

Kuwait University

College of Engineering and Petroleum



جامعة الكويت
KUWAIT UNIVERSITY

ME319 MECHATRONICS

PART II: THE CELLS – ELECTRONIC CIRCUITS

LECTURE 3: OPERATIONAL AMPLIFIERS

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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



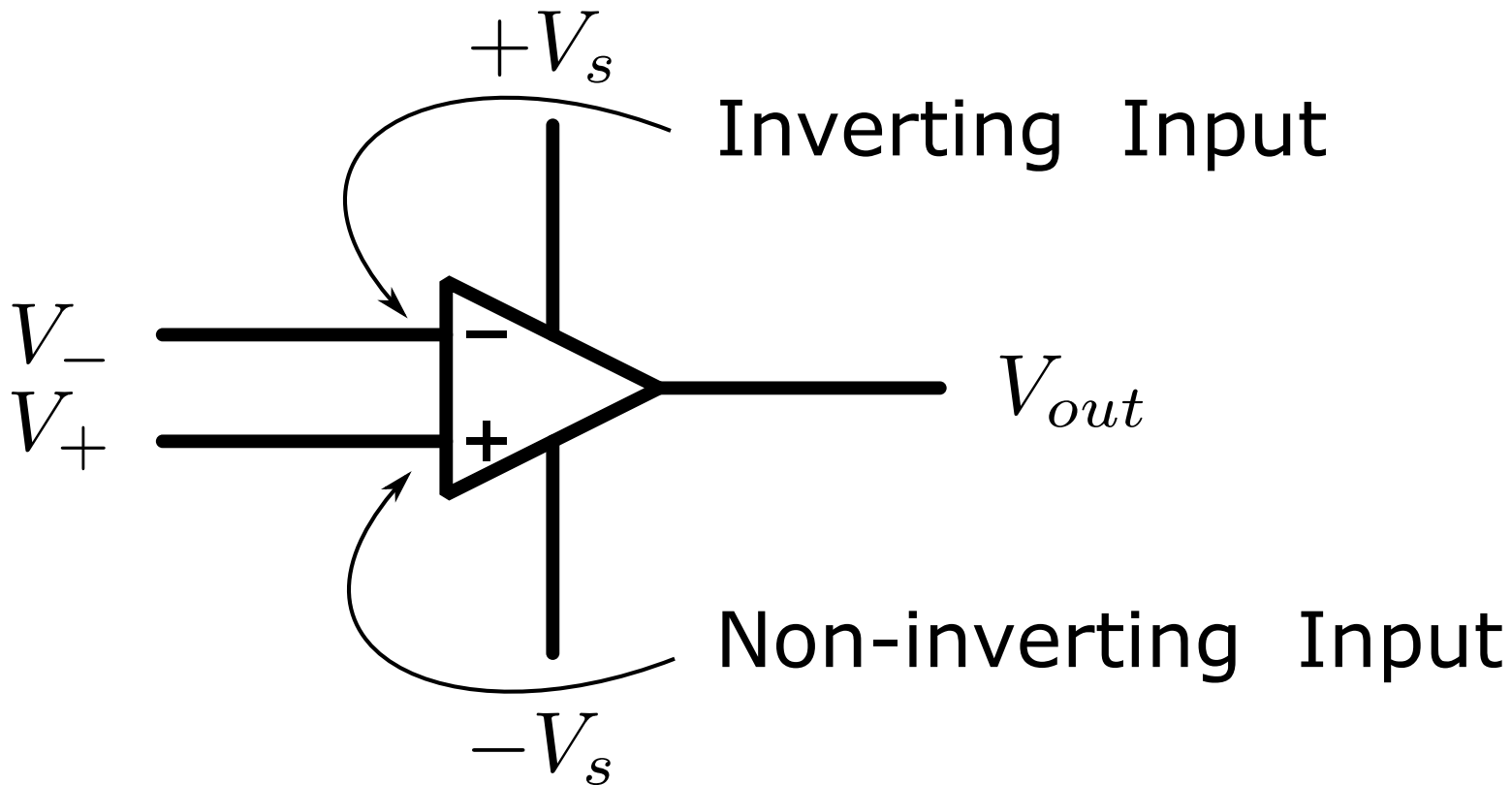
Why Op-Amps?

- 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.



Operational-Amplifier

- 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.



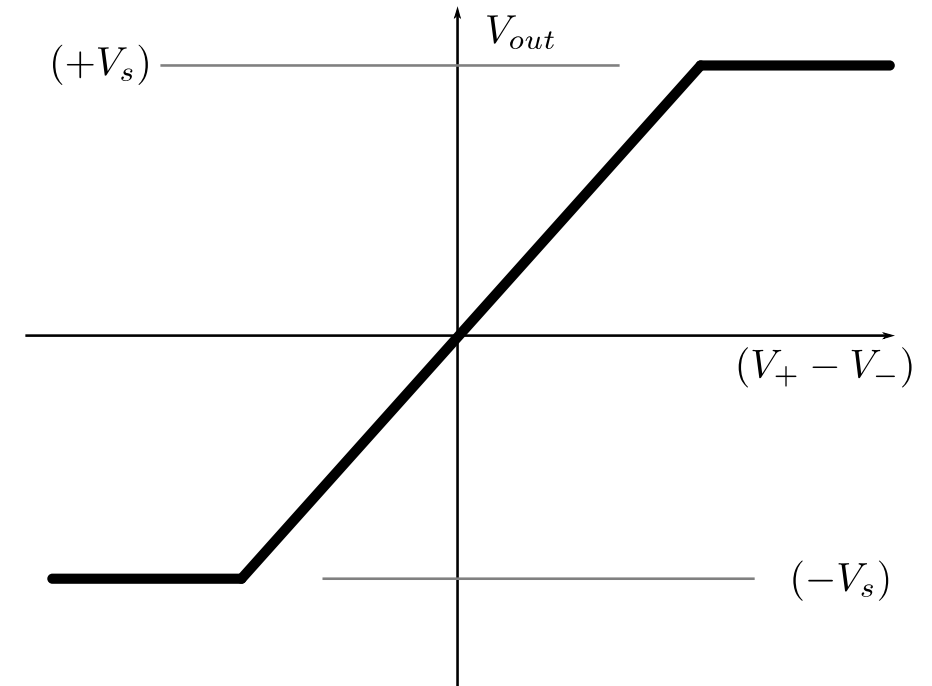
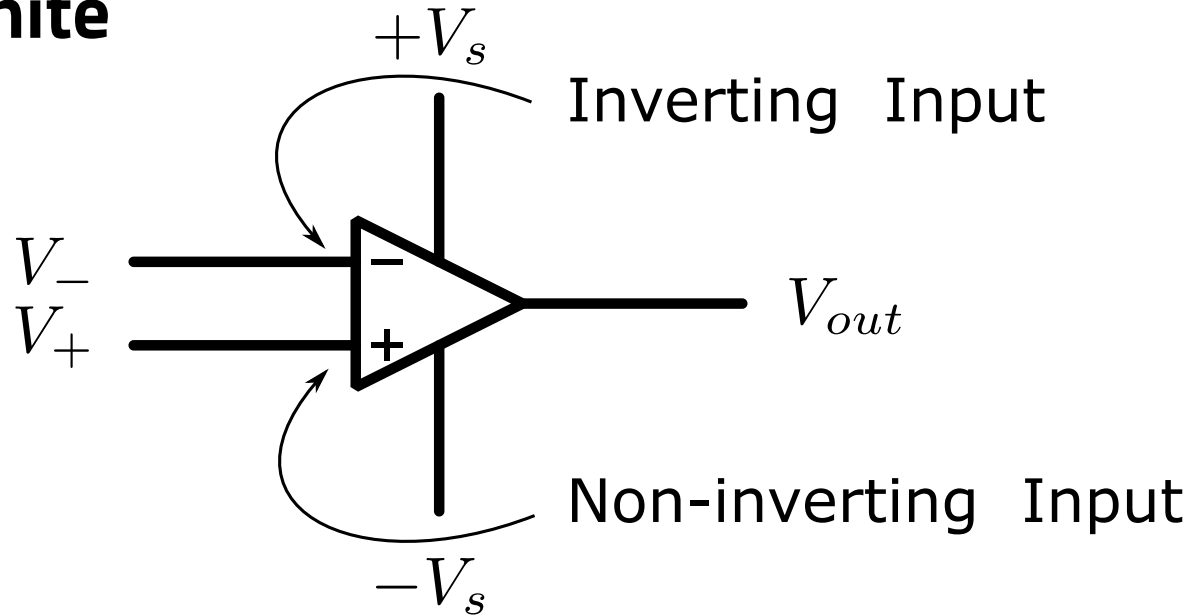
Open-Loop Op-Amp

- 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

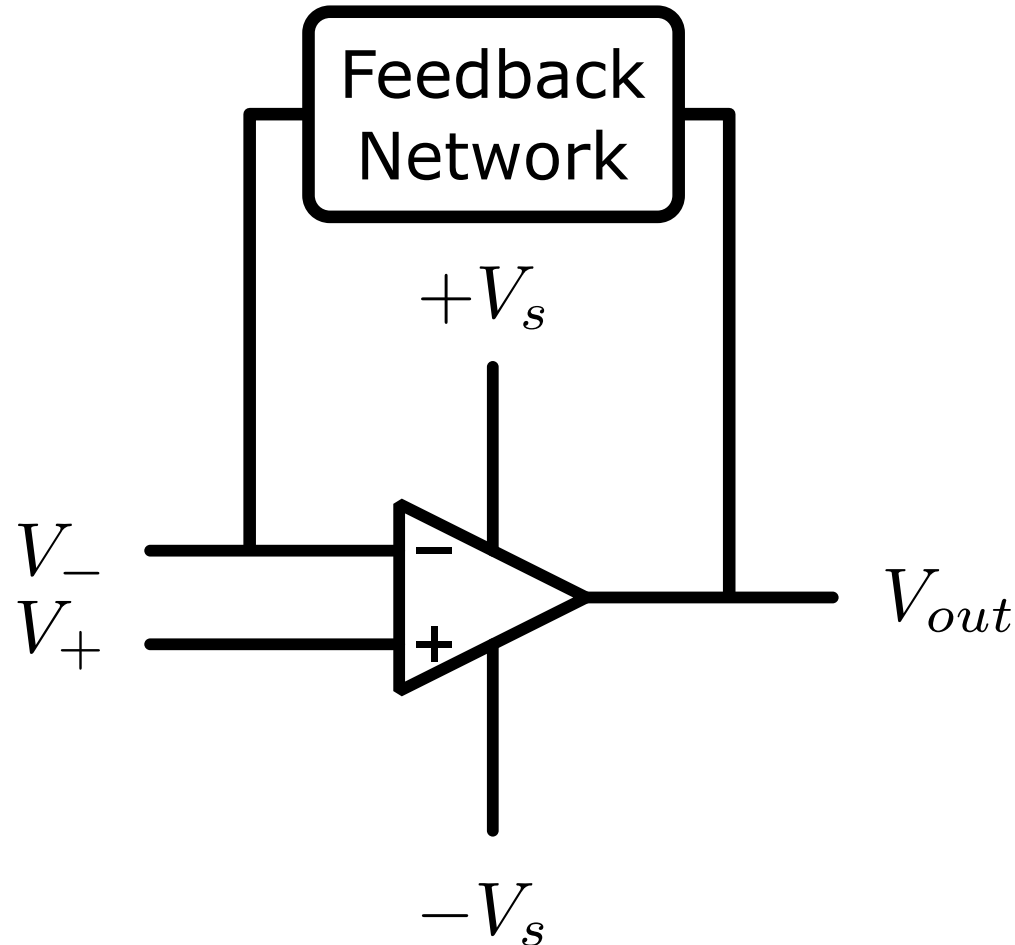
$$V_{out} = G(V_+ - V_-)$$

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



Closed-Loop Op-Amp

- 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



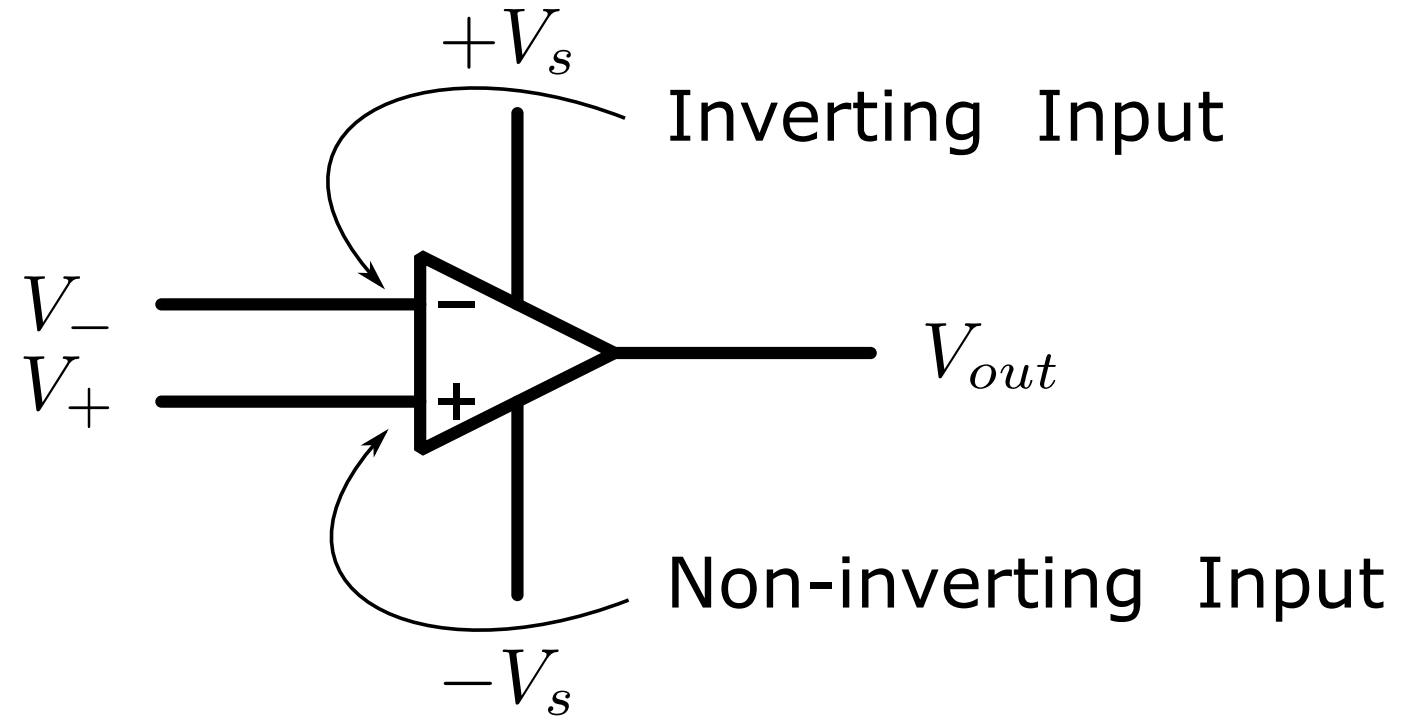
Ideal Op-Amp

- 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



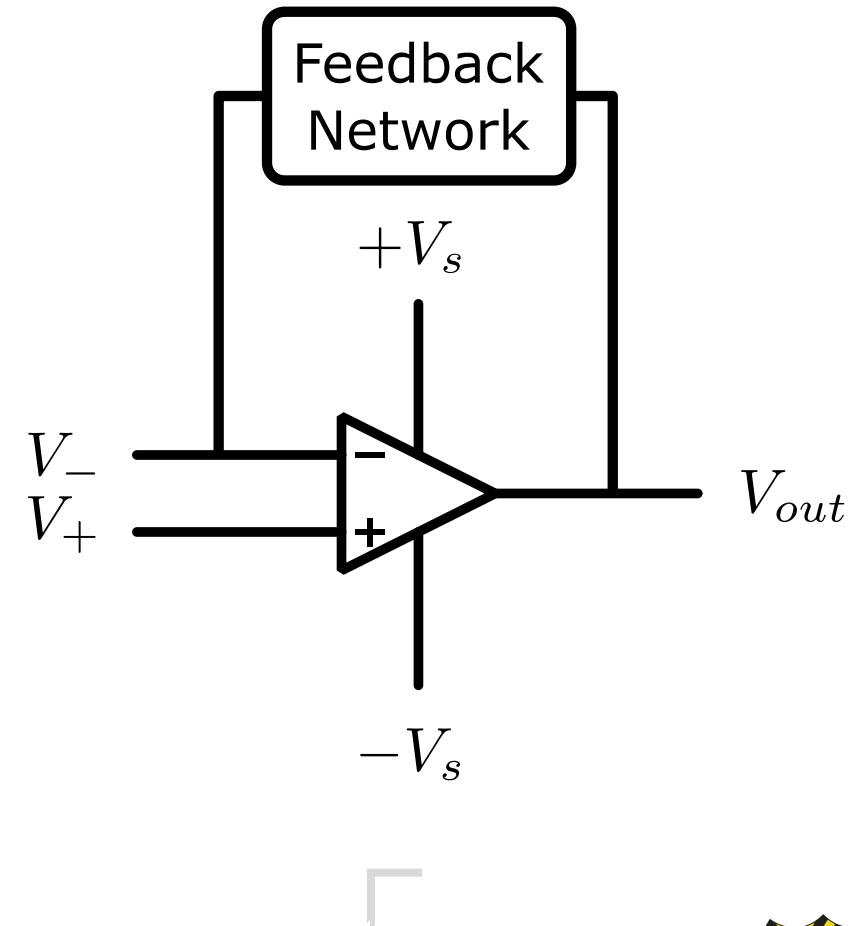
Ideal Op-Amp Golden Rules

- There are two rules to follow for op-amps from which we derive all op-amp 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.



Deriving Op-Amp Configuration Equations

- To derive the equation for an op-amp configuration, we just need:
 - Op-Amps Golden **Rules #1 & #2**
 - Kirchoff'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



The Non-inverting Op-Amp Configuration

- Given Rule #1 (No current into inputs)

$$i_1 = i_2 \Rightarrow \frac{V_{out} - V_A}{R_f} = \frac{V_A - 0}{R_i} \quad (1)$$

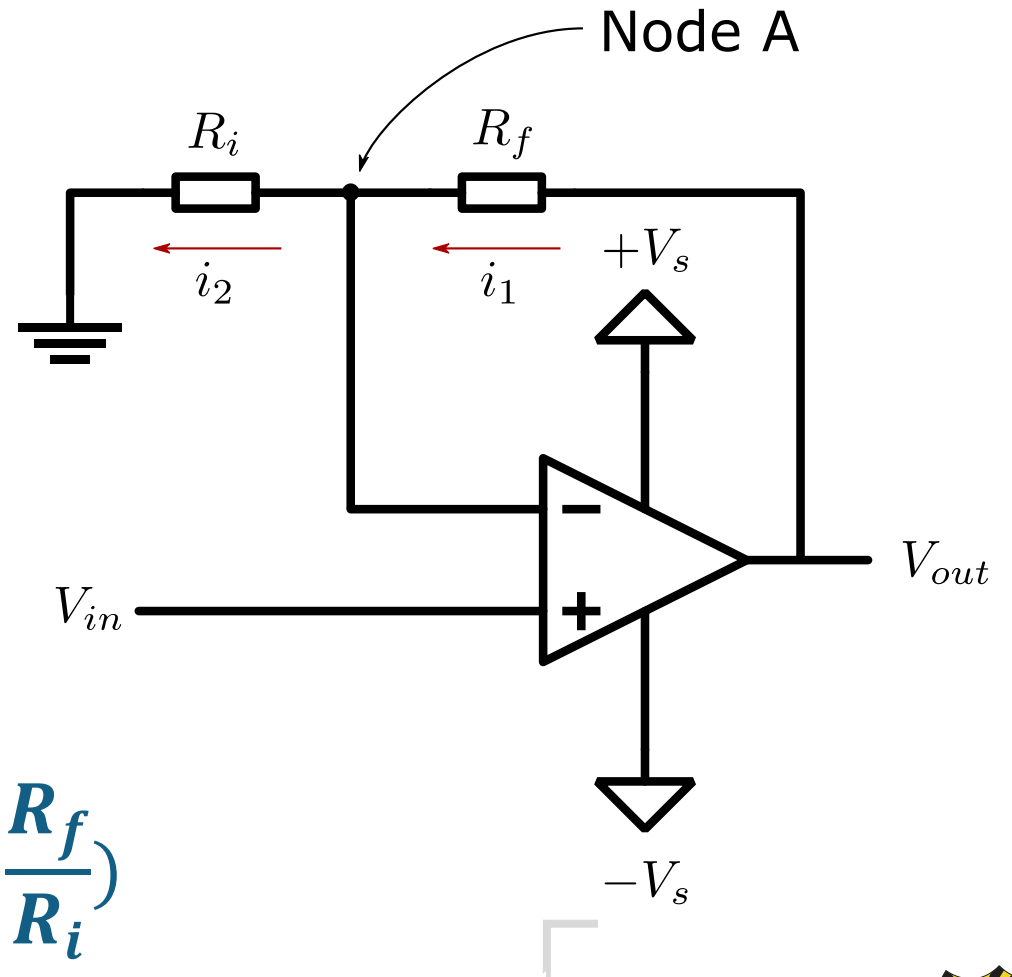
- Given Rule #2 ($V_- = V_+$)

$$V_A = V_- = V_+ = V_{in} \quad (2)$$

- Then, substitute (2) into (1):

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

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



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.



The Inverting Op-Amp Configuration

- 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 ($V_- = V_+$)

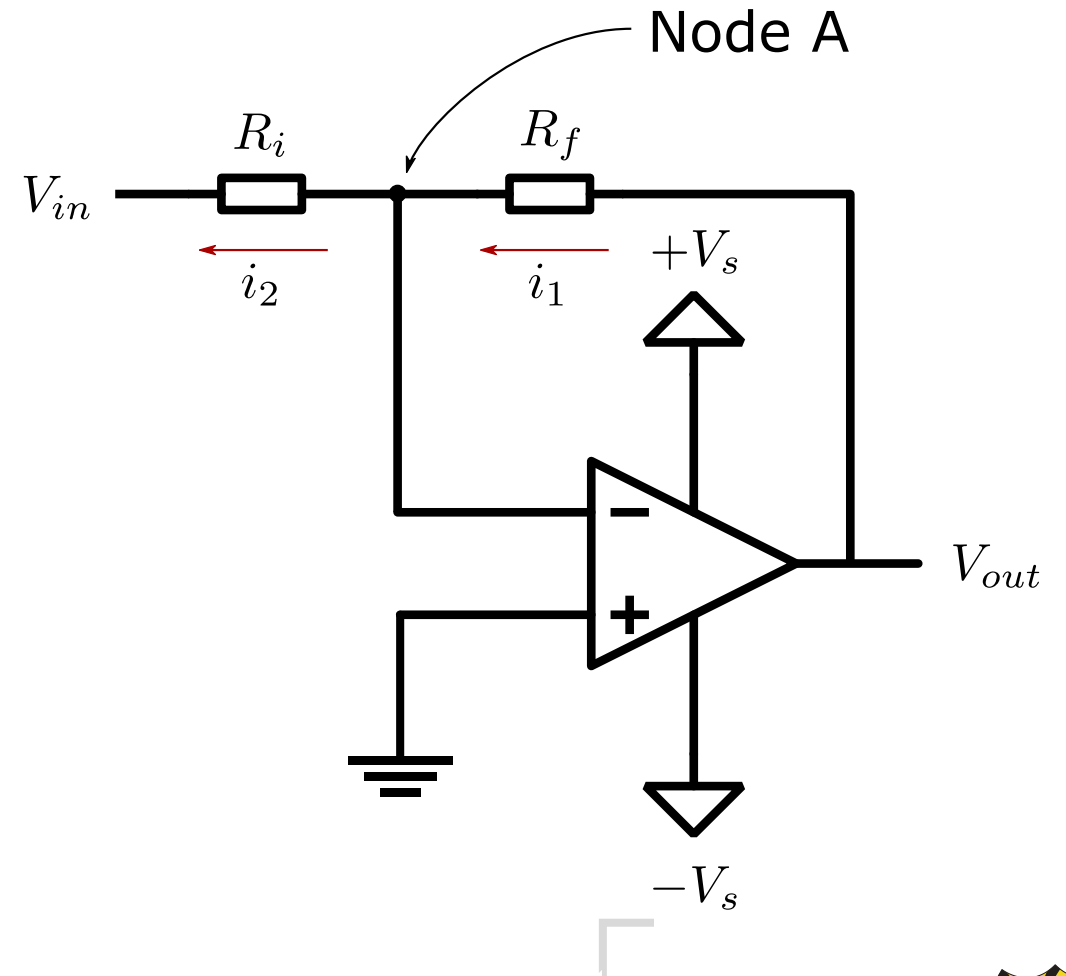
- $V_A = 0$ (Virtual Ground)

- Then:

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

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

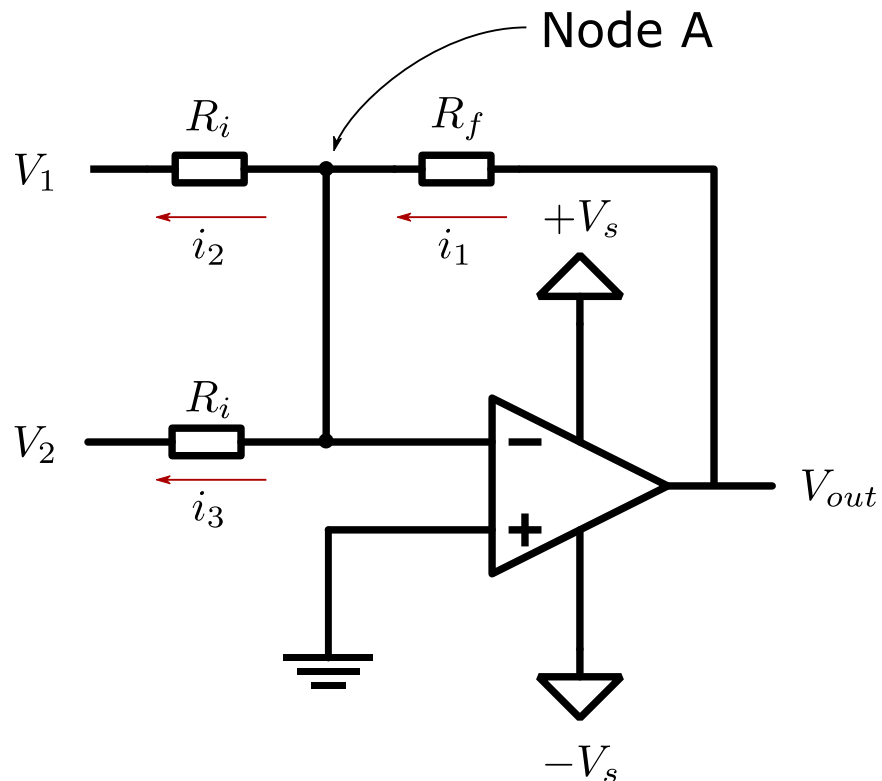
Note the input and output have opposite polarity (inverted)



The Summer and Difference Op-Amp Configurations

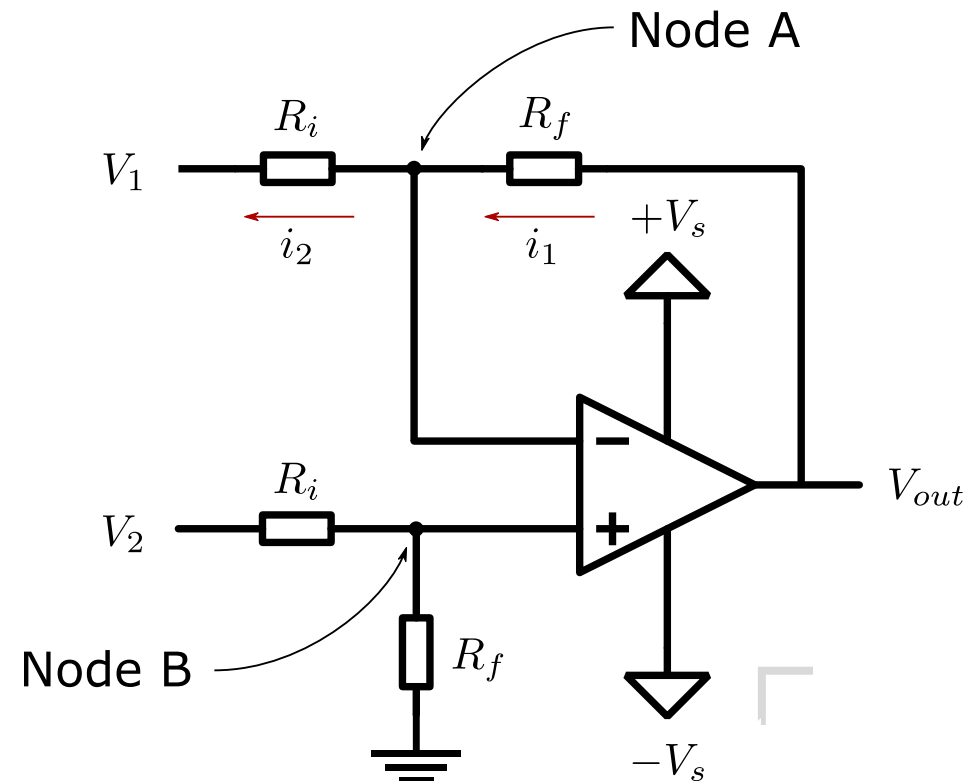
The inverting summer configuration

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



The difference configuration

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



Amplification relative to an offset

- 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

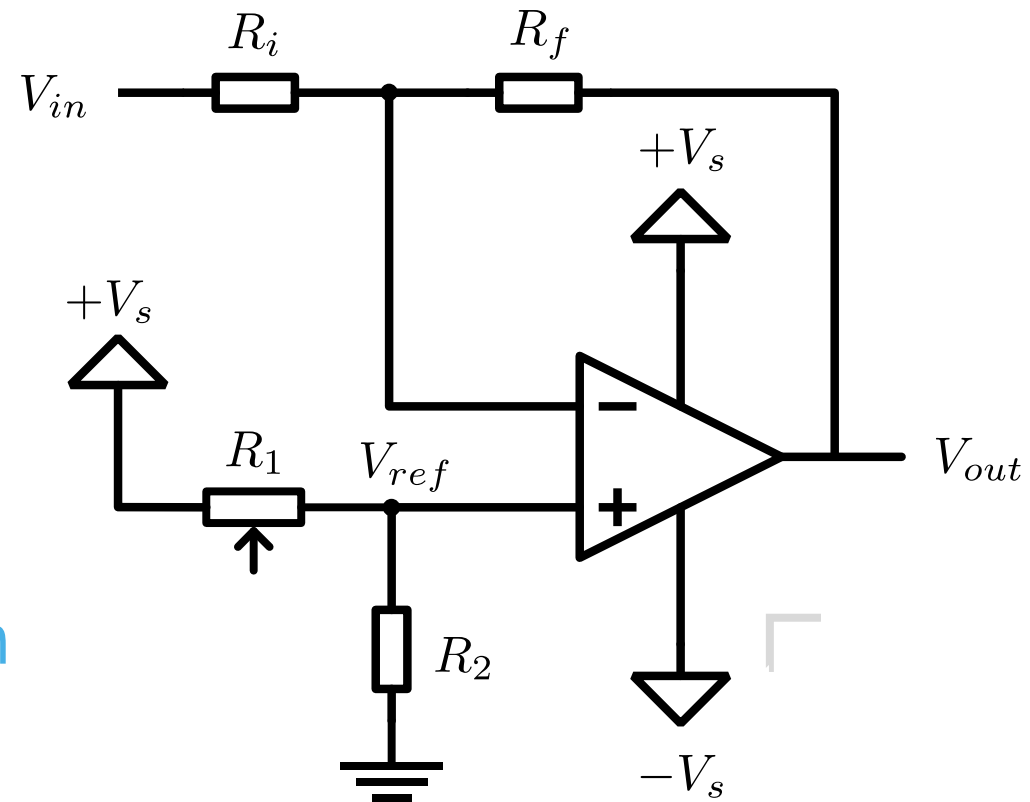
$$V_{out} = (V_{ref} - V_{in}) \left(\frac{R_f}{R_i} \right) + V_{ref}$$

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

Example, note the conf. is inverting:

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

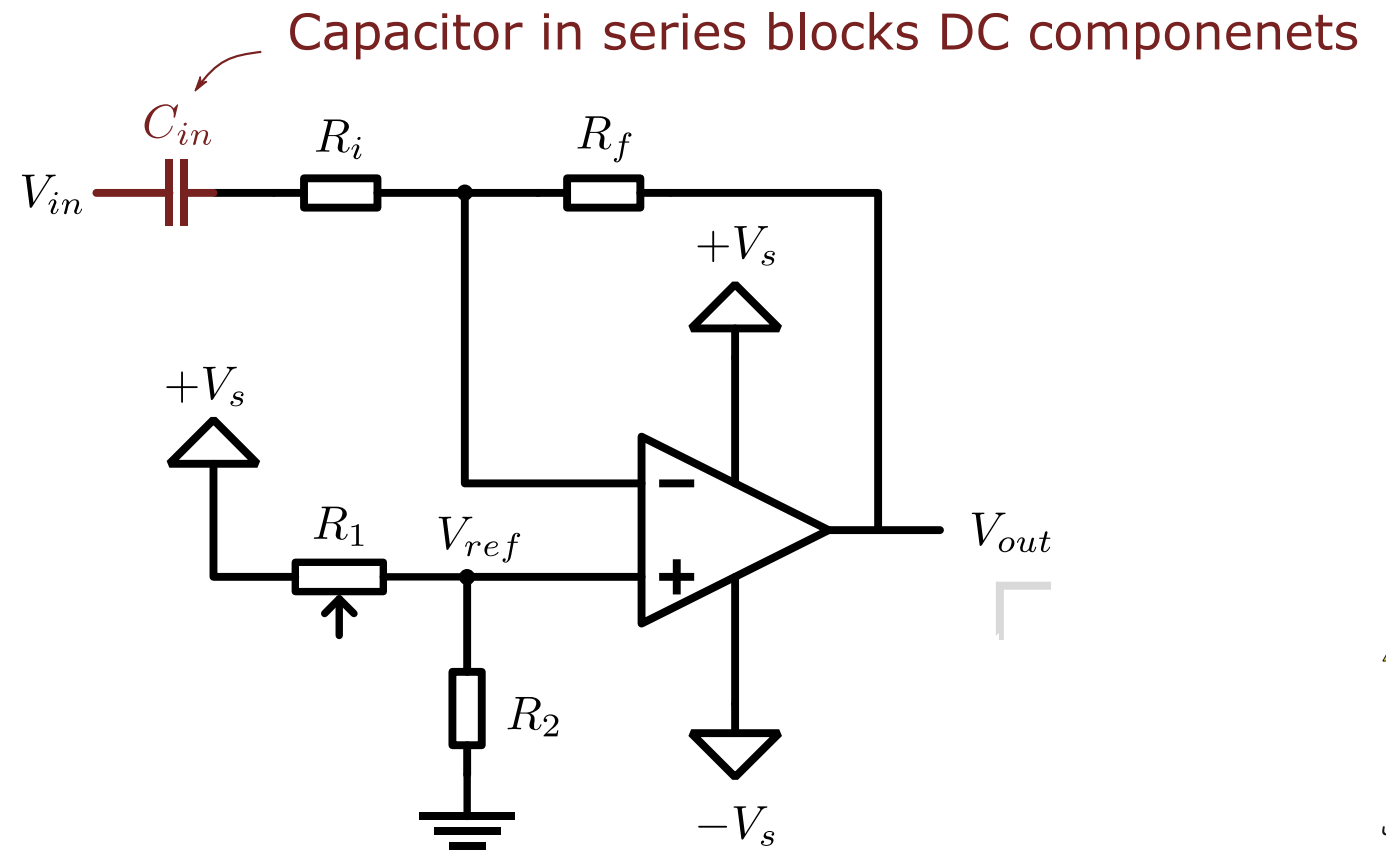
$$V_{out}(t) = (5 - (6 + 2 \sin(t))) \left(\frac{R_f}{R_i} \right) + 5$$



Offset Removal By AC Coupling

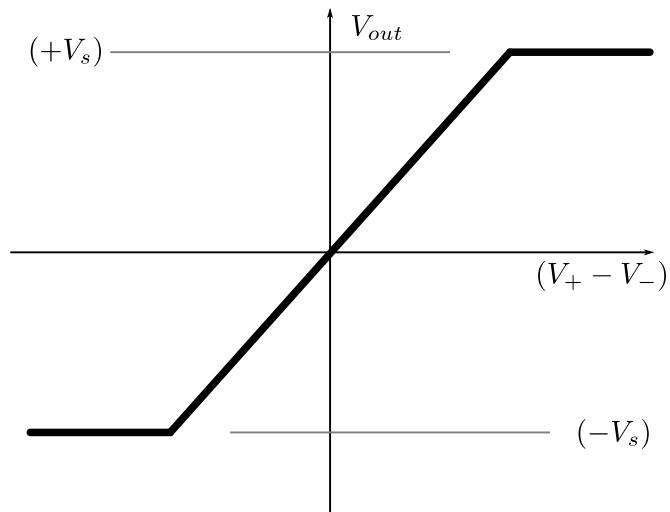
- By adding a capacitor in series with the input, the DC components can be blocked. AC components allowed through.
- Remember the impedance (resistance) of a capacitor:

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

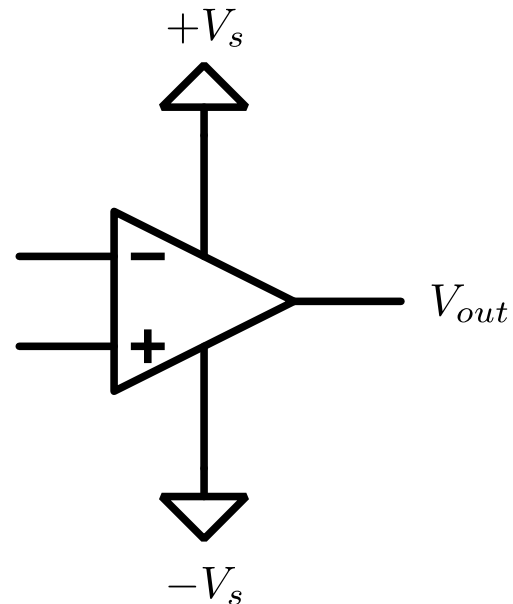


Single Side vs. Dual Side Supply

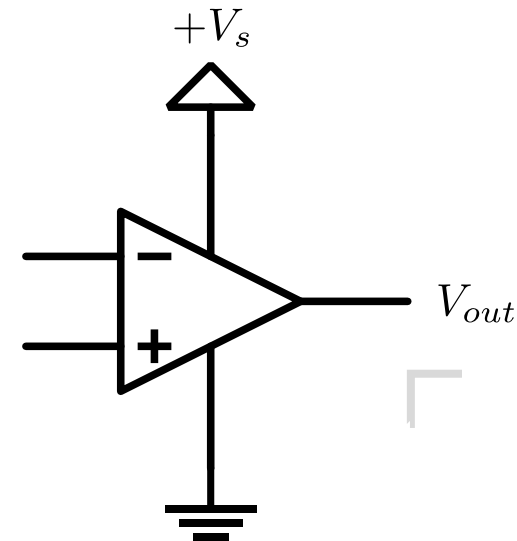
- Op amps can either be single or dual side supply
- The output can only swing within the supply voltage range
- Dual side supply is required if output is expected to be AC (has negative values)
- Single side supply is simpler. Good for +DC range applications.



Dual Side Supply



Single Side Supply



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

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

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

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





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



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 $V_+ - 1.5V$



Choosing an Op-Amp

- There are many options to choose from. There are general purpose and purpose specific op-amps to choose from. (Digikey Op-Amp Search)

Search Within Results

Filter Options: **Stacked** Scrolling

Manufacturer	Packaging	Series	Part Status	Amplifier Type	Number of Circuits	Output Type	Slew Rate
ABLIC U.S.A. Inc.	Box	-	Active	-	1	Differential	-
Advanced Linear Devices Inc.	Bulk	-	Discontinued at Digi-Key	Audio	2	Differential, Rail-to-Rail	0.001V/ μ s
AKM Semiconductor Inc.	Cut Tape (CT)	Apex Precision Power®	Last Time Buy	Bipolar	3	Open Drain	0.0012V/ μ s
ams	Digi-Reel®	Automotive	Not For New Designs	Buffer	4	Push-Pull	0.0013V/ μ s
Analog Devices Inc.	Strip	Automotive, ADI0012	Obsolete	Chopper (Zero-Drift)	5	Push-Pull, Rail-to-Rail	0.0015V/ μ s
Apex Microtechnology	Tape & Reel (TR)	Automotive, AEC-Q100	Preliminary	CMOS	6	Rail-to-Rail	0.0018V/ μ s
Broadcom Limited	Tray	Automotive, AEC-Q100, e-trim™		Current Feedback	8	Single-Ended	0.002V/ μ s
CEL	Tube	Automotive, AEC-Q100, Excalibur™		Current Sense	10		0.0024V/ μ s
Cirrus Logic Inc.		Automotive, AEC-Q100, LinCMOS™		Differential			0.0025V/ μ s
Dialog Semiconductor GmbH		Automotive, AEC-Q100, LMP®		General Purpose			0.0027V/ μ s

Gain Bandwidth Product	-3db Bandwidth	Current - Input Bias	Voltage - Input Offset	Current - Supply	Current - Output / Channel	Voltage - Supply, Single/Dual (±)	Operating Temperature
1kHz	250Hz	0.002pA	0.1 μ V	-	12 μ A	-15V ~ 60V	-55°C ~ 105°C
1.5kHz	400Hz	0.003pA	0.12 μ V	290nA	50 μ A	-	-55°C ~ 125°C
2kHz	500Hz	0.005pA	0.2 μ V	320nA	200 μ A	Out of Bounds	-55°C ~ 125°C (TA)
2.5kHz	1kHz	0.01pA	0.25 μ V	330nA	400 μ A	\pm 1.35V ~ 6V	-55°C ~ 140°C
2.7kHz	1.5kHz	0.02pA	250nV	350nA	450 μ A	\pm 1.5V ~ 22V	-55°C ~ 150°C
3kHz	1.8kHz	0.03pA	0.3 μ V	380nA	500 μ A	\pm 1.8V ~ 5.5V	-55°C ~ 150°C (TA)
3.5kHz	2.5kHz	0.04pA	0.4 μ V	400nA	550 μ A	\pm 10.8V ~ 13.2V	-55°C ~ 175°C
4kHz	3kHz	0.05pA	400nV	425nA	560 μ A	\pm 10.8V ~ 26.4V	-55°C ~ 210°C
Min	Min	Min	Min	450nA	Min	\pm 100V ~ 1250V	-55°C ~ 225°C
Max	Max	Max	Max	460nA	Max	\pm 10V ~ 15V	-50°C ~ 125°C

Mounting Type	Package / Case	Supplier Device Package
-	-	-
Surface Mount	Die	0-DIESALE
Surface Mount, Gull Wing	Module	0-XCEPT
Through Hole	Pentawatt-5 (Horizontal, Bent and Staggered Leads)	DDPAK-7
	Pentawatt-5 (Vertical, Bent and Staggered Leads)	DDPAK/TO-263-5
	SC-70, SOT-323	DDPAK/TO-263-7
	SC-74, SOT-457	Die
	SC-74A, SOT-753	Diesale
	SOT-23-5 Thin, TSOT-23-5	ESV
	SOT-23-6	HVSOF5

Clear All Selections

