NANYANG TECHNOLOGICAL UNIVERSITY

MA2011 MECHATRONICS SYSTEMS INTERFACING

Lecture 5

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College of Engineering
School of Mechanical and Aerospace Engineering

RECAP OF LECTURE 4

RECAP OF LECTURE 4

Shannon-Nyquist Theorem

Sampling rate (f_s)> 2* Nyquist frequency (f_{max})

Aliasing

Sampling rate (f_s) < 2* Nyquist frequency

Quantizing & Coding

Undersampled & oversampled

PART 5: ANALOG SIGNAL PROCESSING USING OPERATIONAL AMPLIFIERS

PART 5.1 BACKGROUND

VACUUM TUBE TECHNOLOGY

VTT in the 1960s

VACUUM TUBE TECHNOLOGY

VTT in the 1960s

Drawbacks

- Heavy power consumers
- Significant heat dissipation
- Large size
- Heavy weight
- Requiring frequent battery replacement for portable units

SOLID STATE TECHNOLOGY

VTT in the 1960s

Solid State Technology (SST) vs. Vacuum Tube Technology (VTT)

- SST: Charge carriers move through a solid semiconduct material.
- VTT: Bulky tubes enclosed a gas at low pressure through which electronics flowed.

SST has replaced the VTT

Solid state transistors and integrated circuits make the amplifier design

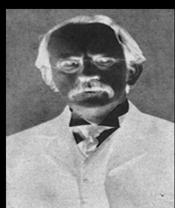
- Small size
- Portable using rechargable battery
- Low weight
- Cool-running
- Energy saving

SOLID STATE TECHNOLOGY

Solid State Technology (SST) vs. Vacuum Tube Technology (VTT)

John Bardeen, Walter Brattain, & William Shockley
(Bell Lab)
Nobel Prize Physics, 1956

Sir Joseph John Thomson
(18 Dec 1856 – 30 Aug 1940)
Nobel Prize Physics, 1906



LEARNING OBJECTIVES

1. Understand input/output characteristics of a linear amplifier
2. Use model of an ideal operational amplifier in circuit analysis
3. Design operational amplifier circuits
4. Design several operational amplifier
5. Understand characteristics and limitation of a real operational amplifier

MOTIVATIONS

Motivation #1 Signal out of transducers usually are too small, say few millivolts

Motivation #2 Signals out of transducers usually are too noisy

Motivation #3 Signals out of transducers usually contain wrong information due to design and installation of transducers

Motivation #4 Signals out of transducers usually have a DC offset due to design of transducer and instrumentation

SOLUTIONS

Many of these problems can be fixed by analog signal processing:

- Signal amplification
- Signal inversion
- Signal differentiation
- Signal integration
- Signal addition
- Signal subtraction
- Signal comparison

FOCUSES

1. Salient features of amplifiers
2. Determine how we may design an amplifier using intergrated circuits

PART 5.2 AMPLIFIERS

AMPLIFIER

Ideally, an amplifier increases the amplitudes of a signal without affecting the phase relationship of different components of the signal.

LINEARITY

Measurement system with linearity

Linear dynamic system

Linearity with amplifiers

AMPLIFIER LINEARITY

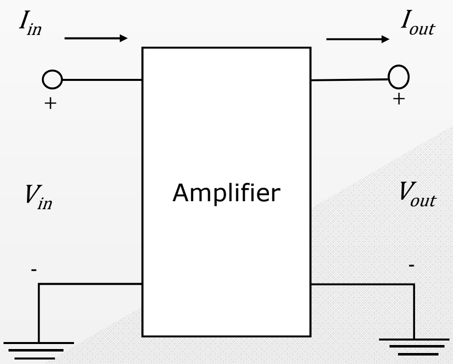
Voltage gain

- Constant for all frequencies
- Filtering

AMPLIFIER AND AMPLIFIER LINEARITY

Relationship between output and input

Where A_v is the gain. Ideally, Av is constant for all frequencies but practically there is a bandwidth associated with cutoff frequencies.



$$V_{out} = A_v V_{in}$$

FILTERING AND AMPLIFIER LINEARITY

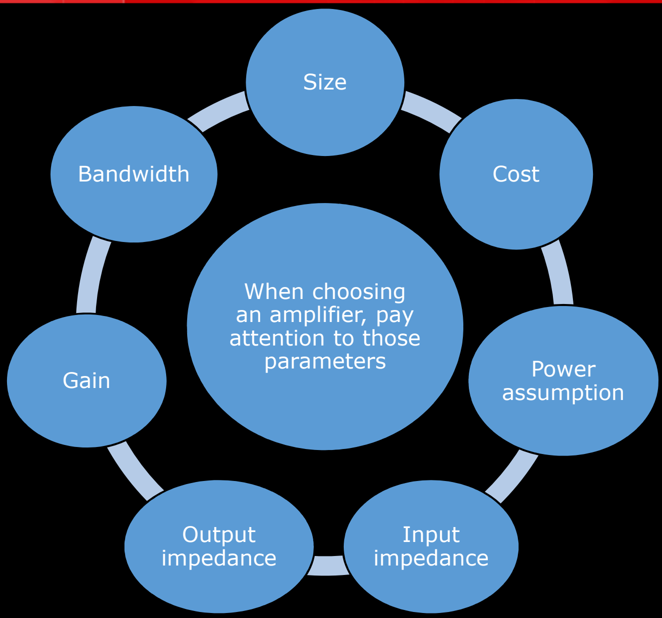
Filtering

Amplifiers are designed for certain frequencies instead of all frequencies

Output charactersitics are governed by the of amplifiers' bandwidth

There are associated cutoff frequencies (thresholds)

CHARACTERISTICS OF AMPLIFIERS



THE INPUT IMPEDANCE

Most of amplifiers designed to have

- Large input impedance
- Little current is drawn from the input

Input impedance Z_{in} is

$$Z_{in} = \frac{V_{in}}{I_{in}}$$

Input impedance should be large to have little current drawn from the input.

THE OUTPUT IMPEDANCE

- The voltage drop ΔV_{out} is a measure of how much the output voltage drops with output current
- Most of the amplifiers are designed to have a very small output impedance so the output voltage will not change much as the output current changes

Output impedance Z_{out} is

$$Z_{out} = \frac{\Delta V_{out}}{I_{in}}$$

Where the voltage drop ΔV_{out} is measured relative to the output voltage with no current. Output impedance should be small to have little change when the output current changes.

PART 5.3 OPERATIONAL AMPLIFIERS

OPERATIONAL AMPLIFIERS

- #1 Low-cost
- #2 Versatile integrated circuits
- #3 Single chip manufactured consisting of intenal transistors, resistors, and capacitors
- #4 Combining with external discrete components to create a wide variety of signal processing circuits

OPERATIONAL AMPLIFIERS: THE BASIC BLOCK

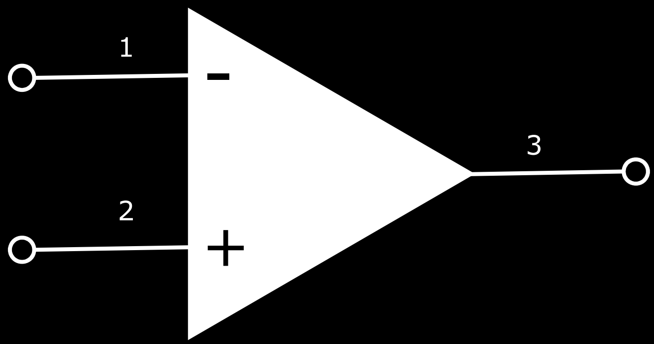
AMPLIFIERS	INTEGRATORS	SUMMERS
A/D CONVERTORS	D/A CONVERTORS	DIFFERENTIATORS
ACTIVE FILTERS	SAMPLE & HOLD AMPLIFIERS	COMPARATORS

OPERATIONAL AMPLIFIER CIRCUITS – FUNCTIONS

INVERTING AMPLIFIERS	SUMMER AMPLIFIERS	INTEGRATOR AMPLFIERS
NONINVERTING AMPLIFIERS	DIFFERENCE AMPLIFIERS	DIFFERENTIATOR AMPLIFIERS

PART 5.4 IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

IDEAL MODEL FOR OPERATIONAL AMPLIFIERS



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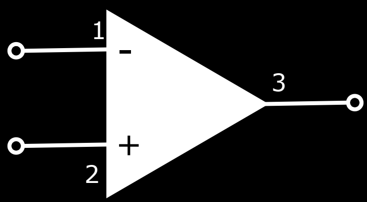
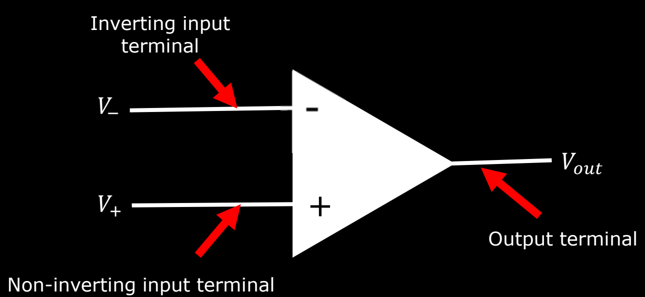
IDEAL MODEL FOR OPERATIONAL AMPLIFIERS



Schematic and nomenclature:



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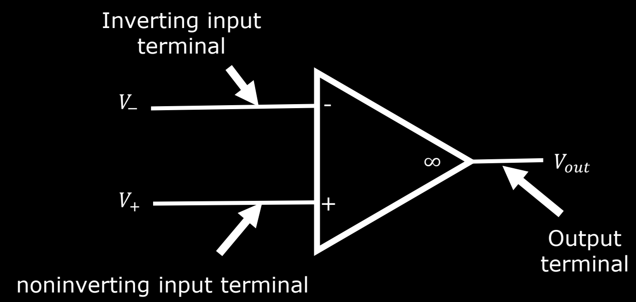
IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

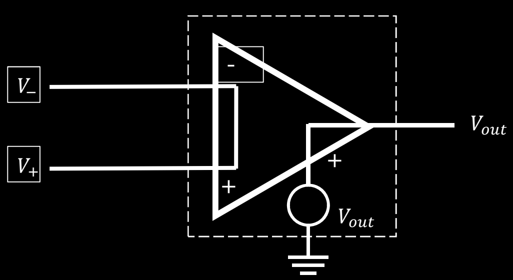
Schematic and nomenclature:



- A differential input
  - The inverting input (-)
  - The non-inverting input (+)
- Single output
- Infinite gain (∞)

IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

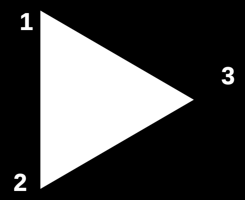
Schematic and nomenclature:



The voltages are all referenced to a common ground

IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

CHARACTERISTIC OF OPERATIONAL AMPLIFIERS

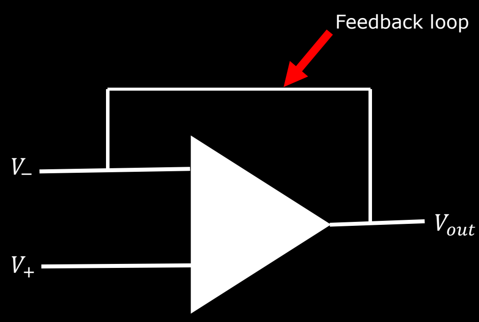


$$V_{out} = A_v \, V_{in}$$

$$V_3 = A(V_2 - V_1)$$

Output voltage is proportional to the difference between the two inputs of the amplifier

IDEAL MODEL FOR OPERATIONAL AMPLIFIERS



Feedback: From the output to the inverting input (-)

IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

CLOSE LOOP OR OPEN LOOP?

Start from here

- Closed loop configuration
  - When feedback is present
  - Stablization of the amplifiers
  - Control of the gain
- Open loop configuration
  - When feedback is absent
  - Considerable instabiity due to the high gain
  - Seldom used

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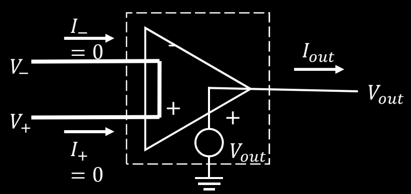
IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

Infinite impedance at both inputs
- No current is drawn from the input circuits
- Therefore, $I_+ = I_- = 0$

- Infinite gain (assume no current flow between the short of the two inputs)
- The difference between the input voltages must be 0 (otherwise, the output would be infinite)
- Therefore $V_+ = V_-$

Operational amplifier equivalent circuit:



Zero output impedance
- The output voltage does not depend on the output current

Note:
1. V_{out}, V_+ and V_- all referenced to a same ground
2. For stable linear behaviour, there must be feedback between the output and the inverting input

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IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

SUMMARY & Assumptions for an ideal op am:

1. It has infinite impedance at both inputs, so no current drawn from the input circuit: $I_{+}= I_{-}=0$
2. It has infinite gain, so difference between input voltages is zero: $V_{+} = V_{-}$
3. It has zero output impedance, so output voltage does not depend on output current

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IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

INFINITE OR ZERO?

1. The Open-Loop gain A is VERY VERY LARGE ⇒ can be considered as INFINITE
2. The input impedances of the two terminals are VERY VERY LARGE ⇒ can be considered as INFINITE
3. The output impedance is VERY VERY SMALL ⇒ can be considered as ZERO

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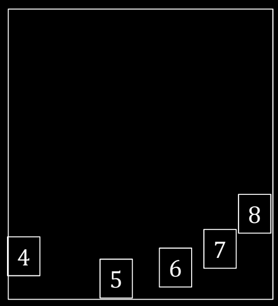
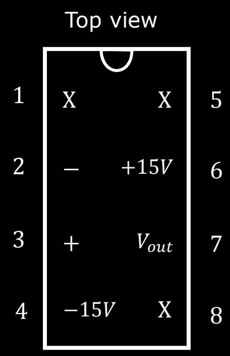
IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

A real operational amplifier looks like:





And is accompanied by data sheets with details

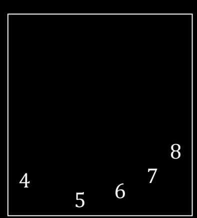
IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

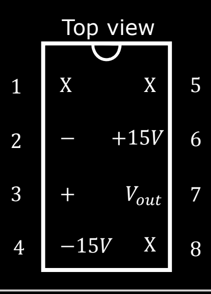
PACKAGING

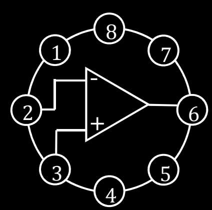
- Eight pin & dual in-line package (DIP) integrated circuit (or a chip)
- **741**- Designation of a general purpose op amp by many manufacturers

PIN CONFIGURATION (PIN-OUT)

- One indention or spot
- The pins are numbered counterclockwise







IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

741

Pin 2: Inverting input (-)

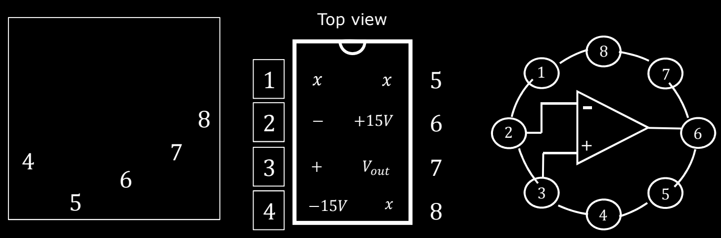
Pin 3: Non-inverting input (+)

Pin 4: External power supply (-15V)

Pin 7: External power supply (+15V)

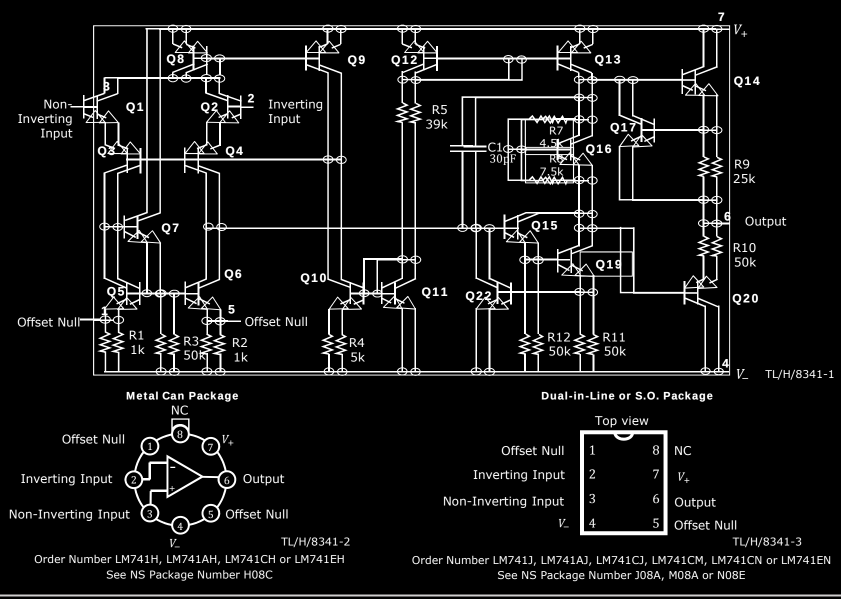
Pin 6: The op amp output

Pins 1, 5 and 8: not normally used, no connections are required



IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

Internal design of a 741, Metal Can Package and Dual In-line Package



IDEAL MODEL FOR OPERATIONAL AMPLIFIERS

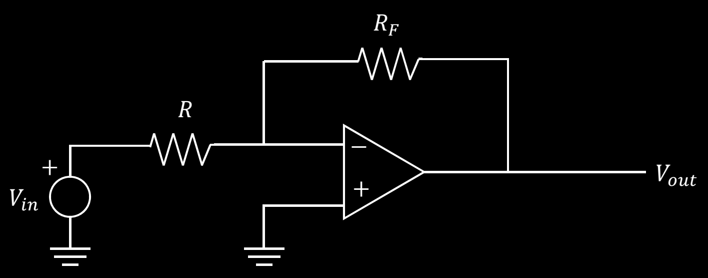
MANY MANUFACTURERS WITH DIFFERENT PRODUCTS

- Input impedances
- Bandwidth
- Power ratings
- Some may require only a single-output (unipolar) power supply
- Data sheets: Detail information on the IC chips from a specific manufactuerer

PART 5.5 INVERTING AMPLIFIER

INVERTING AMPLIFIER

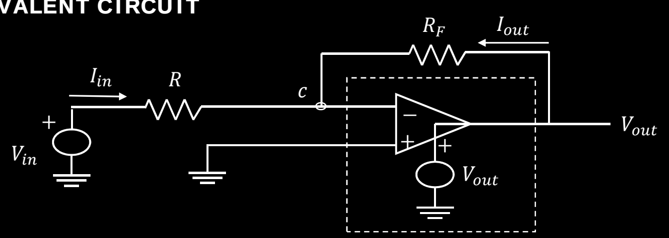
Inverting amplifier inverts and amplifies the input voltage



- Constructed by connecting two external resistors to an op amp
- This circuit inverts and amplifies the input voltage
- The resistor R_F forms the feedback loop
  - ➢ The loop always goes from the output to the inverting input of the op amp
  - ➢ So it is a negative feedback

INVERTING AMPLIFIER

EQUIVALENT CIRCUIT



ideal model

At node C: $I_{in} = -I_{out}$ $V_c = 0$

Since no currents flow into inputs of op am (Assumption 1).
Voltage across the resistor R is $V_{in} - V_c = V_{in}$, from Ohm's law:

$$V_{in} = I_{in}R$$

Voltage across the resistor R_F is $V_{out} - V_c = V_{out}$, from Ohm's law:

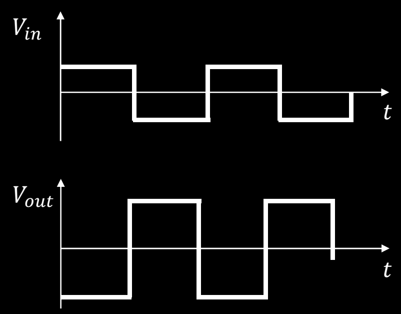
$$V_{out} = I_{out}R_F = -I_{in}R_F$$

Hence

$$\frac{V_{out}}{V_{in}} = -\frac{R_F}{R}$$

INVERTING AMPLIFIER

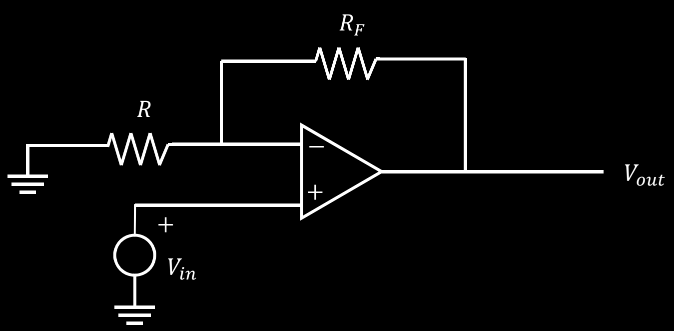
- The voltage gain of the amplifier is determined simply by the external resisters R_F and R
- The voltage gain of the amplifier is always negative
- An example: Inverting (-) + amplifying (2)



PART 5.6 NONINVERTING AMPLIFIER

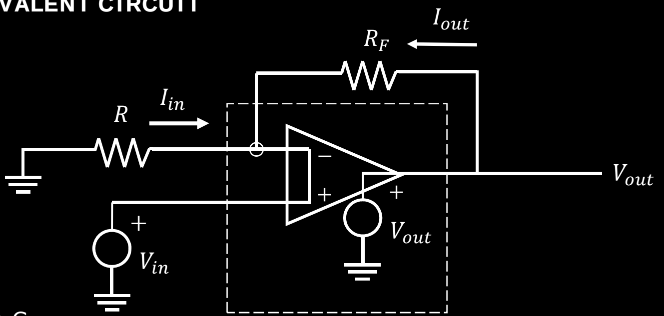
NON-INVERTING AMPLIFIER

Non-inverting amplifier amplifies the input voltage without inverting the signal.



NON-INVERTING AMPLIFIER

EQUIVALENT CIRCUIT



At node C,

$$V_c = V_{in} \qquad V_{in} = -I_{in}R, \qquad I_{in} + I_{out} = 0$$

Voltage across R_F:

$$V_{out} = I_{out}R_F + V_{in}$$

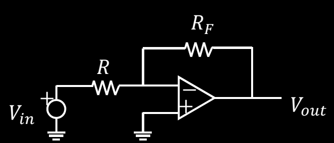
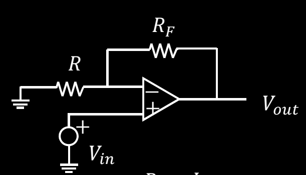
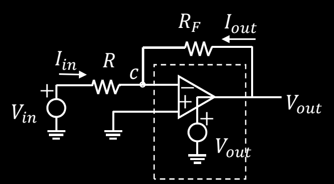
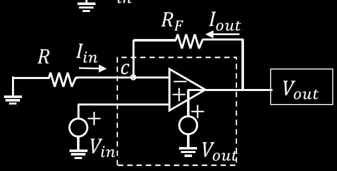
Therefore $$\frac{V_{out}}{V_{in}} = \frac{I_{out}R_F + V_{in}}{-I_{in}R} = \frac{I_{out}R_F - I_{in}R}{-I_{in}R} = \frac{-I_{in}R_F - I_{in}\ R}{-I_{in}R} = 1 + \frac{R_F}{R}$$

NONINVERTING AMPLIFIER

SUMMARY

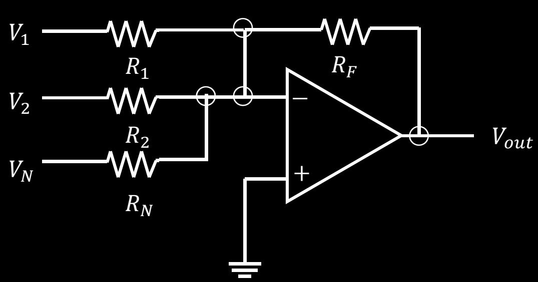
- Amplifying the input without inverting the signal
- Positive gain greater than or equal to 1

NON-INVERTING AMPLIFIER

	INVERTING	NON-INVERTING
Amplifier		
Equivalent circuit		
Gain	Opposite sign	Same sign

PART 5.7 SUMMER AMPLIFIER

SUMMER AMPLIFIER



The Adder Circuit

$$V_{outN} = -\frac{R_F}{R_N} V_N$$

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

$$V_{out2} = -\frac{R_F}{R_2} V_2$$

$$V_{out} = -\left(\frac{R_F}{R_1} V_1 + \frac{R_F}{R_2} V_2 + \frac{R_F}{R_N} V_N\right)$$

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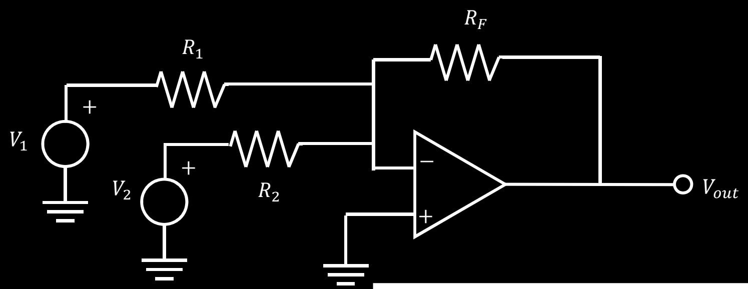
SUMMER AMPLIFIER

Summer is used to add analog signals:



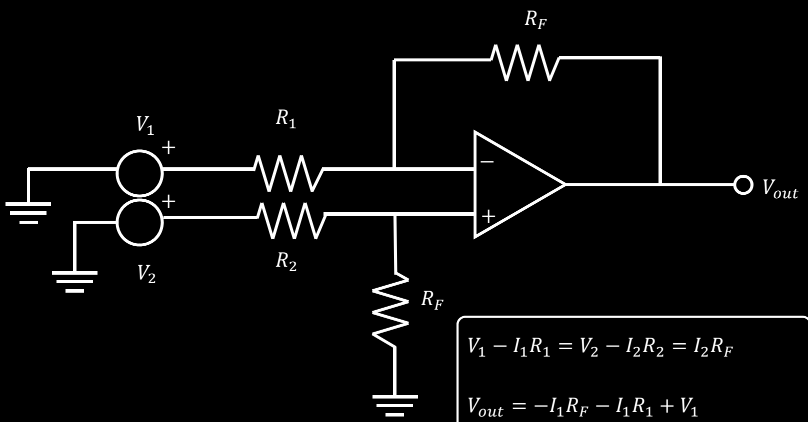
$$\frac{V_1}{R_1} + \frac{V_2}{R_2} = -\frac{V_{out}}{R_F}$$

- Also known as Adder
- Add another analog signal
- Output is the negative sum of the inputs

PART 5.8 DIFFERENCE AMPLIFIER

DIFFERENCE AMPLIFIER

Difference amplifier circuit is used to subtract analog signals:



$$V_1 - I_1R_1 = V_2 - I_2R_2 = I_2R_F$$

$$V_{out} = -I_1R_F - I_1R_1 + V_1$$

DIFFERENCE AMPLIFIER

Hence

$$I_2 = \frac{V_2}{R_F+R_2} \quad \rightarrow \quad I_1 = \frac{V_1}{R_1} - \frac{V_2}{R_F+R_2}\frac{R_F}{R_1}$$

So

$$V_{out} = V_1 - (R_F + R_1)\left(\frac{V_1}{R_1} - \frac{V_2}{R_F+R_2}\frac{R_F}{R_1}\right)$$

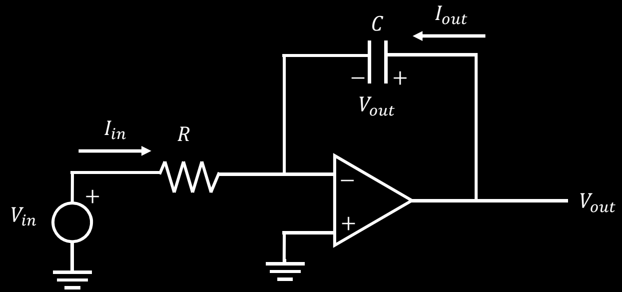
If $R_1 = R_2 = R$,

$$V_{out} = \frac{R_F}{R_1}(V_2 - V_1)$$

PART 5.9 INTEGRATOR

INTEGRATOR

If the feedback resistor of the inverting op amp circuit is replaced by a capacitor to form an integrator circuit



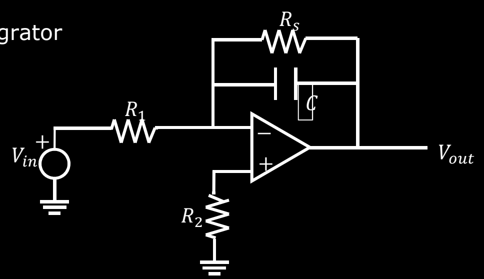
$$\boxed{\frac{dV_{out}}{dt} = \frac{I_{out}}{C} = -\frac{I_{in}}{C} = -\frac{V_{in}}{RC}}$$

So

$$\boxed{V_{out}(t) = -\frac{1}{RC}\int_0^t V_{in}(\tau)d\tau}$$

INTEGRATOR

Practical integrator



So

$$\boxed{C\frac{dV_{out}}{dt} + \frac{V_{out}}{R_s} = I_{out} = -I_{in} = -\frac{V_{in}}{R_1}}$$

$$\boxed{\frac{dV_{out}}{dt} + \frac{1}{CR_s}V_{out} = -\frac{1}{R_1 C}V_{in}}$$

Should choose:

$$\boxed{R_s > 10R_1, \qquad R_2 = -\frac{R_1 R_s}{R_1 + R_s}}$$

i.e., R_2 is an approximation of the parallel combination of R_1 and R_s to minimize DC offset due to input current bias

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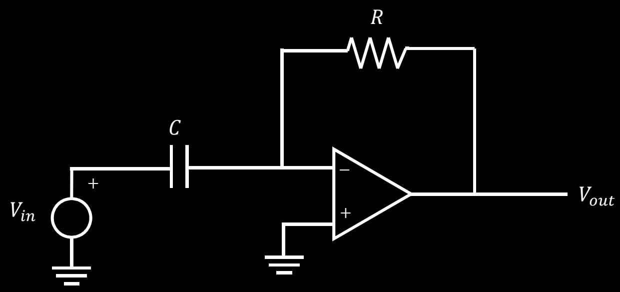
PART 5.10 DIFFERENTIATOR

DIFFERENTIATOR

The input resistor of the inverting op amp circuit is replaced by a capacitor to form a differentiator circuit



$$\frac{dV_{in}}{dt} = \frac{I_{in}}{C} = -\frac{I_{out}}{C} = -\frac{V_{out}}{RC}$$

So

$$V_{out} = -RC\frac{dV_{in}}{dt}$$

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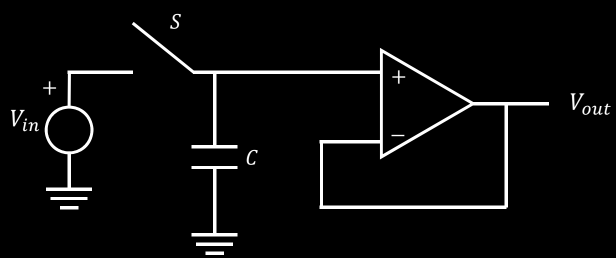
PART 5.11 SAMPLE AND HOLD CIRCUIT

SAMPLE AND HOLD CIRCUIT

1. Extensively used in analog-to-digital conversion
2. Signal value must be stablised while it is converted to a digital representtation
3. Consisting of voltage-holding capacitor and a voltage follower
4. With switch closed

SAMPLE AND HOLD CIRCUIT



Where switch S closed,

$$\boxed{V_{out}(t) = V_{in}(t)}$$

Where switch S opened,

$$\boxed{V_{out}(t - t_{sampled}) = V_{in}(t_{sampled})}$$

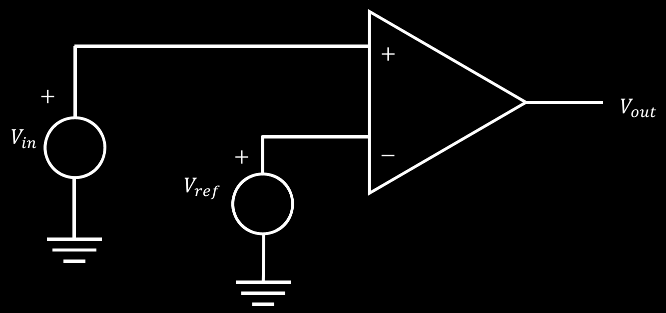
Should choose capacitor C with low leakage

PART 5.12 COMPARATOR

COMPARATOR

1. Used to determine whether one signal is greater than another
2. The comparator is an example of an op amp circuit where there is no negative feedback and the circuit exhibits infinite gain
3. The result is that the op amp saturates
4. Saturation implies that the output remains at its most positive or most negative output value

COMPARATOR



$$V_{out} = \begin{cases} +V_{sat}, & V_{in} > V_{ref} \\ -V_{sat}, & V_{in} < V_{ref} \end{cases}$$

Where V_{sat} is the saturation voltage of the comparator. Most comparators are specially built.

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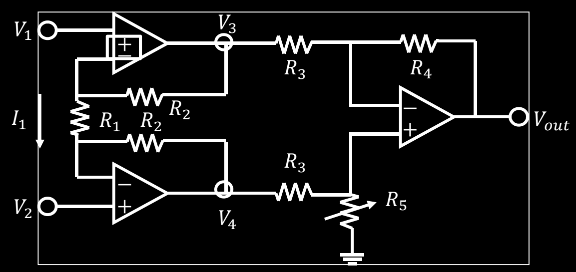
5.13 INSTRUMENTATION AMPLIFIER

INSTRUMENTATION AMPLIFIER

- Subtracting analog signals
- Non-inversion illustration



The left part:

$$V_3 - V_1 = I_1 R_2$$
$$V_2 - V_4 = I_1 R_2$$
$$V_1 - V_2 = I_1 R_1$$

The right part:

$$V_3 - I_3 R_3 = V_4 - I_4 R_3 = I_4 R_5$$
$$V_{out} = -I_3 R_4 - I_3 R_3 + V_3$$

Where I_3 and I_4 are currents through R_3 and $R_{4.}$

INSTRUMENTATION AMPLIFIER

So

$$V_3 = \left(\frac{R_2}{R_1} + 1\right) V_1 - \frac{R_2}{R_1} V_2, \qquad V_4 = \left(\frac{R_2}{R_1} + 1\right) V_2 - \frac{R_2}{R_1} V_1$$

$$V_{out} = \frac{R_5 (R_3 + R_4)}{R_3 (R_3 + R_5)} V_4 - \frac{R_4}{R_3} V_3$$

If $\mathrm{R}_4 = \mathrm{R}_5$, then

$$V_{out} = \left[\frac{R_4}{R_3}\left(1 + 2\frac{R_2}{R_1}\right)\right](V_2 - V_1)$$

So if $V_1 = V_2$, then $V_{out} = 0$.
In practice, we need a variable resistor R_5 to tune such that $R_4 = R_5$

INSTRUMENTATION AMPLIFIER

- Difference amplifier may be satisfactory for low-impedance source, but its imput impedance is too low for high-output impedance source
- If the levels of the input signals are very low and the signals include noise, the difference amplifier is unable to extract a satisfactory difference signal
- Instrumentation amplifier is a solution for this problem

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INSTRUMENTATION AMPLIFIER

- Very high input impedance
- Large common mode rejection ratio (CMRR): Ratio of the difference mode gain to the common mode gain
- The difference mode gain is the amplification factor for the difference between the input signals
- The common mode gain is the amplification factor for the average of the input signals
- For an ideal difference amplifier, the common mode gain is 0, implying an infinite CMRR.

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INSTRUMENTATION AMPLIFIER

- It is desireable to minimize the common mode gain to supress signals such as noise that are common to both inputs
- Capability to amplify low-level signals in a noise environment, often a requirement in differential-output sensor signal-conditioning applications
- Consistent bandwidth over a large range of gains