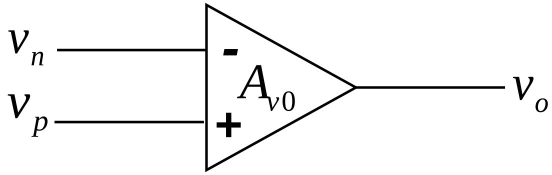
$$v_o = A_{v0}(v_p - v_n)$$

- If $v_p > v_n$:
  v_o driven high
- If $v_n > v_p$:
  v_o driven low

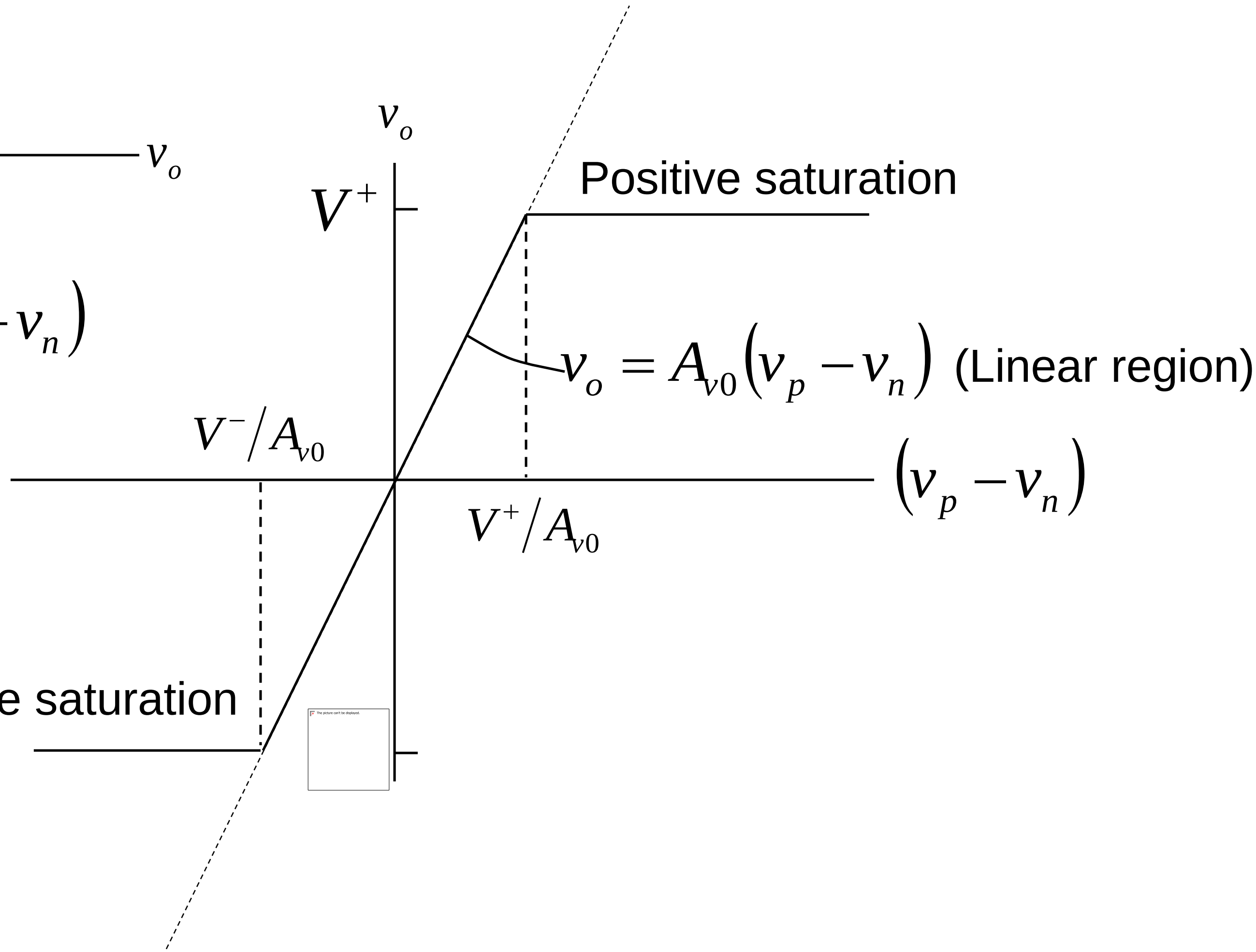
$$R_i = \infty, R_o = \infty$$
$$\mathrm{A} = \infty$$

Open Loop Behaviour

Non-ideal Op Amp, ie, A_{v0} is finite



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

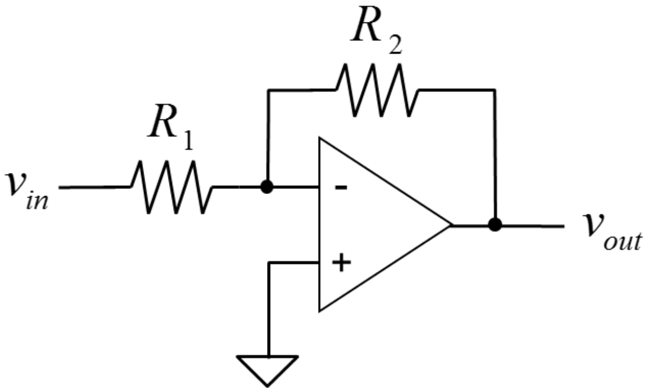


Closed Loop Mode

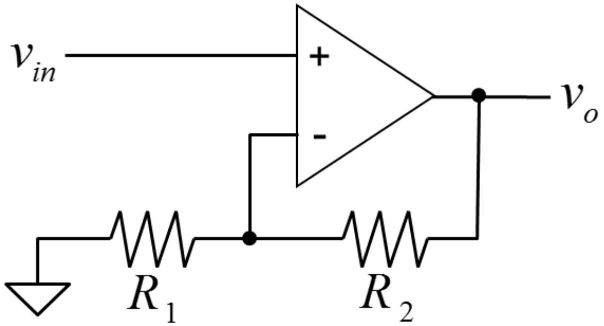
- In *closed loop* operation, a signal proportional to the output is connected back to one of the inputs.
- This is called *feedback*.

Negative Feedback

- In Negative feedback, a signal proportional to the output is connected to the *inverting* input terminal.
-
- Negative feedback circuits:



inverting amplifier



non-inverting amplifier

unity gain follower or buffer

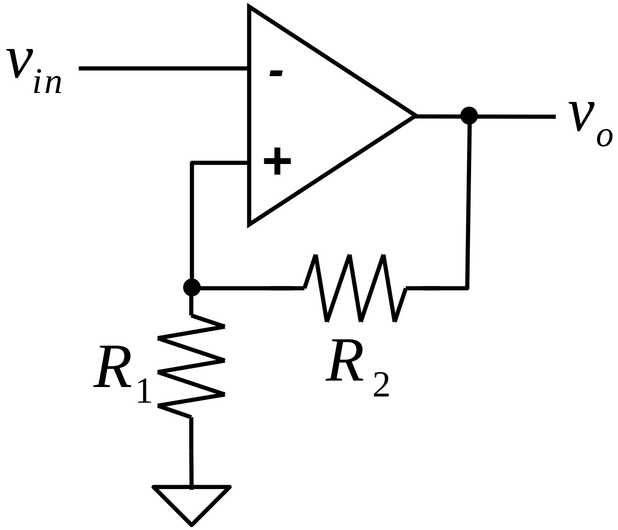
Negative Feedback

- In Negative feedback, a signal proportional to the output is connected to the *inverting* input terminal.
- This forces the difference between the inputs $v_p - v_n$ to be almost zero.
- This effect where the op amp inputs are almost equal is is called the ***virtual short condition***, i.e.:

$$v_n = v_p$$

Positive Feedback

- In Positive feedback, a signal proportional to the output is connected to the *non-inverting* input terminal.
- The effect is that the difference between the inputs becomes larger and the output reaches the positive saturation or the negative saturation value.
- Applications include the Schmitt trigger, square wave generator and pulse generator that will be discussed later.



Schmitt Trigger

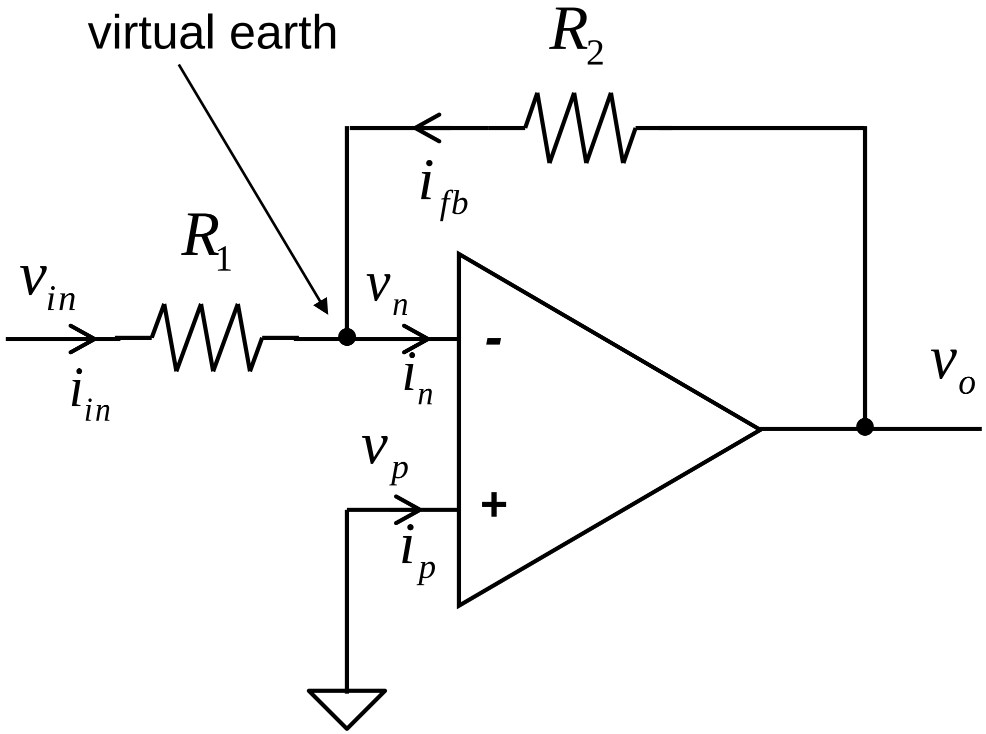
Golden Rules

- “Golden Rules” of Op Amps with negative feedback:
  I. The output attempts to do whatever is necessary to make the voltage difference between the inputs zero.
  II. The inputs draw no current.

Cautions

- The "Golden Rules" do not apply if the op amp output is saturated at one of the supply rails.
- Need a feedback loop at DC or op amp will saturate.
- Some op amps have only a small maximum differential input voltage limit, $v_d = v_p - v_n$.
- Need bypass capacitors (eg, 1μF) on the op amp supply rails, since inductances in the supply rails can lead to instabilities in the amplifiers.

Inverting Amplifier



From Kirchhoff's Current Law, and Golden Rule II:

From Golden Rule I: $v_n = 0$

Inverting Amplifier

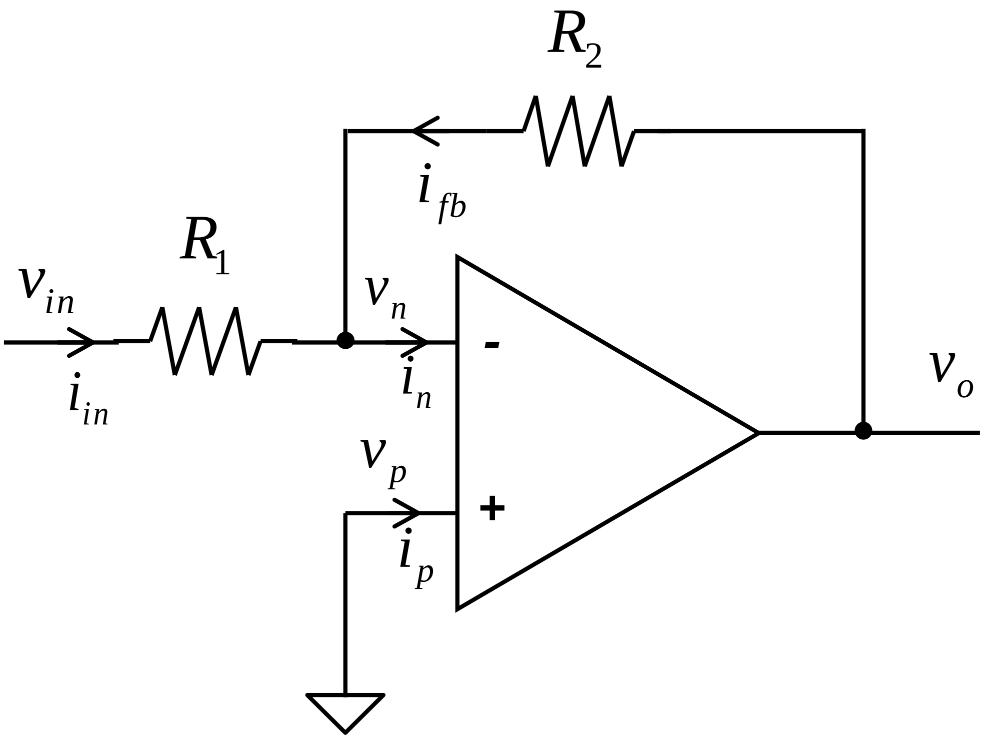
- Negative feedback tends to make the inputs v_n and v_p equal.

- If v_p is incrementally greater than the v_n, output v_o will tend to be driven positive. If v_n is incrementally greater than the v_p, output v_o will tend to be driven negative.

- However the feedback through the R_2/R_1 voltage divider will cause v_o to be held at a value such that $v_n = v_p$.

Inverting Amplifier

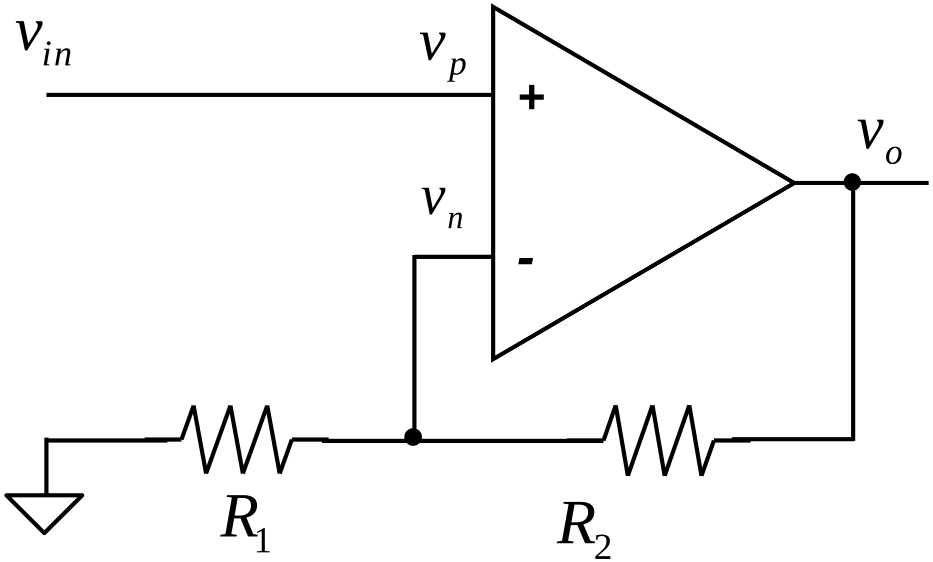
- Example 1: Design an Op Amp circuit with a voltage gain of –10.



Inverting Amplifier

- Values of resistors:
  - Theoretically, any resistor values that work out to give the gain we need would be OK.
  - Very small resistors (eg, 1Ω), are not practical because large currents would have to be supplied by the op amp. Currents of a few mA are usually acceptable.
  - Very large resistors (eg, 10MΩ), also present problems, their values can be unstable, input bias current can result in large offset voltages, and they are susceptible to pick up unwanted noise through stray capacitive coupling)
  - Generally, resistance values of 100 Ω – 1MΩ are suitable for most op amp circuits.

Non-inverting Amplifier

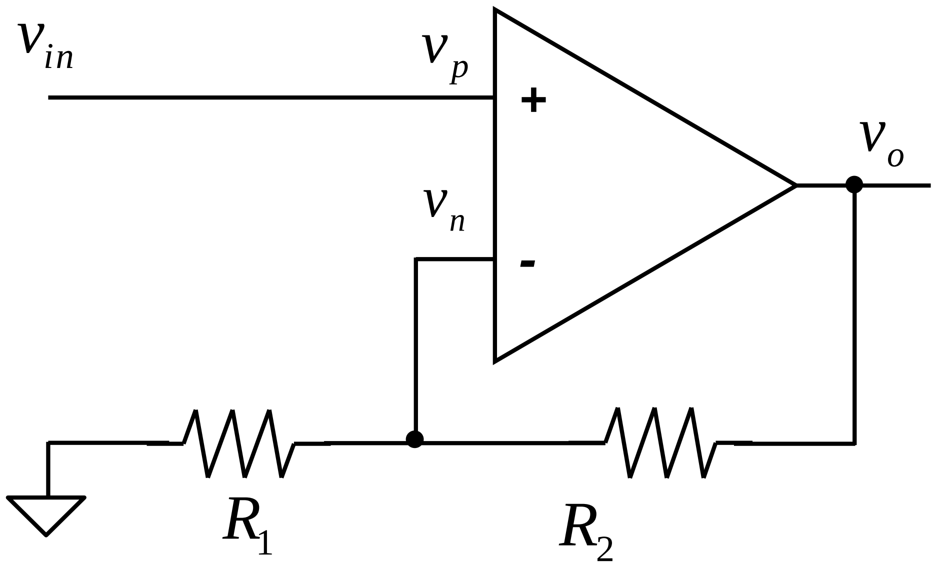


From the voltage divider rule:

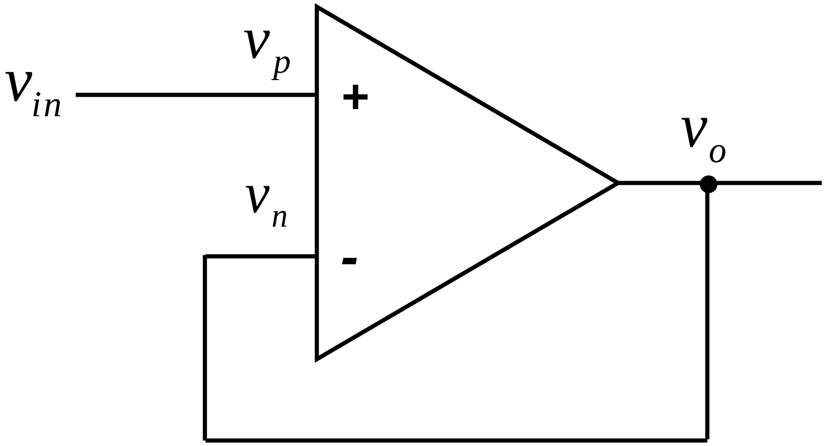
Since $v_{in} = v_p$, from Golden Rule I:

Non-inverting Amplifier

Example 2: Design an Op Amp circuit with a voltage gain of 10.



Unity Gain Follower



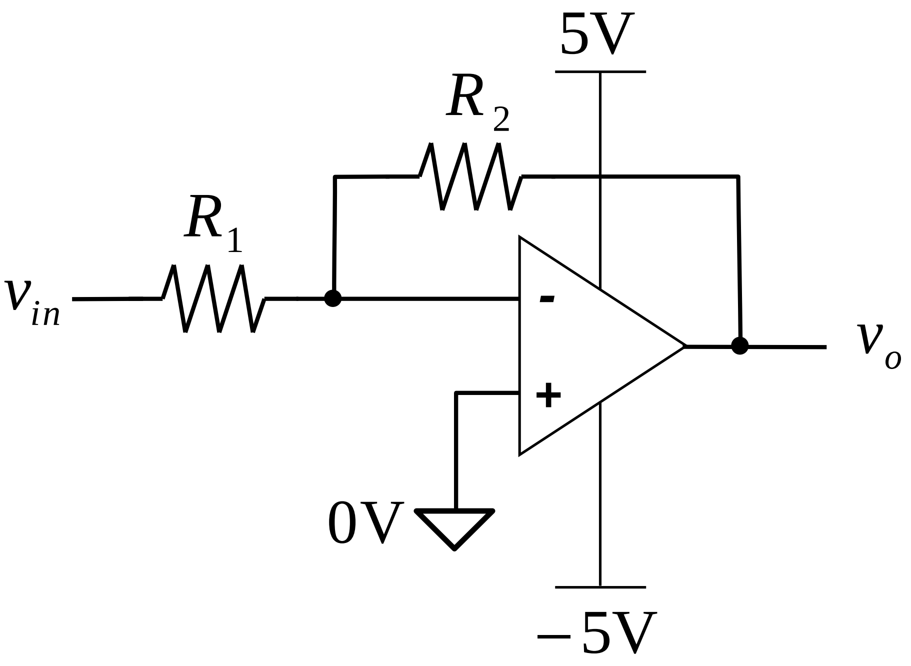
Since $v_{in} = v_p$ and $v_o = v_n$, from Golden Rule I:

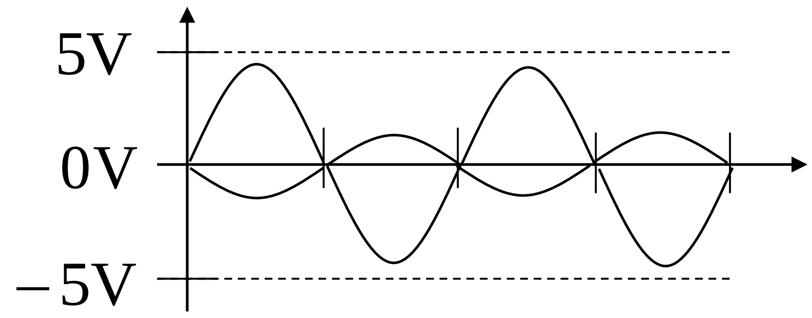
$$v_o = v_{in}$$

$$\boxed{G_v = \frac{v_o}{v_{in}} = 1}$$

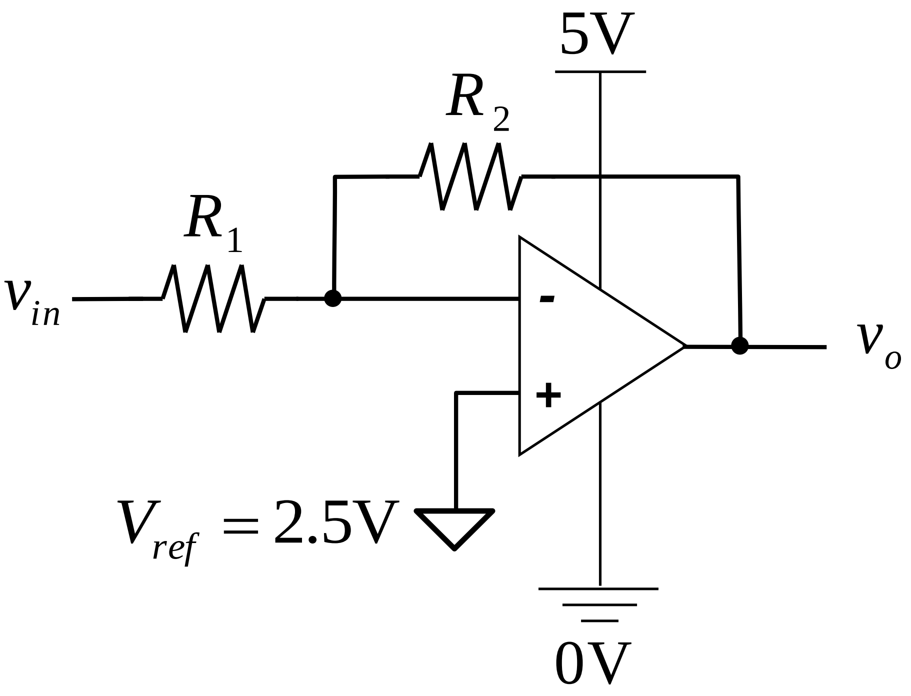
- Used as a buffer because of its isolating properties (high input impedance, low output impedance)

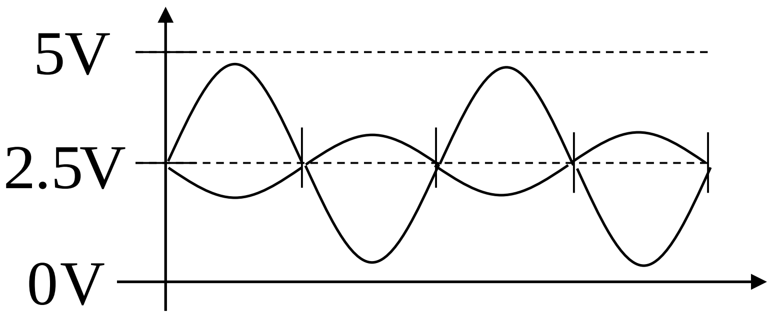
Split Supply Op Amp



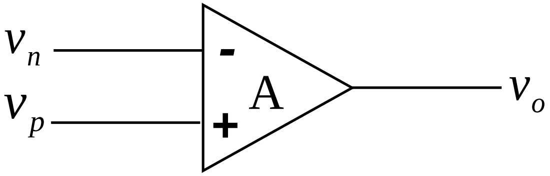


Single Supply Op Amp

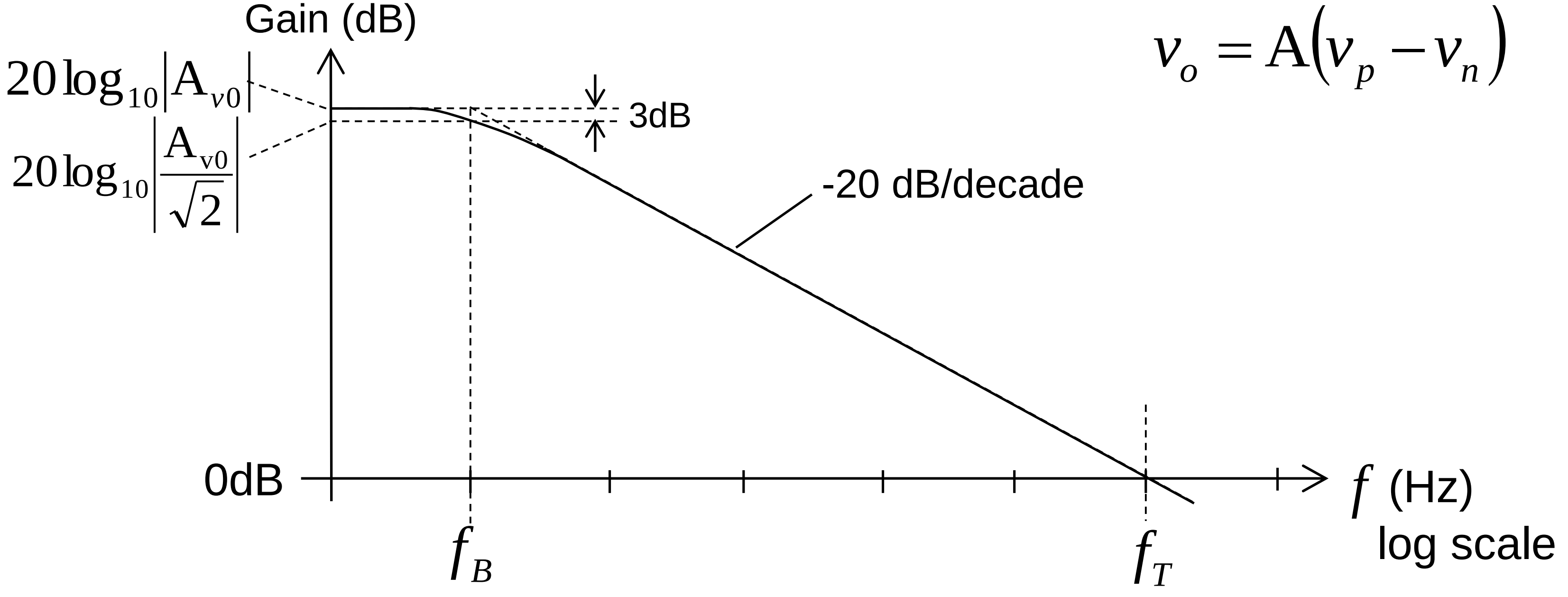




Op Amp Frequency Response – Open Loop



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

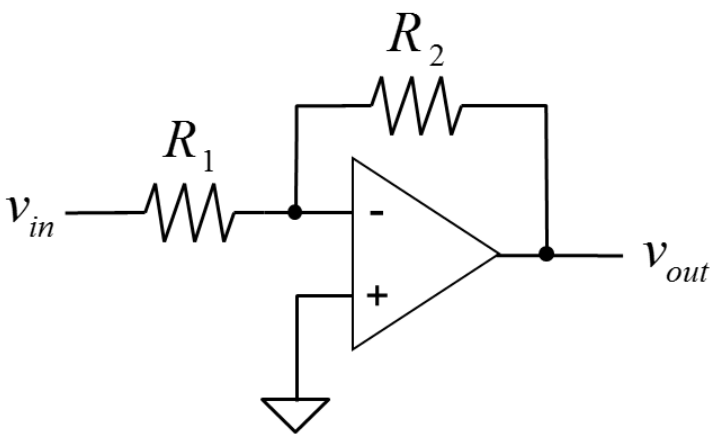


Op Amp Frequency Response – Open Loop

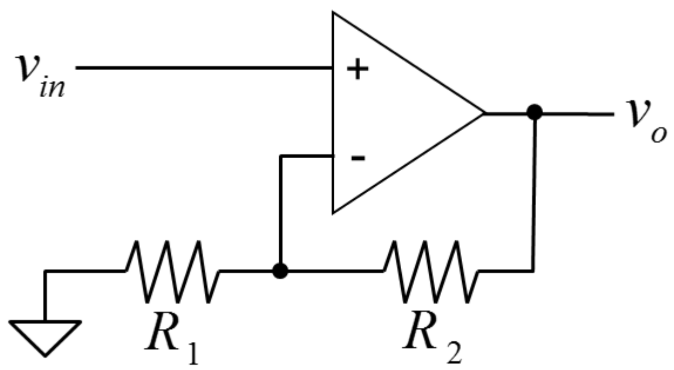
- Non ideal op amp:
  - f_T = gain BW product
  - At frequency = f_T, the gain is 1
  - Typical values: f_T = 1MHz, A = 10^5, f_B = 10Hz

Op Amp Frequency Response – Closed Loop Amplifier

- Non-ideal op amp, inverting and non-inverting amplifiers:



inverting amplifier

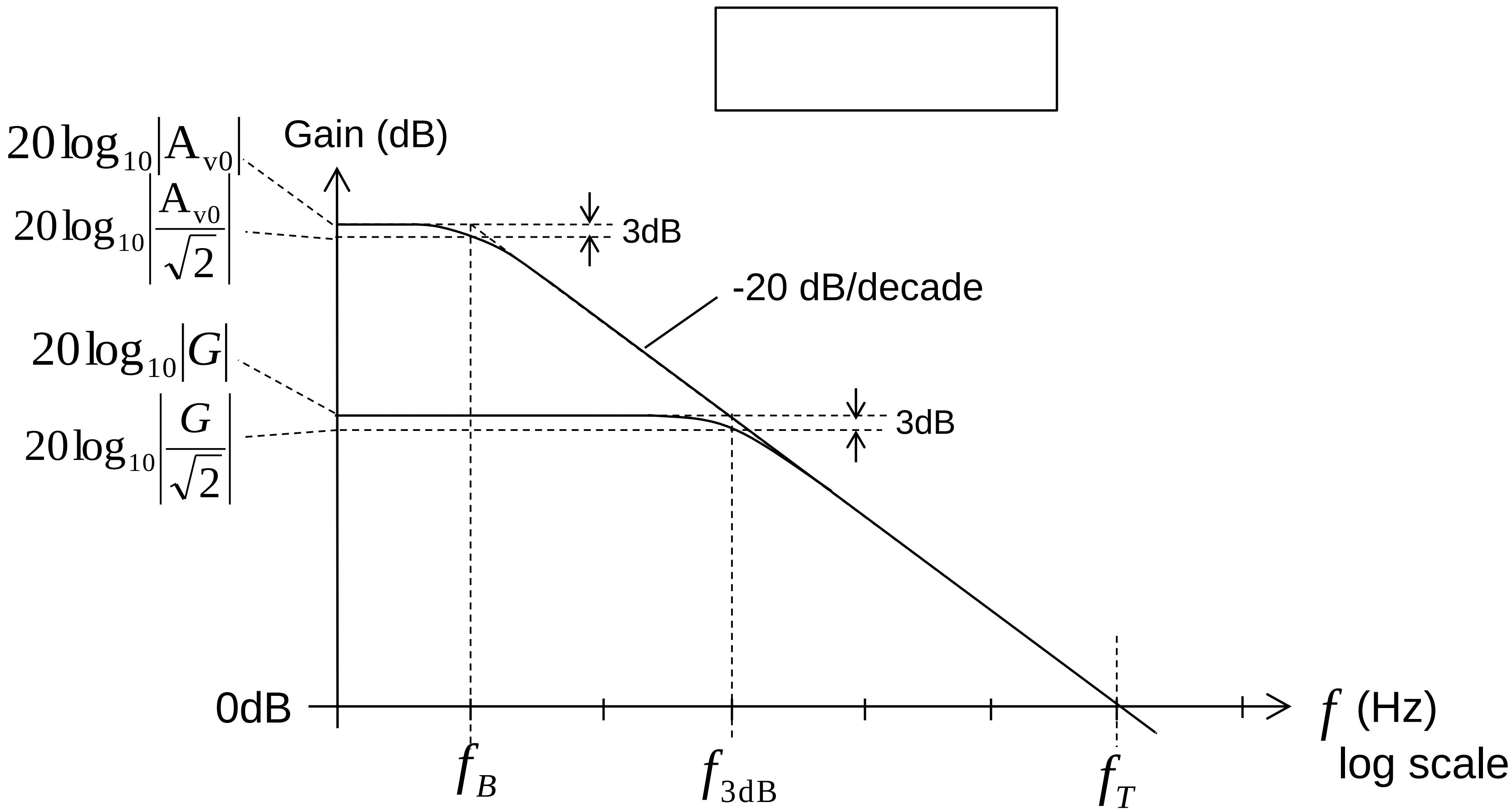


non-inverting amplifier

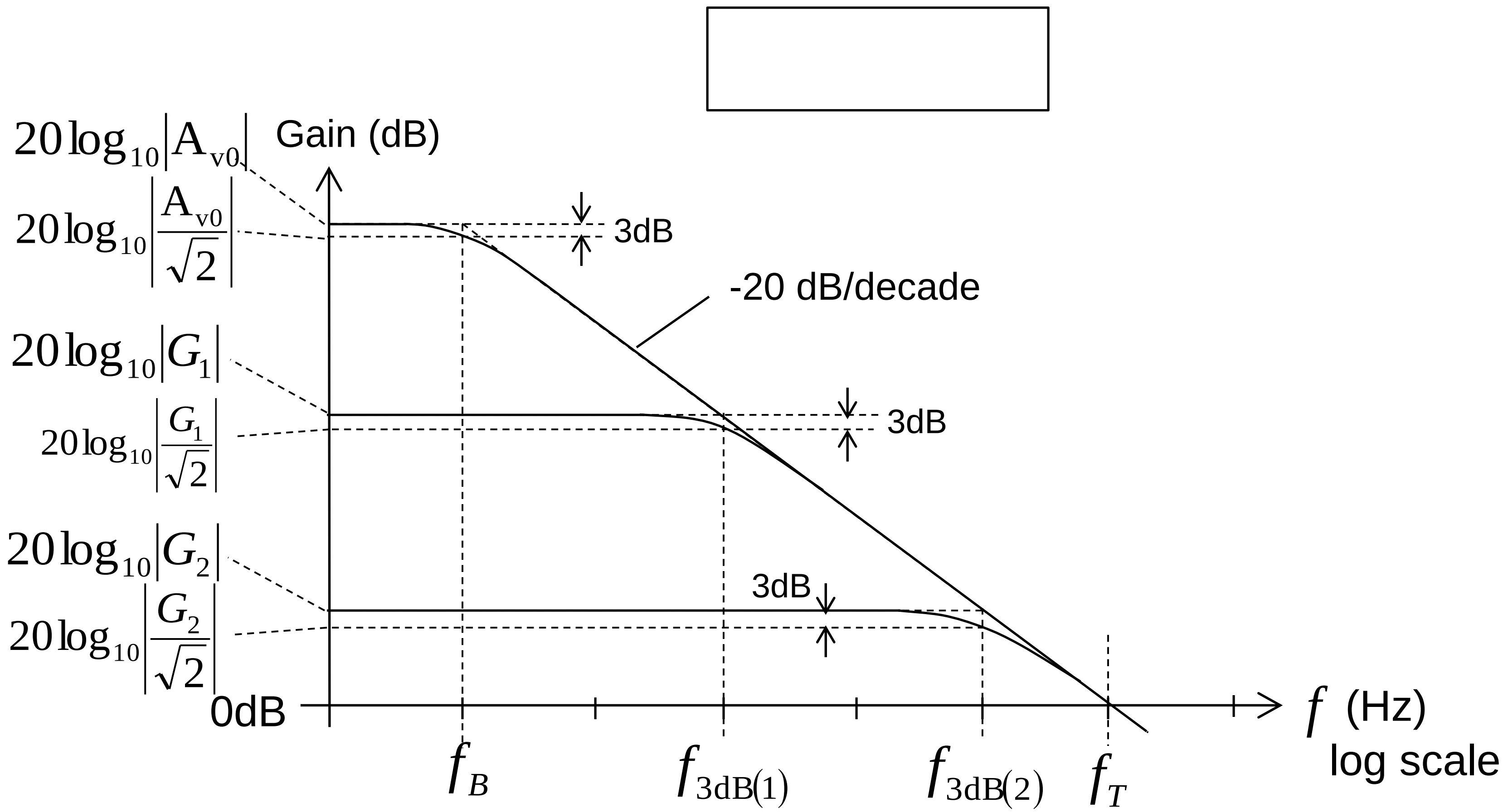
closed loop gain: $G = \frac{v_o}{v_{in}} = -\frac{R_2}{R_1}$

closed loop gain: $G = \frac{v_o}{v_{in}} = 1 + \frac{R_2}{R_1}$

Op Amp Frequency Response – Closed Loop Amplifier

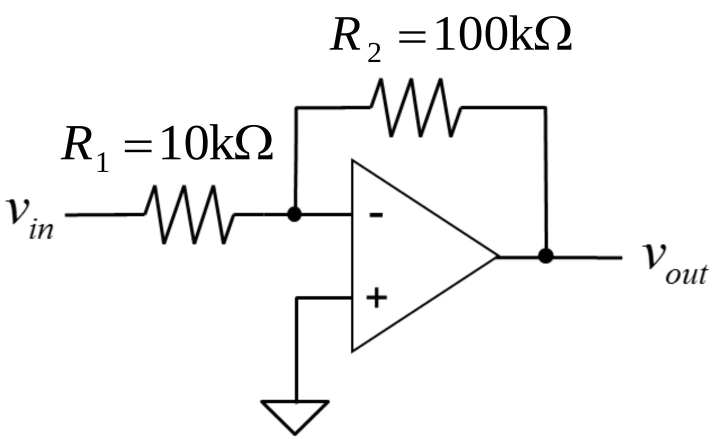


Op Amp Frequency Response – Closed Loop



Op Amp Frequency Response – Closed Loop

- Example 3: An op amp has a gain bandwidth product f_T = 1MHz, $A_{v0} = 10^5$ and f_B = 10Hz. This op amp is used in an inverting amplifier, with R_1=10kΩ and R_2 = 100kΩ. What is the 3dB bandwidth of the inverting amplifier?



inverting amplifier

closed loop gain:

$$G = \frac{v_o}{v_{in}} = -\frac{R_2}{R_1} = -\frac{100\text{k}}{10\text{k}} = -10$$

Op Amp Frequency Response – Closed Loop

- Example 3: