Kuwait University
College of Engineering and Petroleum

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ME319 MECHATRONICS

Part II: The Cells – Electronic Circuits

Lecture 3: Operational Amplifiers

Spring 2021

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Lesson Objectives

- Review the rules for an ideal operational amplifier
- Review common Op-Amp Configuration
- Learn how to read Op-Amp Datasheets

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Why Op-Amps?

- Operational Amplifiers are fundamental in electronic applications:
  - Amplifying small range signals to higher range and vice versa
    - Sensing Applications
    - Current/Voltage Controlled Applications
  - Filtering and Signal Conditioning of Signals
  - Mathematical Operations: Add/Subtract/Differentiate/Integrate
  - Buffering
  - Digital Logic, to name a few
- Operational Amplifiers are **active** circuit components
  - The **output** current is produced from energy **supplied** to operate the op-amp, **not** from the **input** signals.

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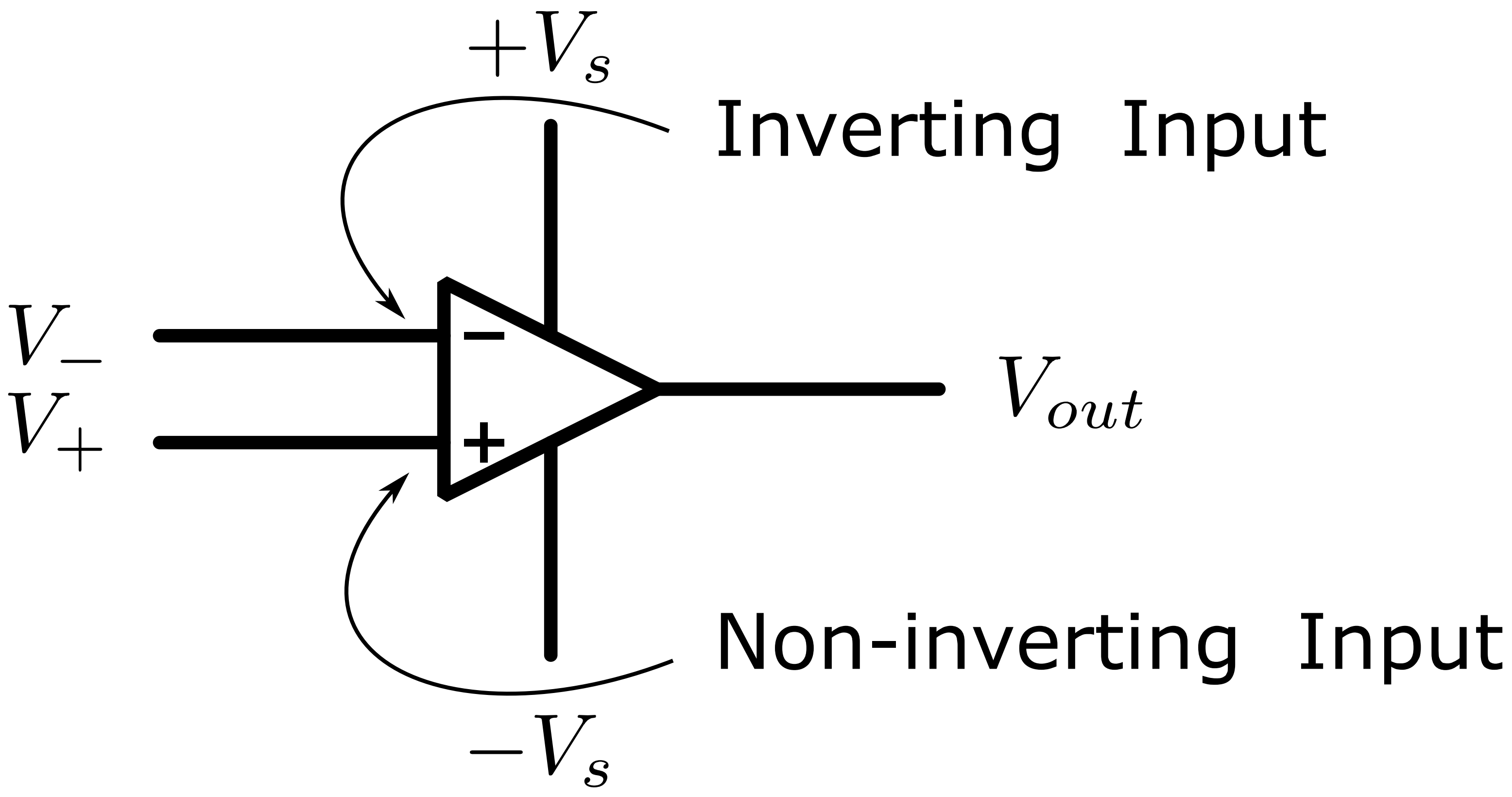
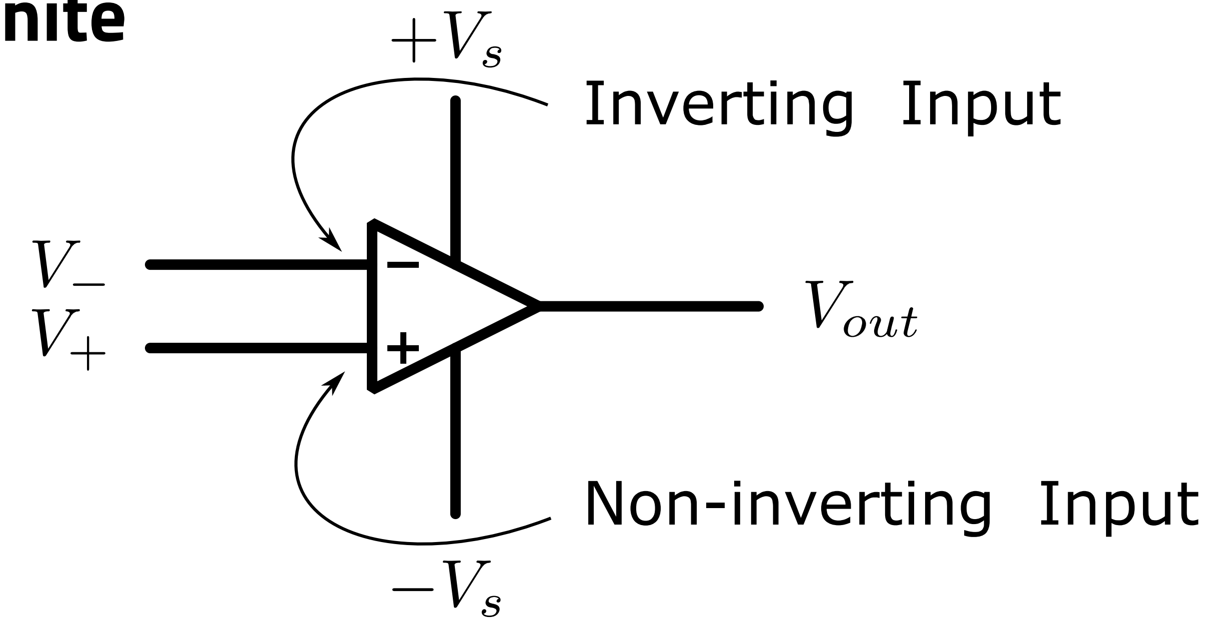
- The op-amp symbol is standard. A standard op-amp has 5 terminals.
- Note the $-V_s$, $+V_s$ are called the supply terminals, and may be omitted from an op-amp diagram for simplification.

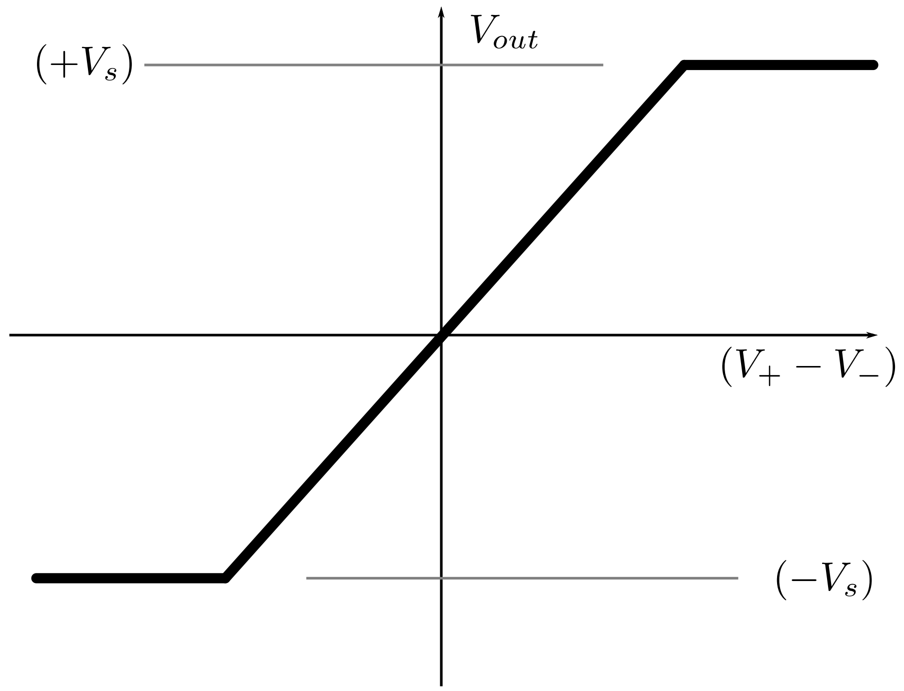


- This configuration, where no signal is fed back from the output to the input is:
  - An Open-Loop Configuration. G is the open-loop gain

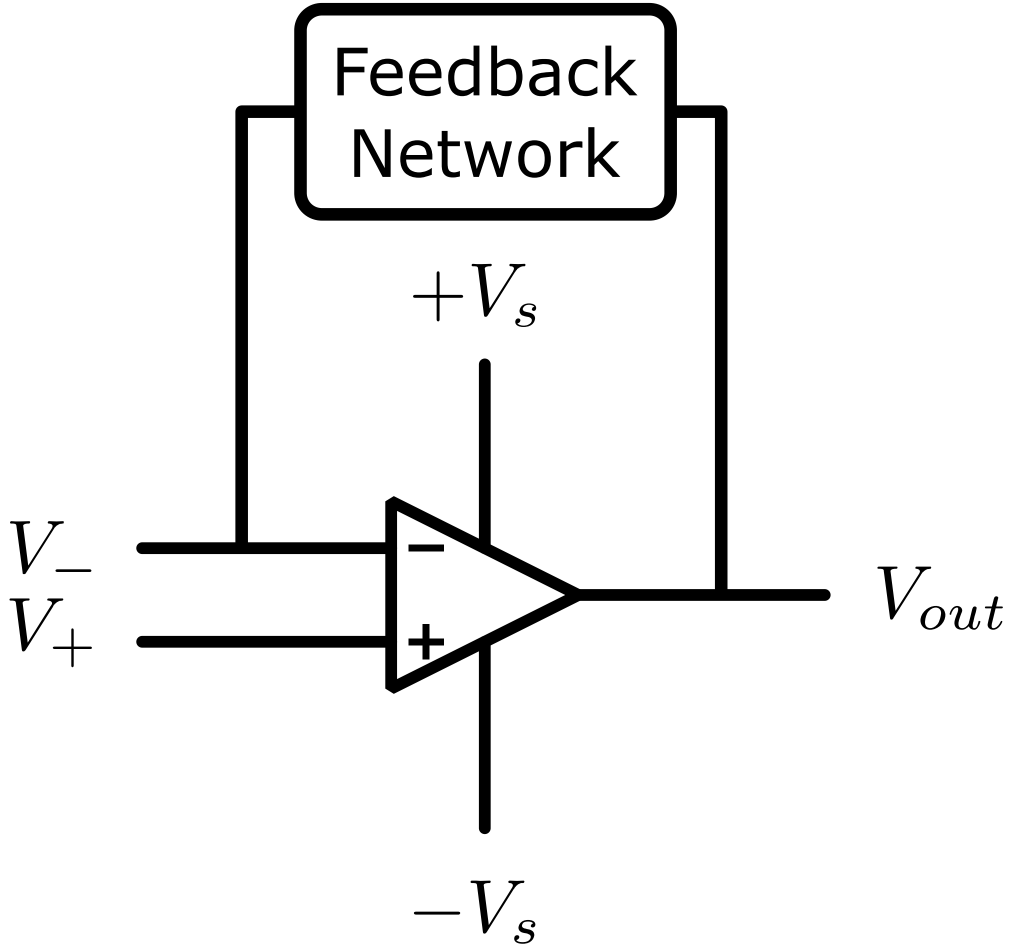
$$V_{out} = G(V_+ - V_-)$$

  - The open-loop gain of an **ideal** op-amp is **infinite**



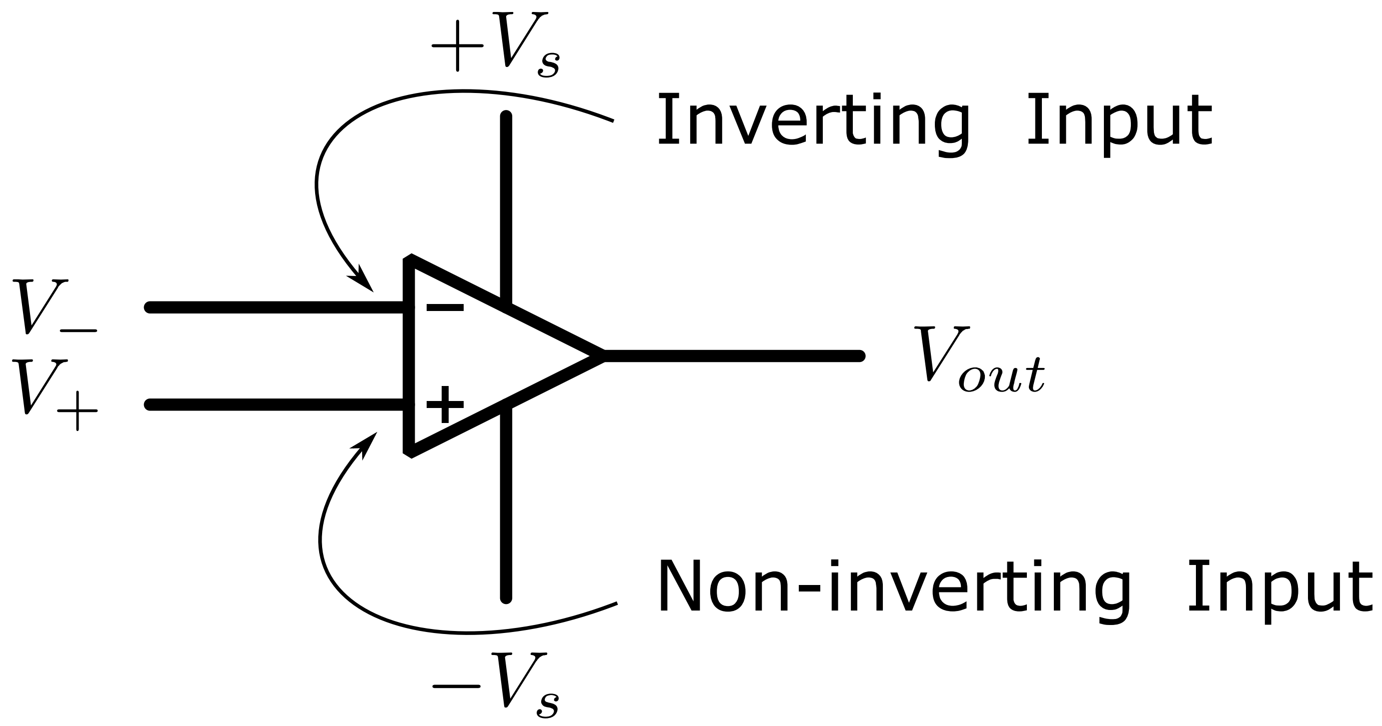


- Op-Amps are used in a closed-loop configuration; usually negative feedback.
- The configuration of the feedback network defines the behavior of the op-amp



- Three assumptions govern the ideal op-amp model

1. The gain $\frac{V_{out}}{V_{+}-V_{-}}$, is infinite.
2. The inputs draw no current.
   - $i@-input,+input=0A$



3. The output impedance is zero.
   - No resistance between input voltage source and output

Ideal Op-Amp Golder Rules

- There are two rules two follow for op-amps from which we derive all op-amps equations
- The rules are for an **IDEAL** op-amp
  - The ideal behavior is quite close to real for many applications
- **RULE #1: The inputs draw no current.**
  - No current goes into either the inverting or noninverting inputs.
  - The op-amp only **measures** the input voltages
- **RULE #2: When operating in negative feedback, the output voltage will change as to cause both inputs to be the same $V_{out} \Rightarrow V_{-} = V_{+}$**
  - This stems from the fact that the open-loop gain of an ideal op-amp is infinite.
  - An op-amp is practically always used with feedback.

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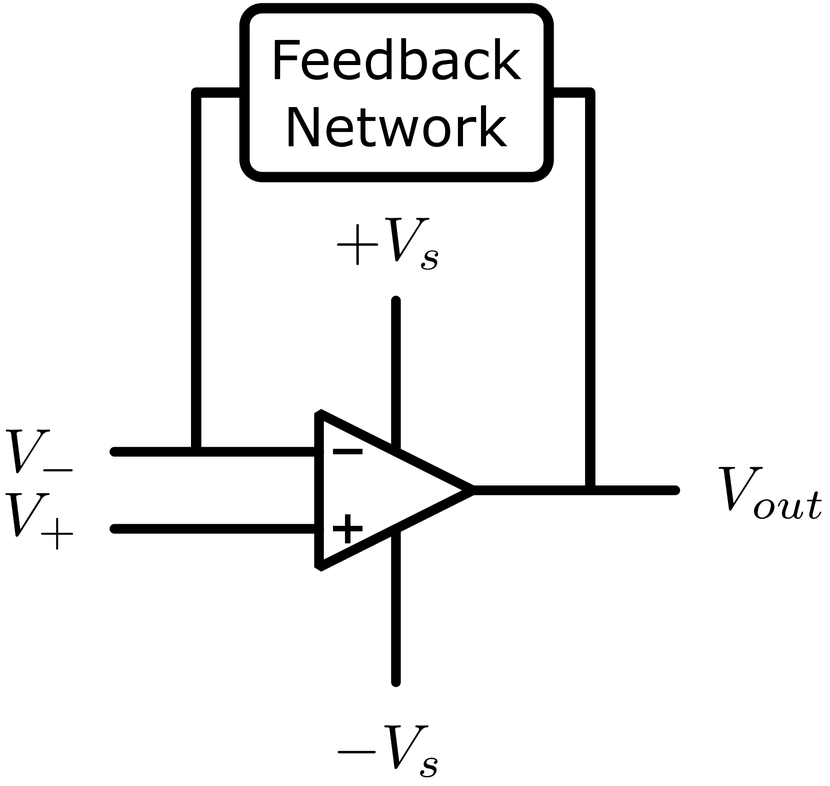
- To derive the equation for an op-amp configuration, we just need:
  - Op-Amps Goldens **Rules #1 & #2**
  - Kirchhoff's **Voltage** and **Current Laws** $\sum_{k=1}^{n} i_k = 0, \sum_{k=1}^{n} V_k = 0$
- Let's derive the equations for a non-inverting op-amp
- Other op-amp configurations equations can be derived in a similar fashion



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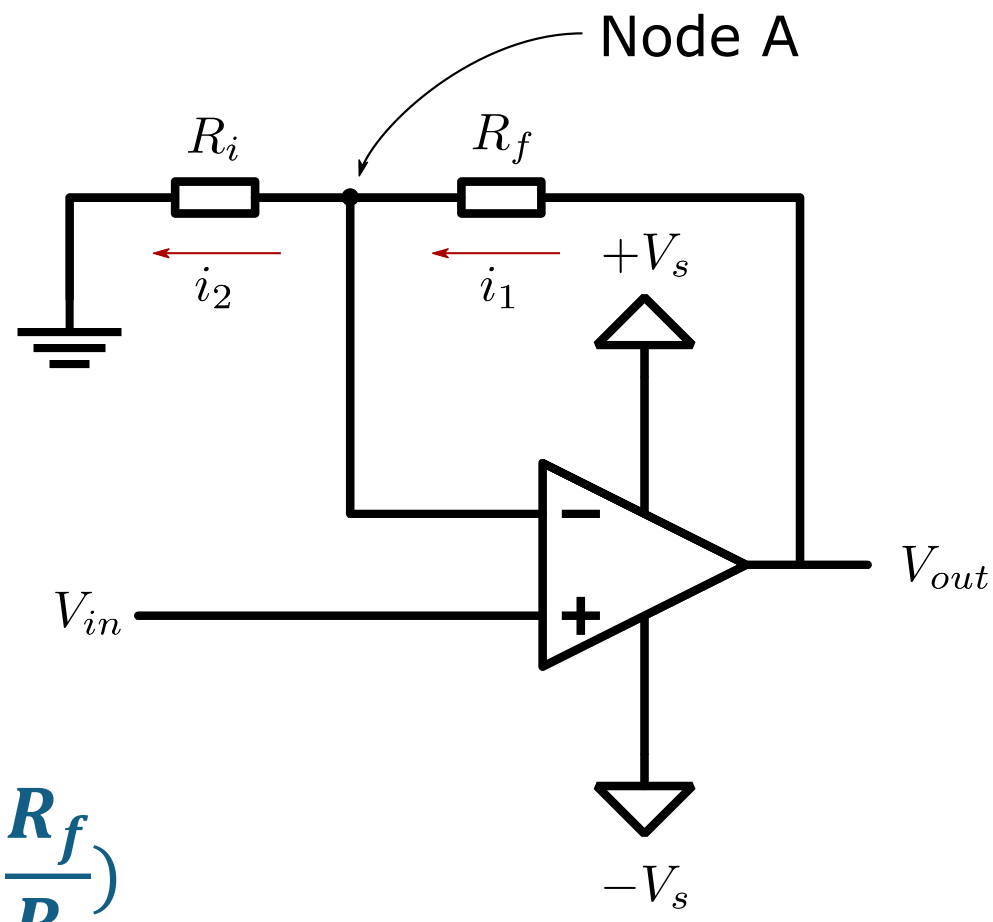
- Given Rule #1 (No current into inputs)
  - $i_1 = i_2 \Rightarrow \frac{V_{out}-V_A}{R_f} = \frac{V_A-0}{R_i}$ (1)
- Given Rule #2 ($V_- = V_+$)
  - $V_A = V_- = V_+ = V_{in}$ (2)
- Then, substitute (2) into (1):

$$\frac{V_{out} - V_{in}}{R_f} = \frac{V_{in} - 0}{R_i} \Rightarrow \frac{V_{out}}{R_f} = \frac{V_{in}}{R_i} + \frac{V_{in}}{R_f}$$



$$\boldsymbol{V_{out} = V_{in}\left(1 + \frac{R_f}{R_i}\right)}$$

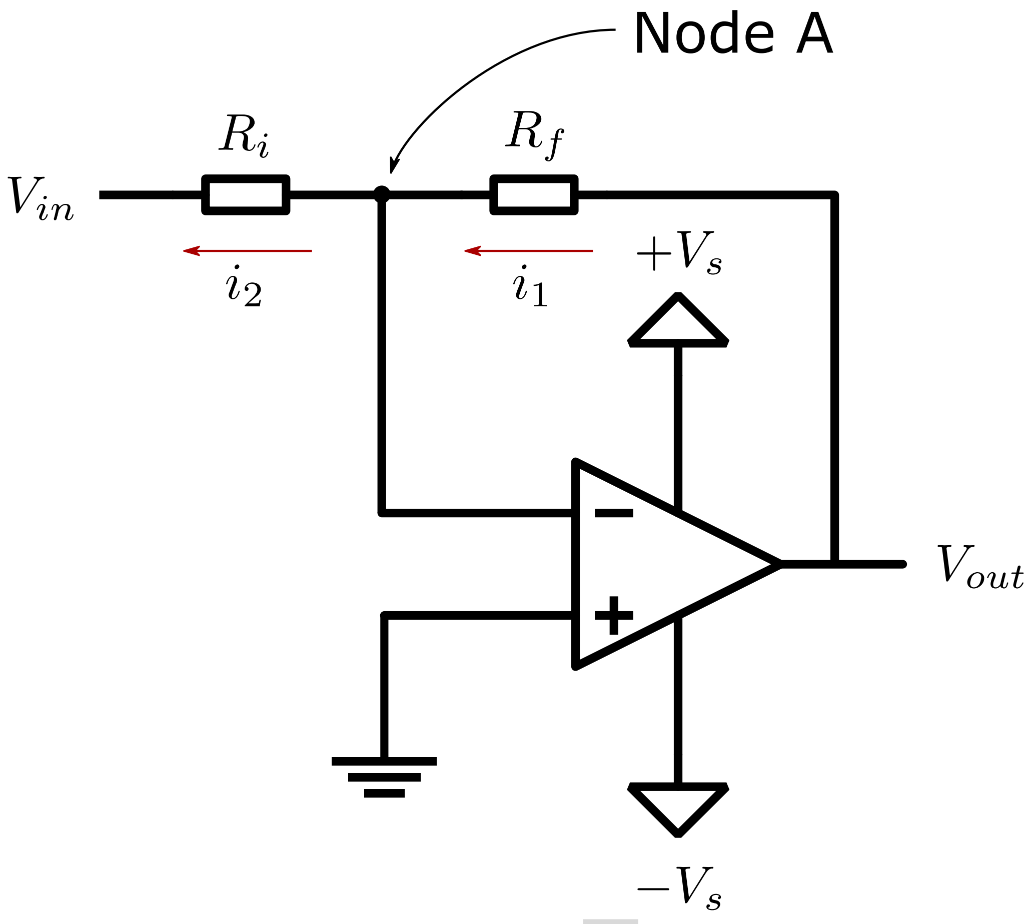
Then we can control the gain by choosing R_f, R_i

Keep the values of R in the $1k\Omega$ to $200k\Omega$ range.

- Given Rule #1 (No current into inputs)
  - $i_1 = i_2 \Rightarrow \frac{V_{out}-V_A}{R_f} = \frac{V_A-V_{in}}{R_i}$
- Given Rule #2 ($V_- = V_+$)
  - $V_A = 0$ (Virtual Ground)
- Then:

$$\frac{V_{out}-0}{R_f} = \frac{0-V_{in}}{R_i} \Rightarrow -\frac{V_{in}}{R_i} = \frac{V_{out}}{R_f}$$

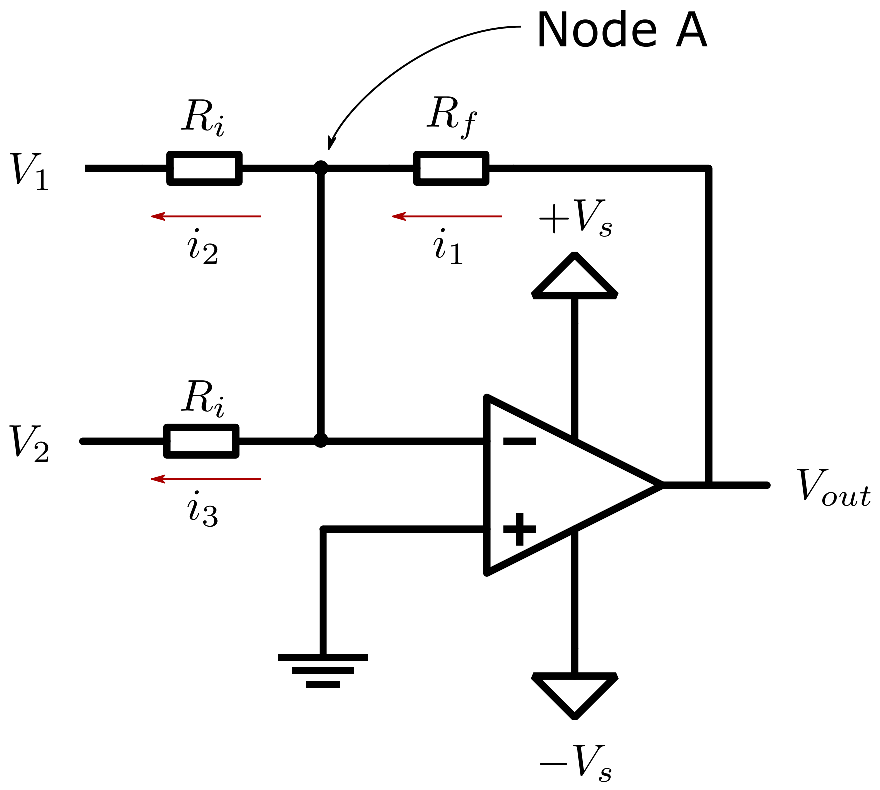
$$\boldsymbol{V_{out} = -V_{in}\left(\frac{R_f}{R_i}\right)}$$



Note the input and output have opposite polarity (inverted)

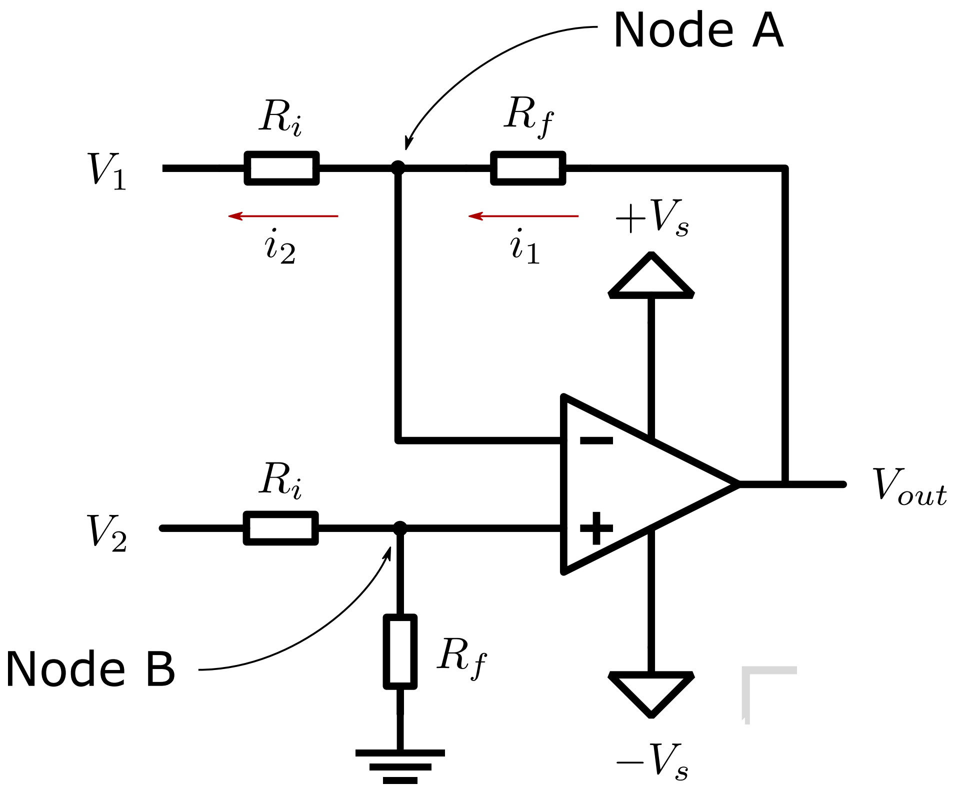
The inverting summer configuration

$$V_{out} = -\frac{R_f}{R_i}(V_1 + V_2)$$



The difference configuration

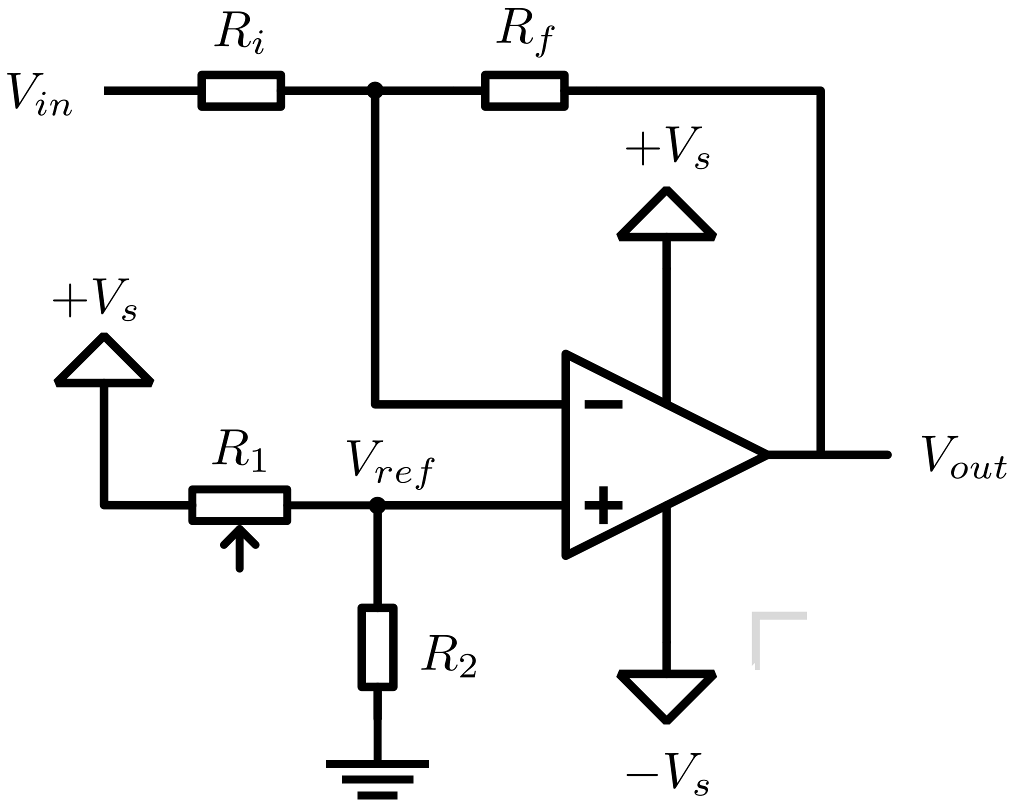
$$V_{out} = (V_2 - V_1)\frac{R_f}{R_i}$$



- Similar to a difference amplifier, but V_{ref} can be tuned using a voltage divider
  - Or even a variable resistor voltage divider
- This configuration can be useful in amplifying relative to an offset

$$V_{out} = (V_{ref} - V_{in})\left(\frac{R_f}{R_i}\right) + V_{ref}$$

$$V_{ref} = V_s \frac{R_2}{(R_1 + R_2)}$$



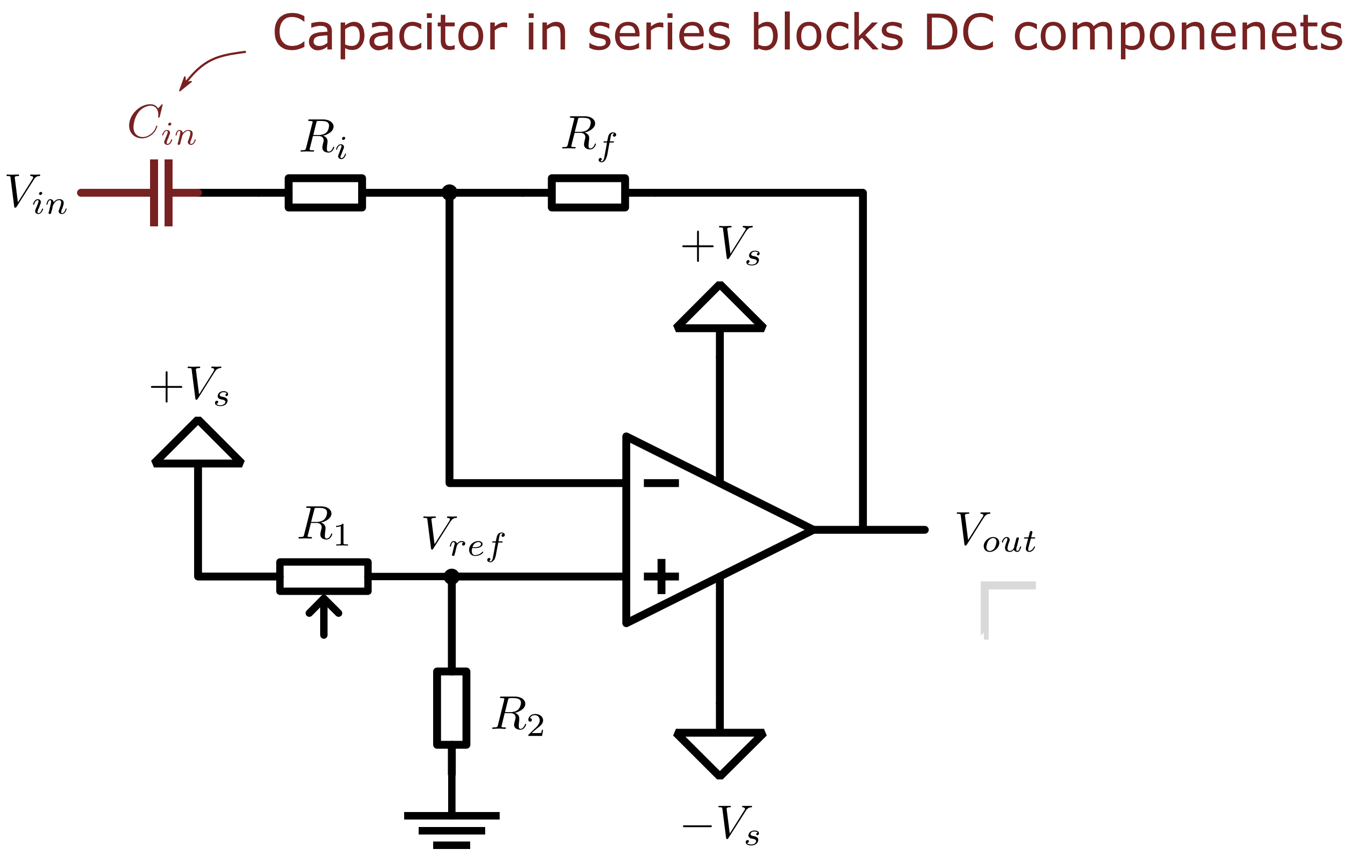
Example, note the conf. is inverting:

$$V_{in}(t) = 6 + 2\sin(t),\, V_{ref}(t) = 5, \text{ then}$$

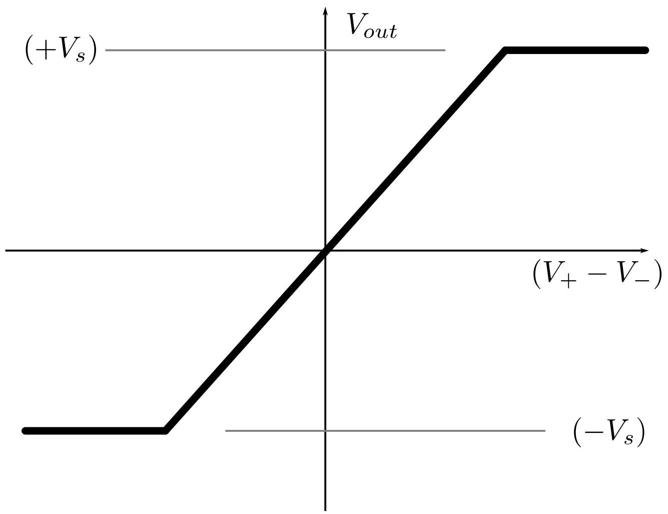
$$V_{out}(t) = (5 - (6 + 2\sin(t)))\left(\frac{R_f}{R_i}\right) + 5$$

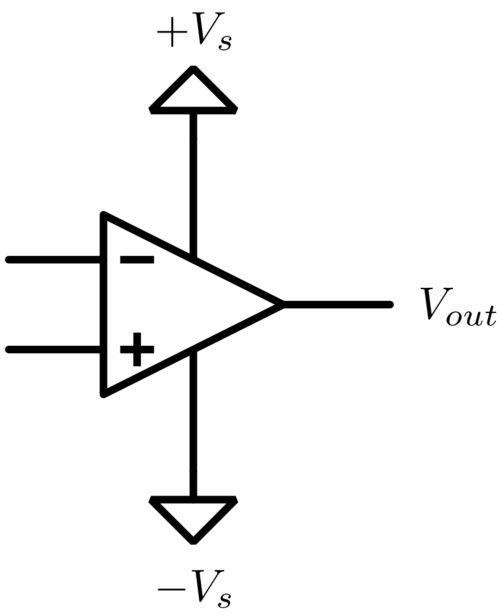
- By adding a capacitor in series with the input, the DC components can be blocked. AC components allowed through.
- Remember the impedance (resistance) of a capacitor:

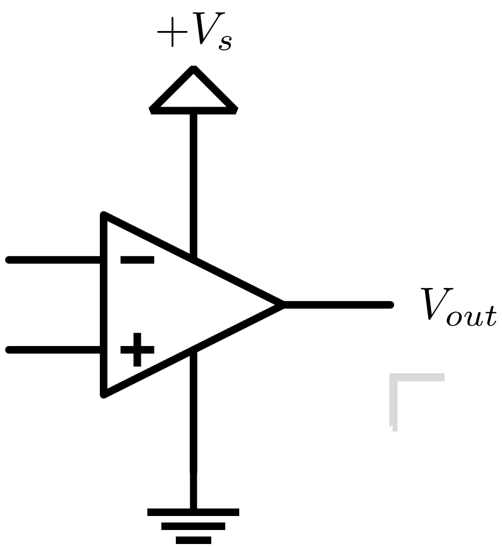
$$\frac{V}{I} = \frac{1}{C\omega j}, \text{ for } \omega = 0, \text{ is } \infty$$



- Op amps can either be single or dual side supply
- The output can only swing within the supply voltage range
- Dual side supply is required if output is expected to be AC (has negative values)
- Single side supply is simpler. Good for +DC range applications.







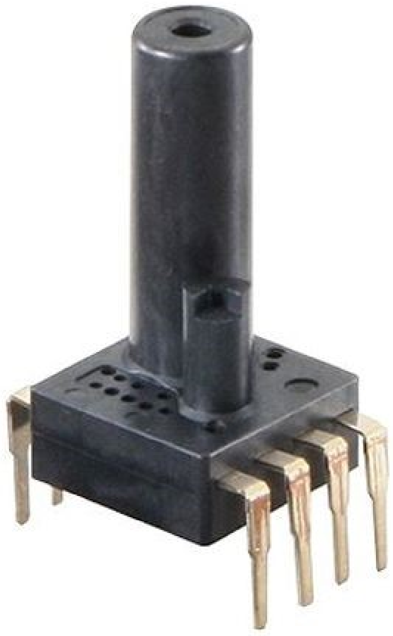
Example 1

We have an analog pressure sensor. We expect to measure gauge pressure in the range $[0psi, 20psi]$, which translates linearly to $[0mV, 45mV]$.

We want to connect this sensor to one of the ADC pins on the STM32Nucleo, which can measure input voltages in the range $[0,3.3V]$

Which type of op-amp is suitable to use in this case?

Calculate the gain required and the resistor values in the feedback network.



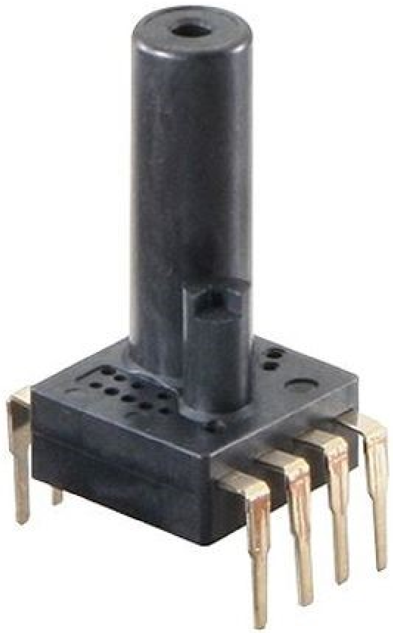
Continue

Example 2

Repeat the previous example but assume this time that the pressure readings translate linearly to $[-10mV, 35mV]$ instead.

Which type of op-amp is suitable to use in this case?

Calculate the gain required and the resistor values in the feedback network.



Reading an Op-Amp Datasheet

- There are many options to choose from. There are general purpose and purpose specific op-amps to choose from. (Digikey Op-Amp Search)
- Key things to consider
  - Maximum Voltage and Current Capabilities
  - General Purpose or Specific Use
  - Dual vs. Single Side Supply
  - Bandwidth
  - Input offsets
  - Input Common Mode Voltage Range
  - Output Voltage Swing

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LM324 Datasheet

- Explore the linked datasheet for LM324: A general purpose op-amp
- The LM324 actually encompasses 4 op-amps
- Single Side Supply: 3V to 32V
- Bandwidth: up to 1MHz
- Input offset Voltage: 2mV
- Input Common Mode Voltage Range: : 0 to $V_+ - 1.5V$
- Output Voltage Swing: 0 to $V_+ - 1.5V$

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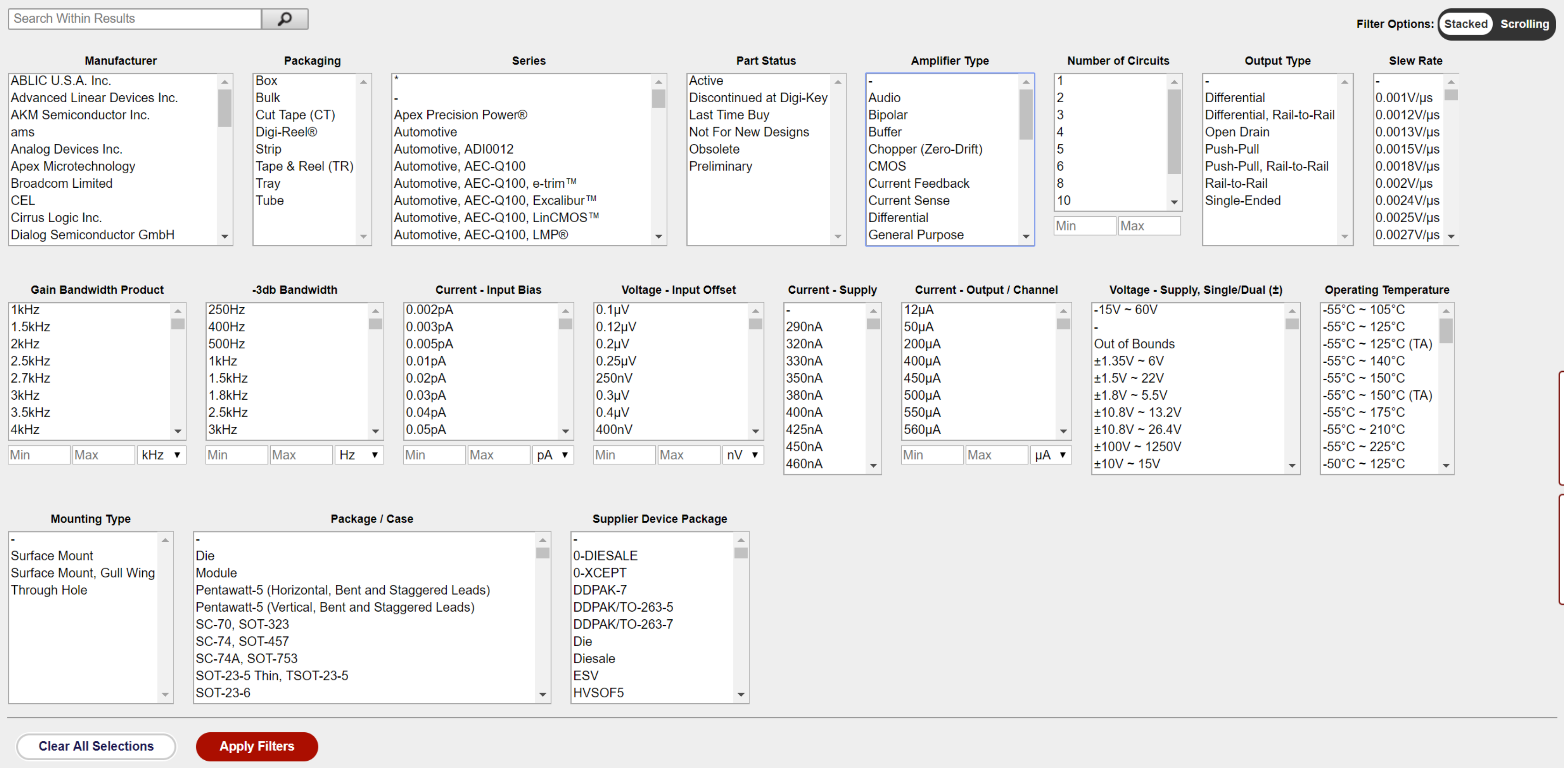

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