

Electromechanical Systems and Mechatronics

Signal Conditioning: Lecture 3

Signal Conditioning Processes

The Operational Amplifier

Filtering

Digital Signals

Multiplexers

Data Acquisition

Digital Signal Processing

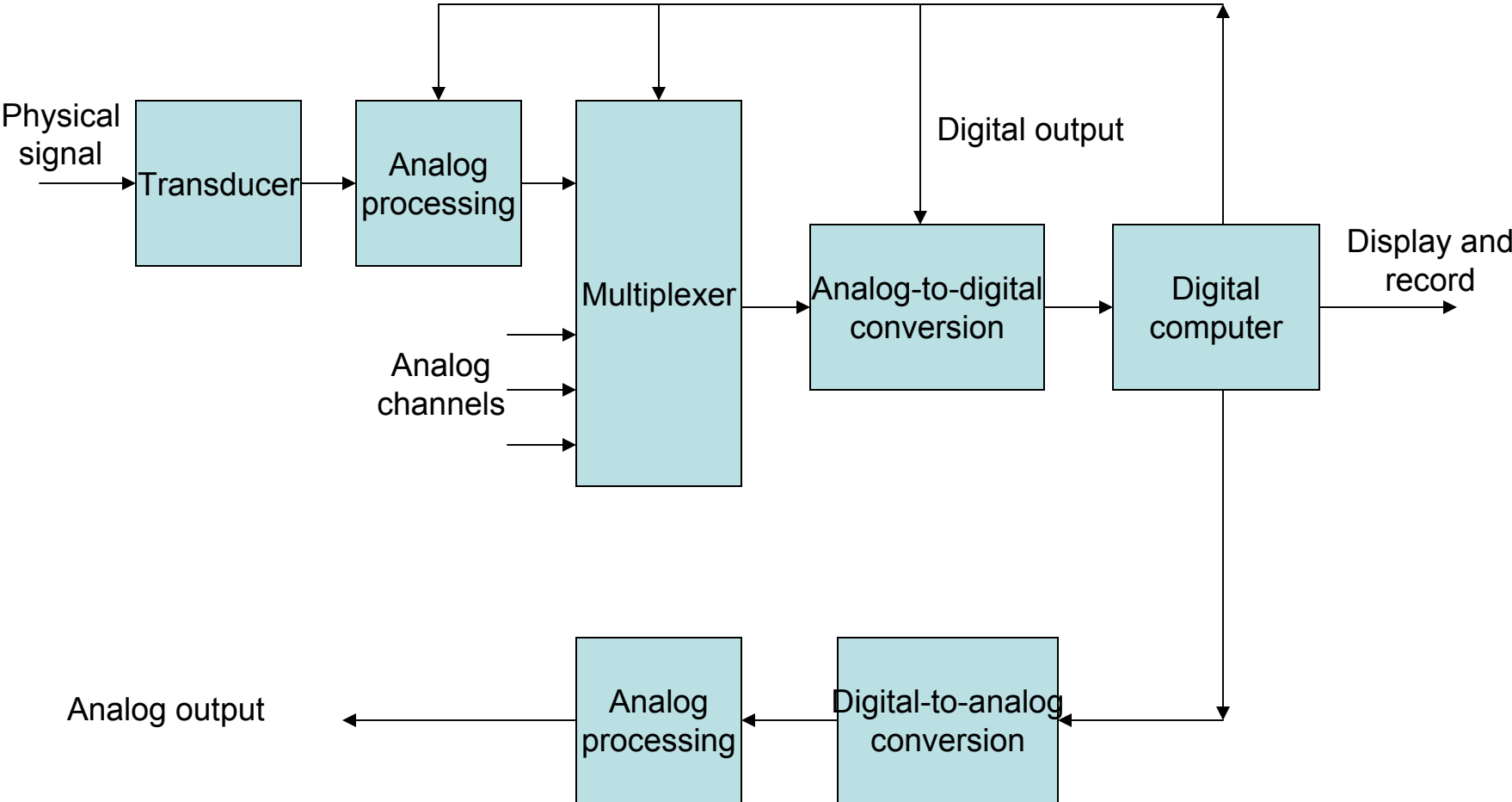
Pulse Modulation

References

Giorgio Rizzoni, Principles and Applications of Electrical Engineering, Fourth Edition, 2003

W. Bolton, Mechatronics: Electronic Control Systems in Mechanical and Electrical Engineering, Prentice Hall, 2003.

Instrumentation System

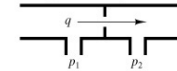


Sensors: Signal Classification

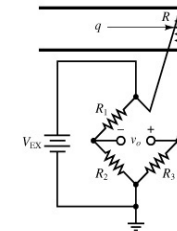
Sensor design always involves the application of some law or principle of physics or chemistry that relates the quantity of interest to some measurement event.

- **Motion, position and dimensional variable:**
 - *Potentiometers; stress and strain gages; capacitive sensors; differential transformers, optical sensors.*
- **Force, torque, pressure and flow:**
 - *Strain gages; piezoelectric sensors; capacitive sensors.*
- **Flow:**
 - *Turbine meters; electromagnetic sensors; imaging sensors.*
- **Temperature:**
 - *Thermocouples; thermometers.*
- **Liquid level:**
 - *Motion transducers; Force transducers.*
- **Humidity: Semiconductor sensors and MEMS.**
- **Chemical composition: Gas analysis equipment; semiconductor gas sensors.**

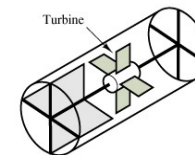
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Differential-pressure flow-meter: A calibrated orifice and a pair of pressure transducers permit the measurement of flow rate.
(a)



Hot-wire anemometer: A heated wire is cooled by the gas flow. The resistance of the wire changes with temperature.
(b)



Turbine flowmeter: Fluid flow induces rotation of the turbine; measurement of turbine velocity provides an indication of flow rate.
(c)

Instrumentation: Sensors and Transducers

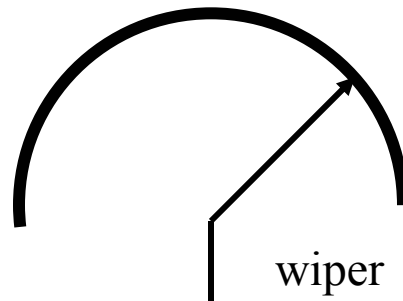
- An important component in mechatronic systems that is linked to instrumentation is the sensor, whose function is to provide a mechanism for collecting information about a particular process.
- Sensors transform real-world data into electrical signals. The sensor may be defined as a device that produces an output signal for the purpose of sensing of a physical phenomenon. Sensors are also referred as transducers.
- The extent to which sensors and transducers are used depends upon the level of automation and the complexity of the control system. There is always a need for faster, sensitive, and precise measuring devices, accordingly, sensors are being miniaturized in solid state form by combining several sensors and signal processing mechanisms.

Types of Sensors

- **Active Sensors:** They require external power for their operation.
- **Passive Sensors:** Examples include piezoelectric, thermoelectric, and radioactive.
- **Analog Sensors:** They have an output that is proportional to the variable being measured.
- **Digital Sensors:** They are accurate and precision.
- **Deflection Sensors:** They are used in a physical setup where the output is proportional to the measured quantity that is displayed.
- **Null Sensors:** In this type, any deflection due to the measured quantity is balanced by the opposing calibrated force so that any imbalance is detected.

Resistance Transducers

- A displacement transducer that uses the variable resistance transduction principle may be manufactured with a **rotary** or **linear** potentiometer (rotation or displacement is converted into a potential difference).
- Such potentiometers consist of a wiper that makes contact with a resistive element, and as this point of contact moves, the resistance between the wiper and end leads of the device changes in proportion to the angular displacement.
- Through voltage division, the change in resistance can be used to create an output voltage that is directly proportional to the input displacement.



Inductance Transducers

- Inductance transducers are used for proximity sensing when the presence or absence of an object must be detected with an electronic non-contact sensor. They are also used for motion position detection, motion control, and process control applications.
- Variable inductance transducers are based on Faraday's law of induction in a coil: the induced voltage is equal to the rate at which the magnetic flux through the circuit changes

$$V = N \frac{d\phi}{dt} = N \frac{d(BA)}{dt} = \frac{dN(\phi)}{dt} = \frac{d\psi}{dt}$$

(ψ is the total flux linkage in the circuit)

$$L = \frac{\psi}{i} = \frac{N\phi}{i}$$

$$\phi = \frac{Ni}{R}$$

$$L = \frac{N^2}{R}; R = \frac{1}{\mu A} = N^2 \mu \left(\frac{A}{l} \right)$$

Wheatstone Bridge

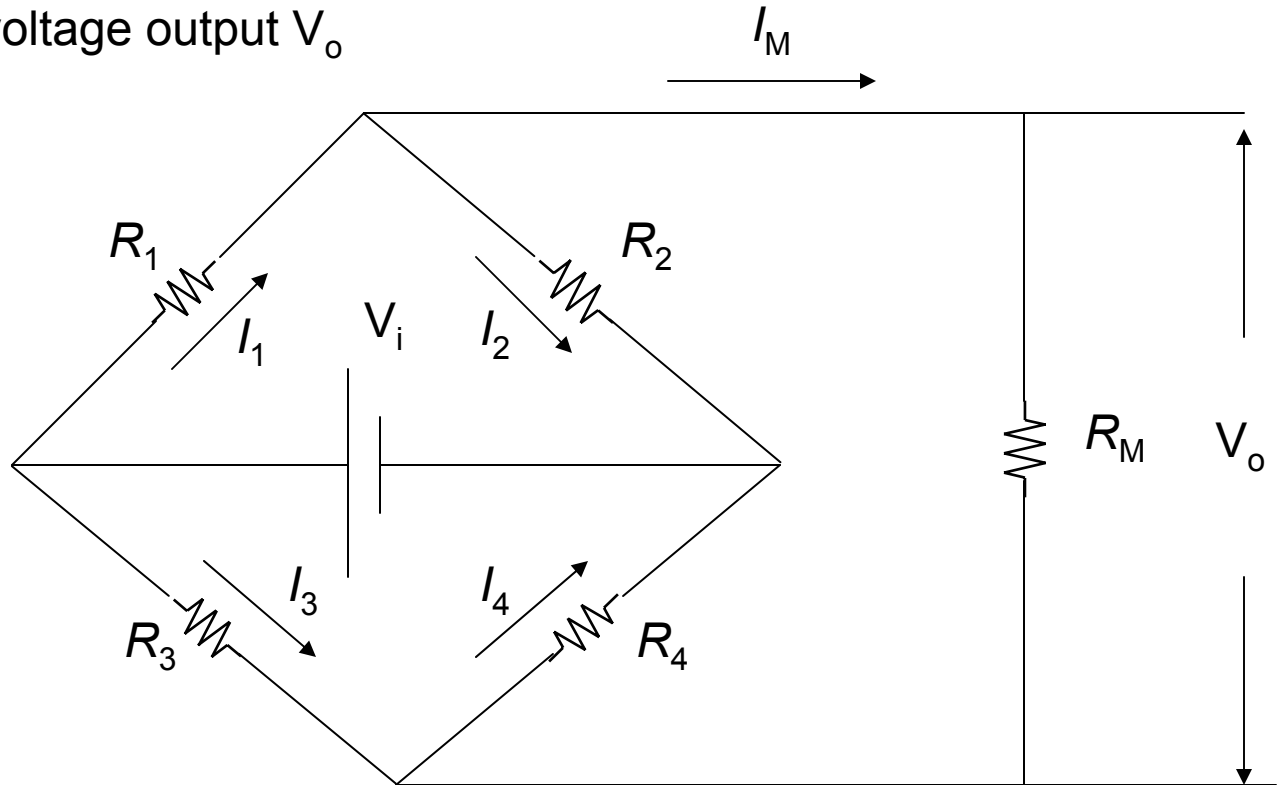
- The bridge converts a relative change of resistance $\delta = \Delta R/R$ into a proportional voltage output V_o

$$I_1 R_1 - I_3 R_3 = 0$$

$$I_2 R_2 - I_4 R_4 = 0$$

$$\frac{I_1 R_1}{I_2 R_2} = \frac{I_3 R_3}{I_4 R_4}$$

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$



Temperature Effect in Strain Gage

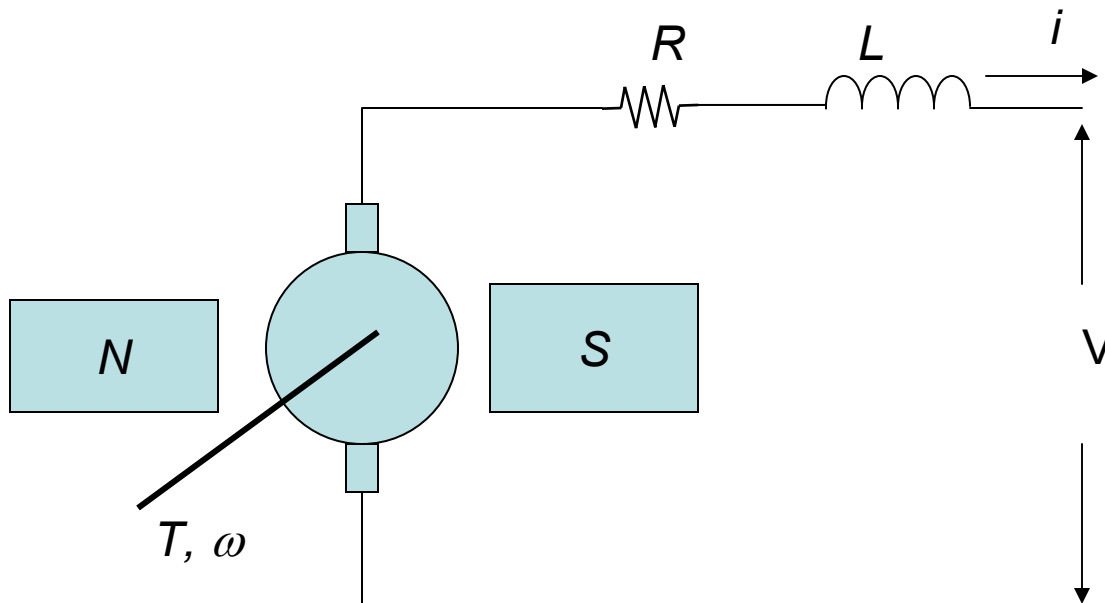
- The strain gauge environment is often influenced by temperature change. The electrical resistivity of most alloys changes with temperature, increasing as temperature rises and decreasing as it falls. Usually metals used in strain gauges have a temperature coefficient (α_0) on the order of $0.004/^\circ\text{C}$. The resistance at temperature T is given by

$$R_T = R_{T_0} (1 + \alpha_0 \Delta T)$$

$$\Delta R_T = R_{T_0} \alpha_0 \Delta T \text{ (Resistance change due to change in Temperature)}$$

Velocity Measurement: Tachometer

- A permanent magnet DC generator can be used for analog measurement of angular velocity. ω is the angular velocity to be measured, T is the torque required to drive the generator, L and R are the inductance and the capacitance of the rotor, I is the current in the rotor windings, and V is the voltage output at the rotor windings terminals.



Signal Conditioning Processes

- **Protection to prevent damage to the next element.**
- **Preparing the signal into the right type of signal.**
- **Providing the right level of signal.**
- **Eliminating or reducing the noise.**
- **Signal manipulation or making it a linear function of some variable.**

Operational Amplifier

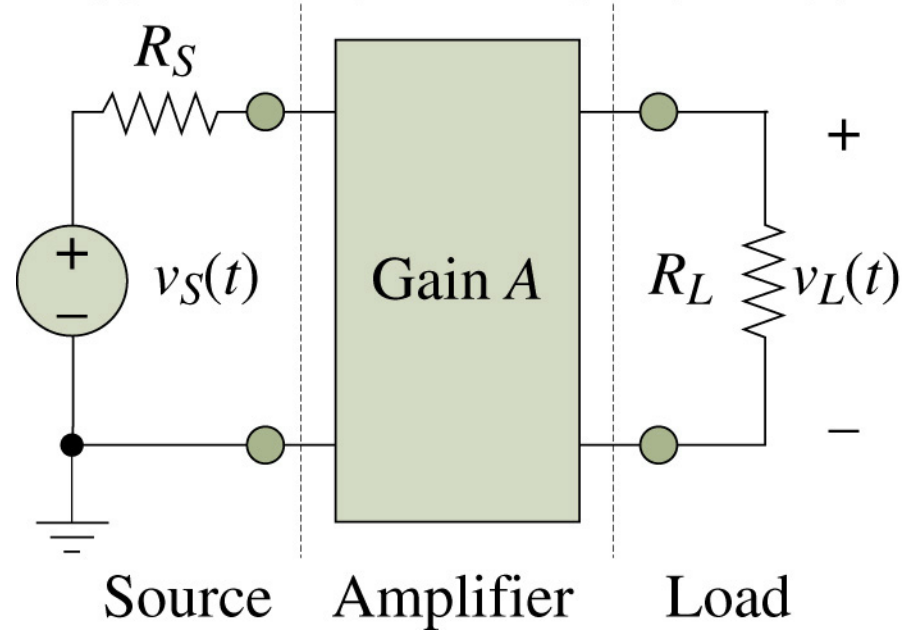
- Inverting Amplifier
- Non-Inverting Amplifier
- Summing Amplifier
- Integrating Amplifier
- Differential Amplifier
- Logarithmic Amplifier
- Comparator

Operational Amplifier

- Operational amplifier is an amplifier whose output voltage is proportional to the negative of its input voltage and that boosts the amplitude of an input signal, many times, i.e., has a very high gain. High-gain amplifiers.
- They were developed to be used in synthesizing mathematical operations in early analog computers, hence their name.
- Typified by the series 741 (The integrated circuit contains 8-pin mini-DIP, 20 transistors and 11 resistors).
- Used for amplifications, as switches, as filters, as rectifiers, and in digital circuits.
- Take advantage of large open-loop gain.
- It is usually connected so that part of the output is fed back to the input.
- Can be used with positive feedback to produce oscillation.

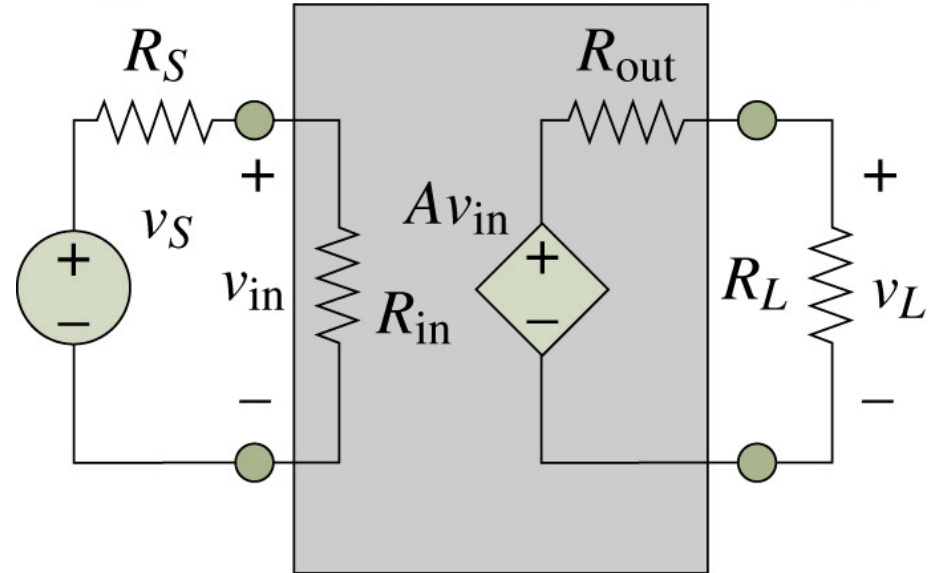
A Voltage Amplifier

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Simple Voltage Amplifier Model

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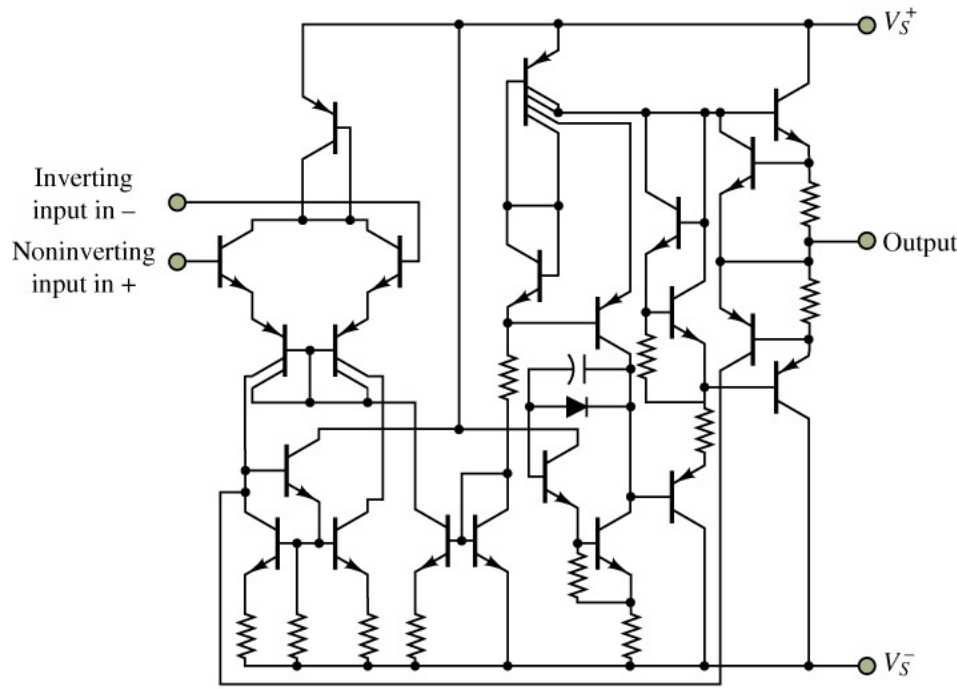
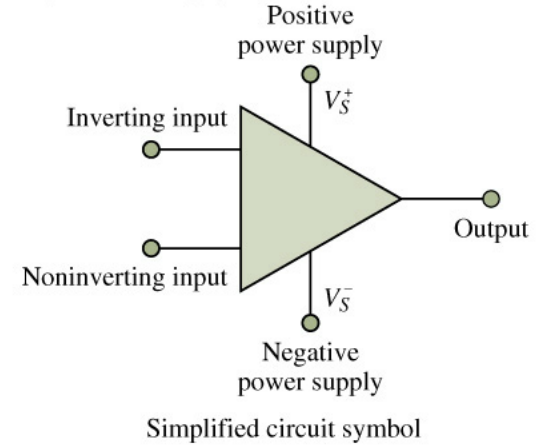
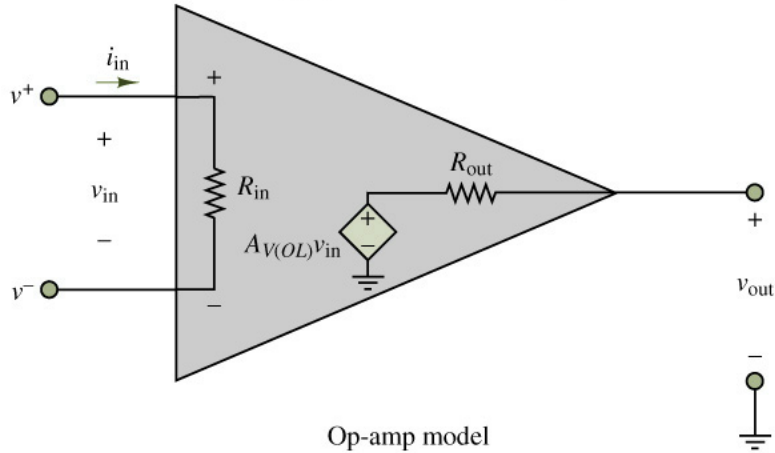


$$v_{in} = \frac{R_{in}}{R_S + R_{in}} v_S; v_L = Av_{in} \frac{R_L}{R_{out} + R_L}$$

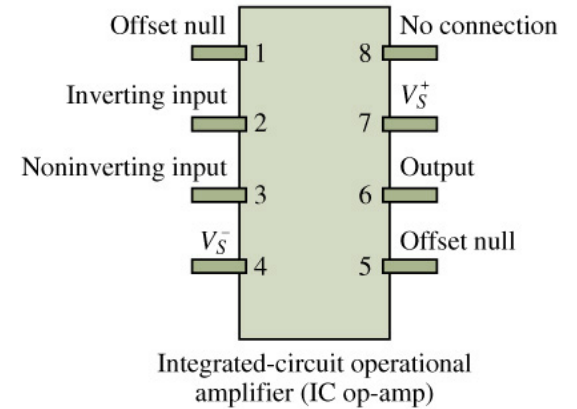
$$v_L = \left(A \frac{R_{in}}{R_S + R_{in}} \frac{R_L}{R_{out} + R_L} \right) v_S; v_{in} \approx v_S; v_L = Av_{in}$$

Operational Amplifier Model Symbols and Circuit Diagram

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IC op-amp diagram



The Ideal and Real Op-Amp

Ideal Amplifier:

- Two Inputs:
 - Inverting.
 - Non-inverting.
- $V_o = A (V_+ - V_-)$
- Gain A is large (∞).
- $V_o = 0$, when $V_+ = V_-$.
- Infinite input resistance, which produces no currents at the inputs.
- The output resistance is zero, so it does not affect the output of the amplifier by loading.
- The gain A is independent of the frequency.

Real Amplifier:

- Gain ($10^5 - 10^9$).
- Input resistance
 - 10^6 for BJTs
 - $10^9 - 10^{12}$
- Output resistance: 100-1000 Ω .

Inverting Amplifier

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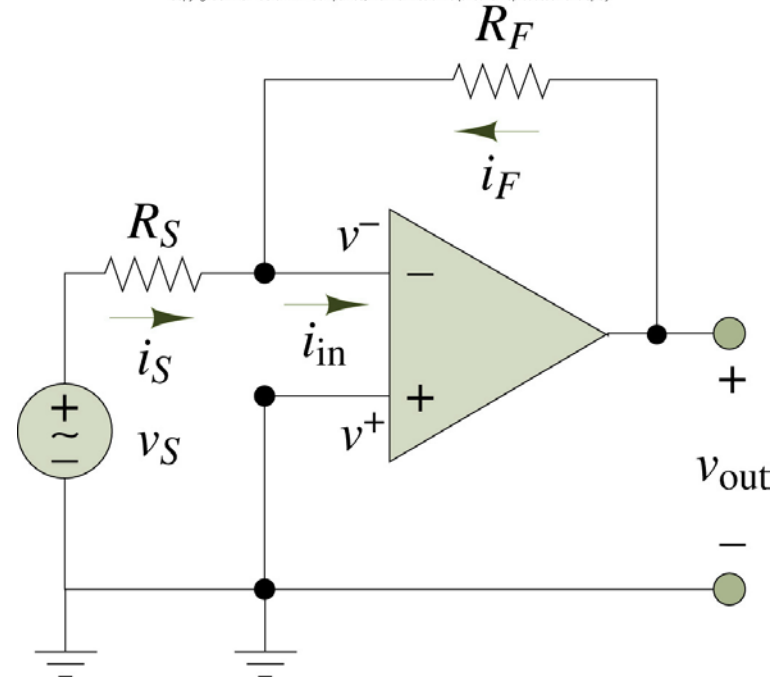
$$i_S + i_S = i_{in}$$

$$i_S = \frac{v_S - v^-}{R_S}; i_F = \frac{v_{out} - v^-}{R_F}; i_{in} = 0$$

$$i_S = -i_F; i_{in} = 0; v^- = v^+$$

$$\frac{v_S}{R_S} + \frac{v_{out}}{A_v R_S} = -\frac{v_{out}}{R_F} - \frac{v_{out}}{A_v R_F}$$

$$v_{out} = -\frac{R_F}{R_S} v_S$$



A Practical Application: Why Feedback

- Self-balancing mechanism, which allows the amplifier to preserve zero potential difference between its input terminals.
- A practical example that illustrates a common application of negative feedback is the thermostat. This simple temperature control system operates by comparing the desired ambient temperature and the temperature measured by the thermometer and turning a heat source on and off to maintain the difference between actual and desired temperature as close to zero as possible.

Summing Amplifier

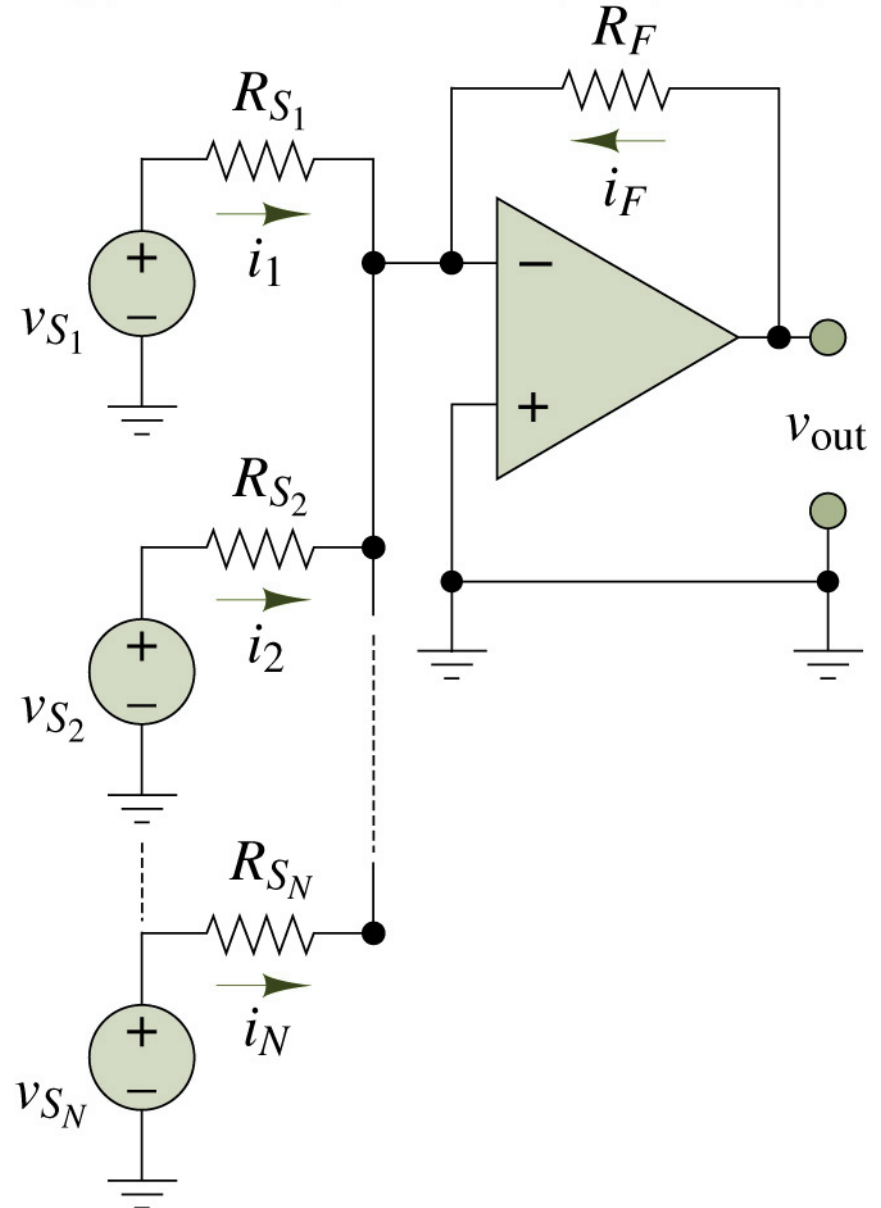
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$$i_1 + i_2 + \dots + i_N = -i_F$$

$$i_n = \frac{v_{S_n}}{R_{S_n}} \dots n = 1, 2, \dots, N$$

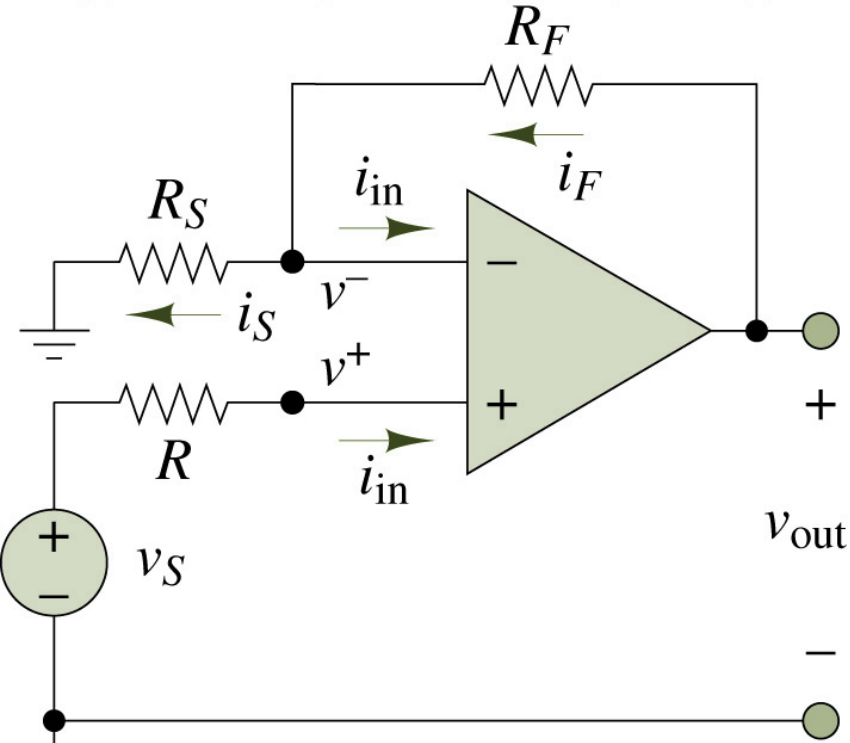
$$i_F = \frac{v_{out}}{R_F}$$

$$v_{out} = - \sum_{n=1}^N \frac{R_F}{R_{S_n}} v_{S_n}$$



Noninverting Amplifier

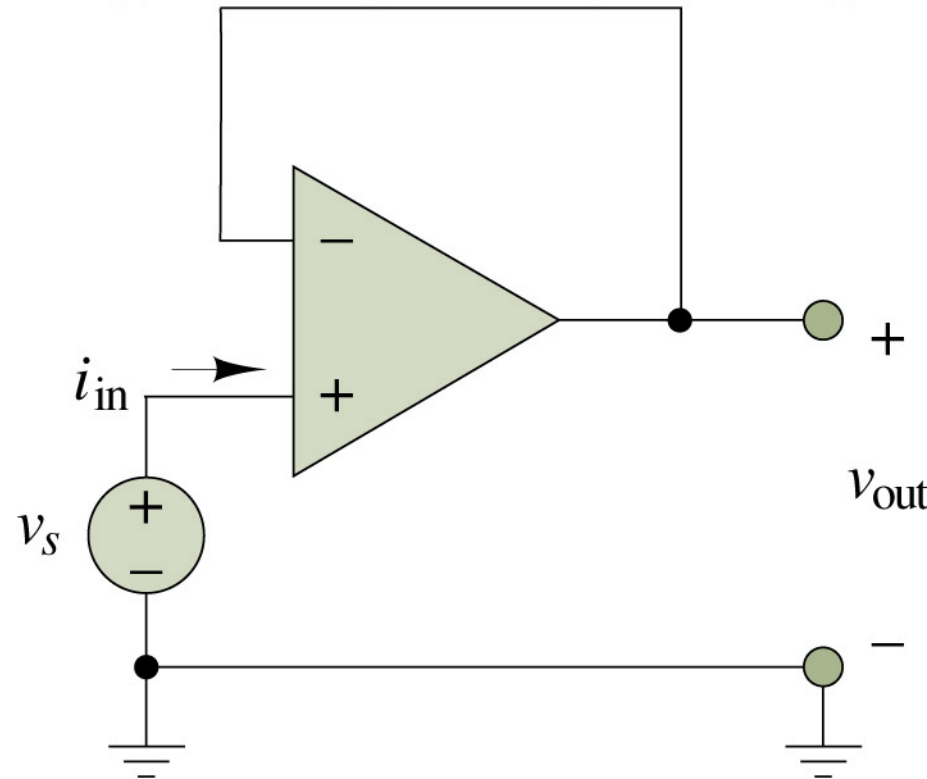
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$$\frac{v_{out}}{v_S} = 1 + \frac{R_F}{R_S}$$

Voltage Follower

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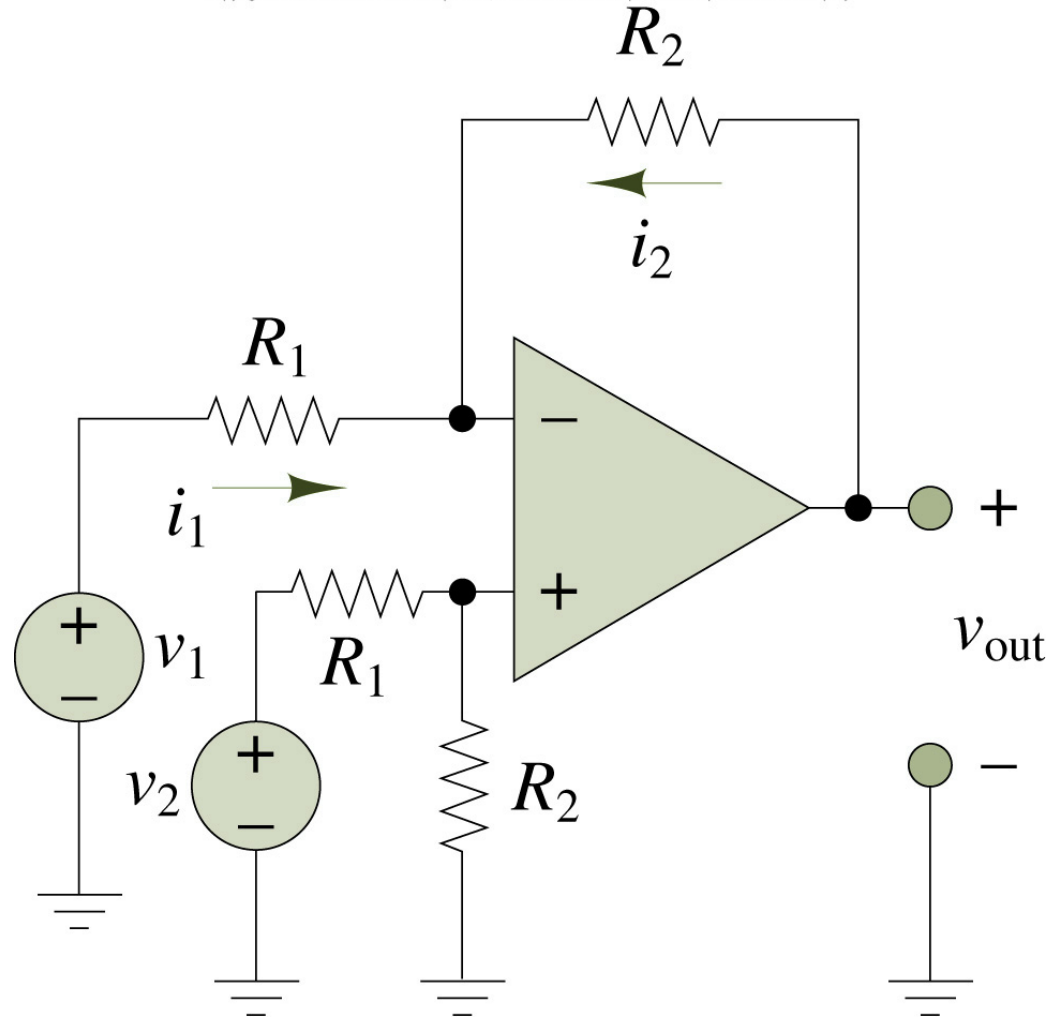


$$v_S = v_{out}$$

Differential Amplifier

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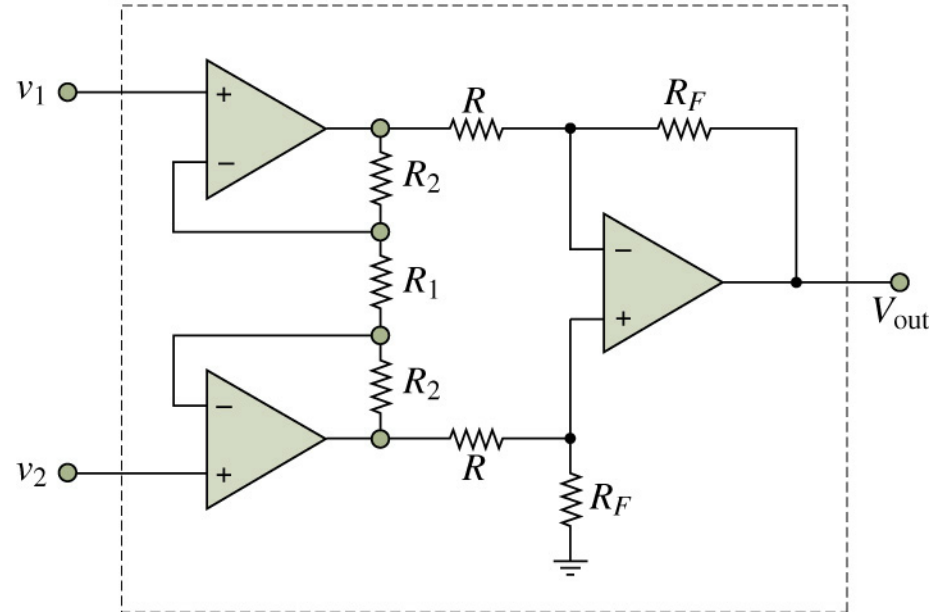
$$v_{out} = \frac{R_2}{R_1} (v_2 - v_1)$$



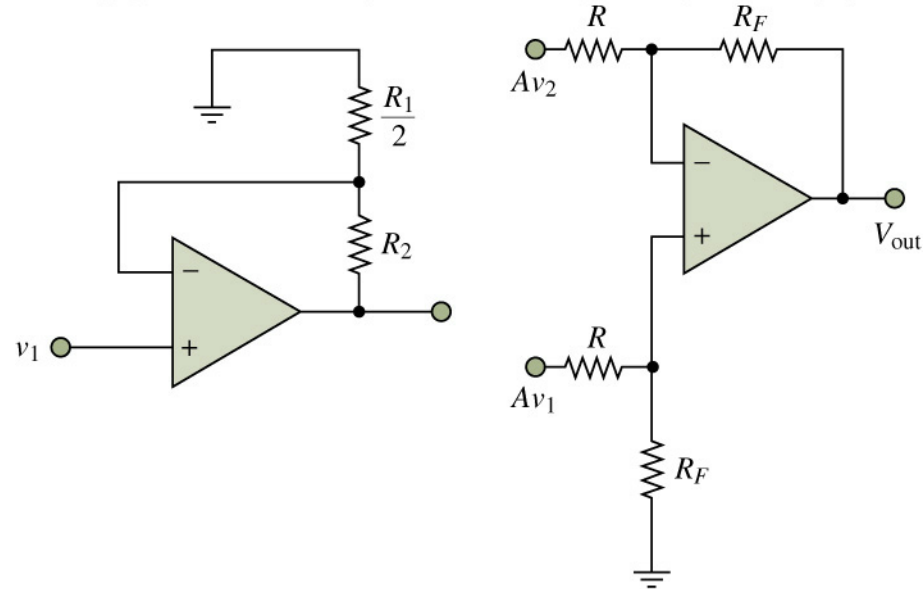
Instrumentation Amplifier

Input (a) and output (b) stages of Instrumentation amplifier

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$$A_V = \frac{v_{out}}{v_1 - v_2} = \frac{R_F}{R} \left(1 + \frac{2R_2}{R_1} \right)^{(a)}$$

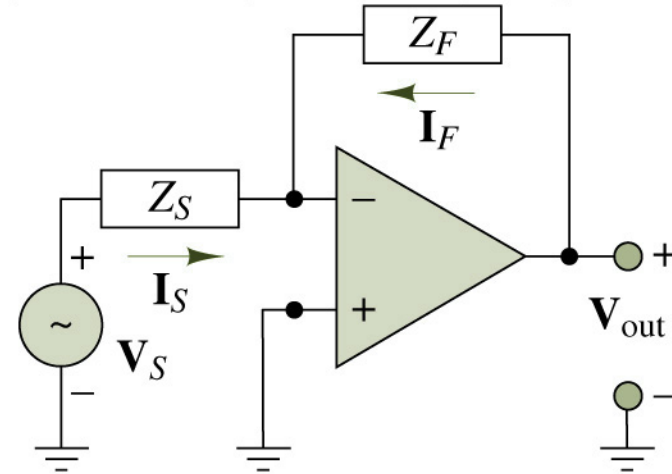
(b)

Op-amp Circuits Employing Complex Impedances

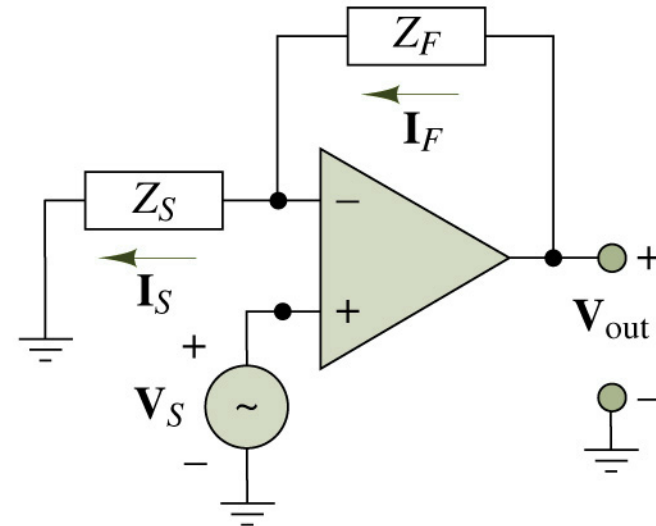
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$$\frac{V_{out}}{V_S}(j\omega) = -\frac{Z_F}{Z_S}$$

$$\frac{V_{out}}{V_S}(j\omega) = 1 + \frac{Z_F}{Z_S}$$



Inverting

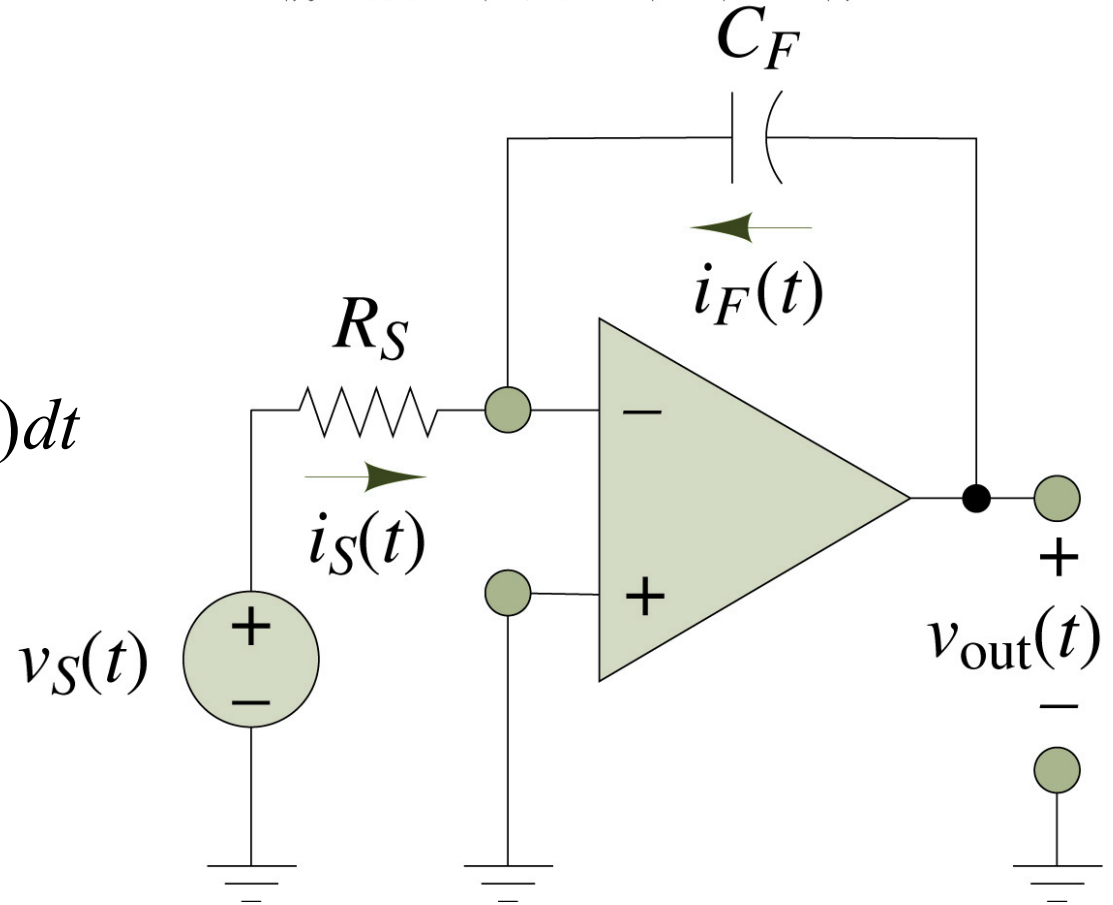


Noninverting

Op-amp Integrator

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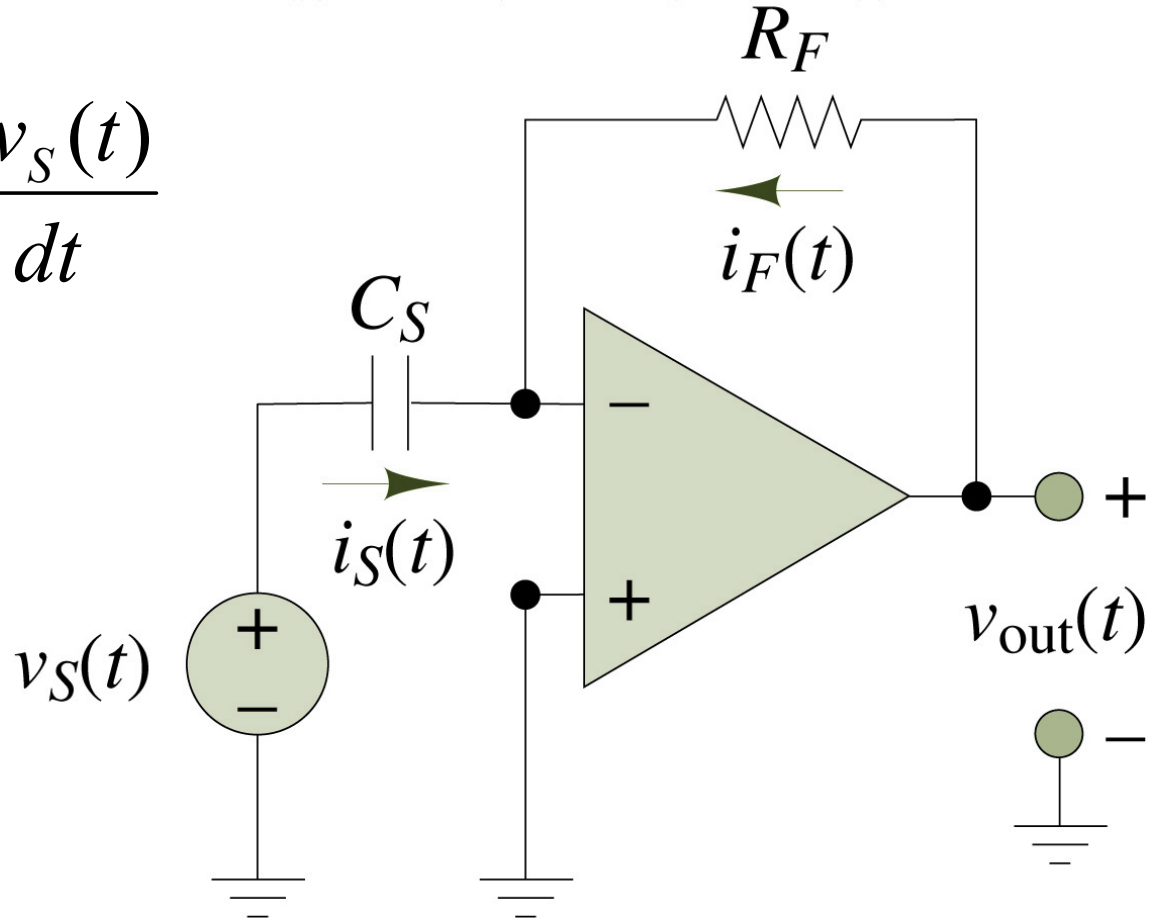
$$v_{out}(t) = -\frac{1}{R_S C_F} \int_{-\infty}^t v_S(t) dt$$



Op-amp Differentiator

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$$v_{out}(t) = -R_F C_S \frac{dv_S(t)}{dt}$$



Protection

- There are cases where the connection of a sensor to the next unit can lead to the possibility of damage as a result of high current or high voltage.
- The high current can be protected against by the incorporation in the input line of a series resistor to limit the current to certain level and a fuse to break if the current does exceed a safe level.
- High voltage and wrong polarity may be protected against by the use of a Zener diode circuit. Zener diodes behave like ordinary diodes up to some breakdown voltage when they become conducting.

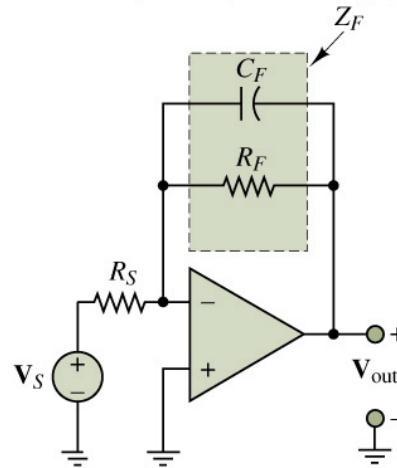
Filtering

The term filtering is used to describe the process of removing a certain band of frequencies from a signal and allowing others to be transmitted. The range of frequencies passed by a filter is known as the pass band. Filters are classified as follows. The term cutoff is defined as being that at which the output voltage is 70.7% of that in the passband.

- **Low Pass Filter:** Allows frequencies from 0 up to some frequency to pass.
- **High Pass Filter:** Allows frequencies from some value up to infinity to be transmitted.
- **Band Pass Filter:** Allows all the frequencies within a specified band to be transmitted.
- **Band-Stop Filter:** Stops all frequencies within a particular band from being transmitted.

Active Low-Pass Filter

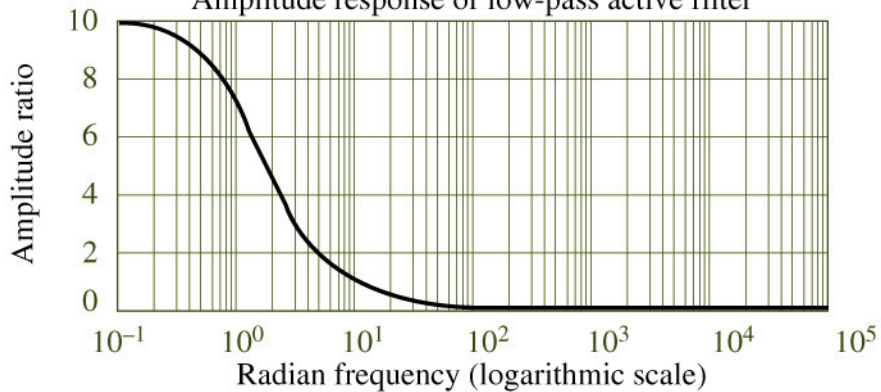
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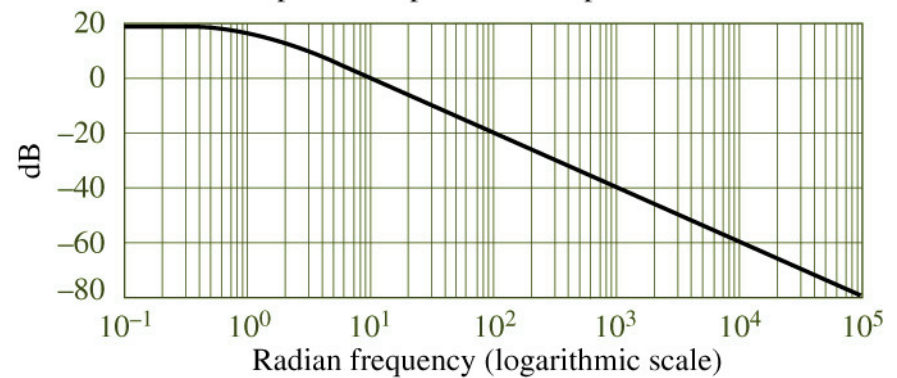
Normalized Response of Active Low-pass Filter

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Amplitude response of low-pass active filter

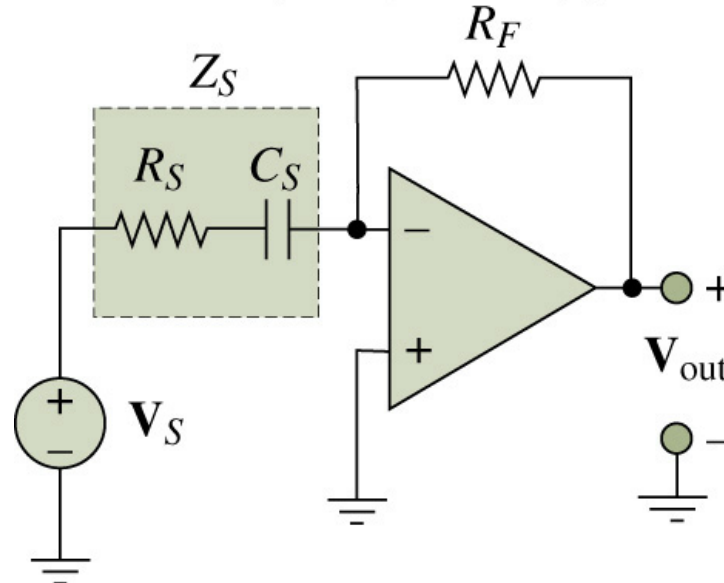


dB amplitude response of low-pass active filter



Active High-Pass Filter

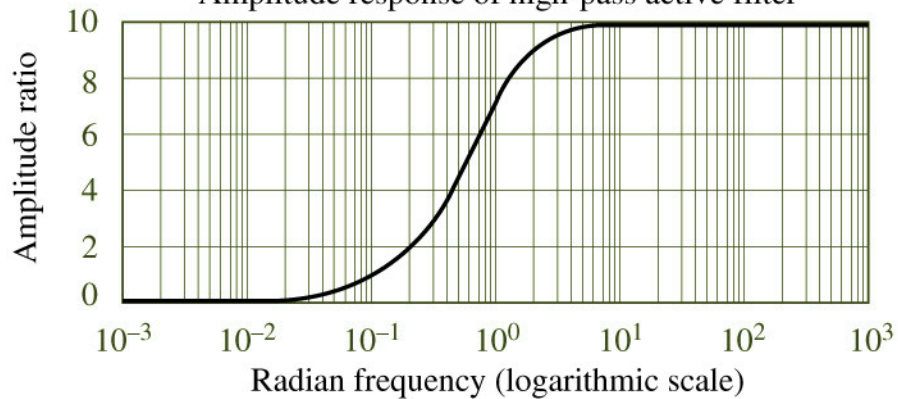
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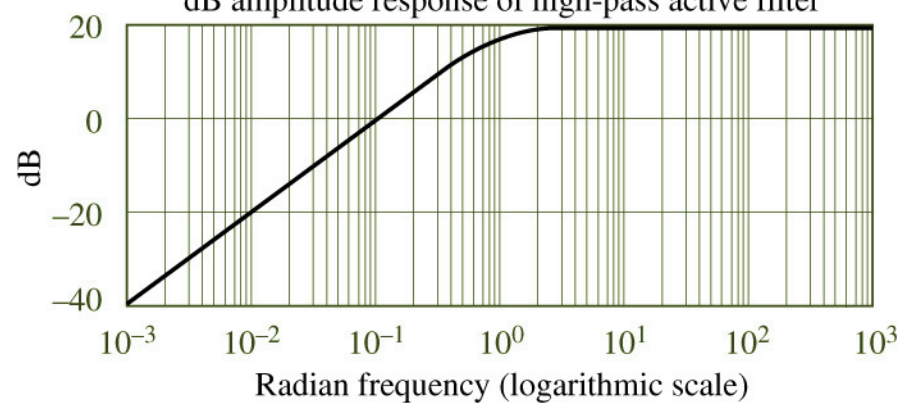
Normalized Response of Active High-pass Filter

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Amplitude response of high-pass active filter

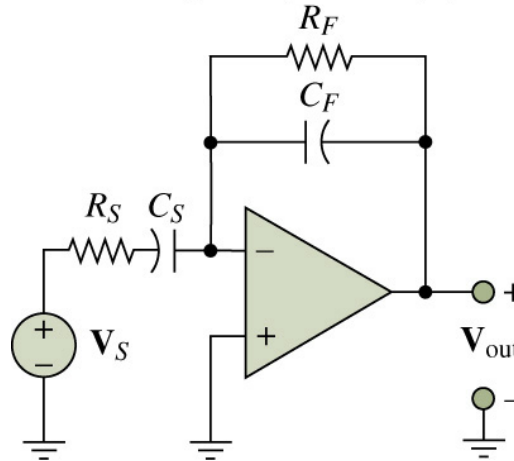


dB amplitude response of high-pass active filter



Active Band-Pass Filter

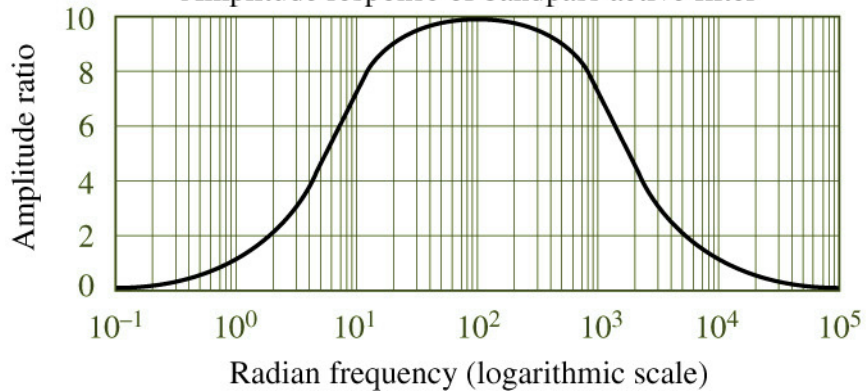
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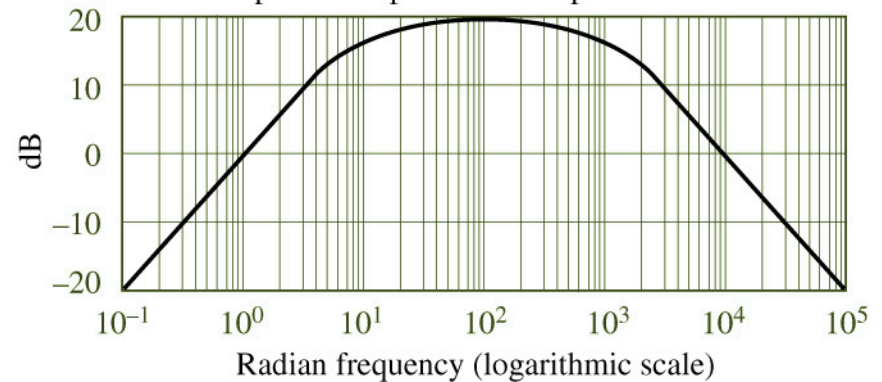
Normalized Amplitude Response of Active Band-pass Filter

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Amplitude response of bandpass active filter



dB amplitude response of bandpass active filter



Digital Signal

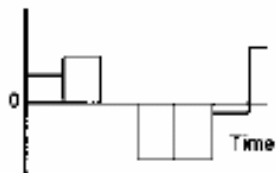
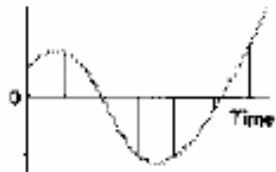
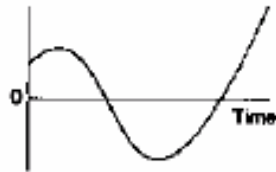
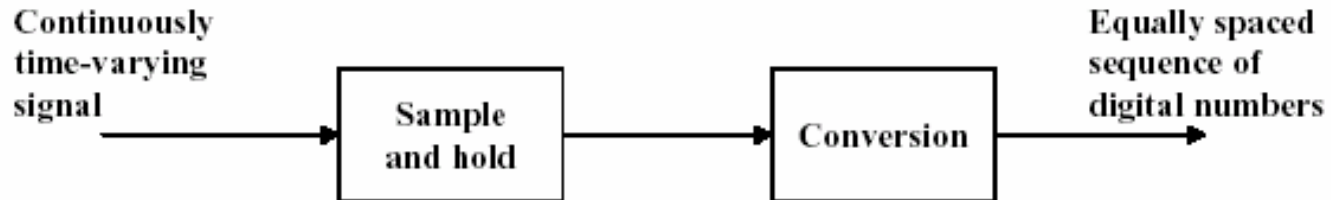
- **Analog to Digital Converter:** The A/D converts the information from analog to digital form. Often, the time variations of the analog signal must be arrested with a sample-and-hold circuit while A/D conversion is taking place.
- **Digital to Analog Converter:** Often, the computer must provide outputs in analog form. If, for example, the data monitor were part of the control system, the computer might furnish analog signals as feedback to the controller of the process affecting the physical measurements.

Analog to Digital Conversion

- ADC, or digitizing, converts analog waveforms to digital representations that can be processed and stored in digital form.
- The analog wave is “sampled,” or read, hundreds or thousands of times per second to map out the wave digitally. Digital music requires extremely high sampling rates (44,100 samples/sec), while it is usually acceptable to sample voice at 11,000 samples/sec or higher. There is also a factor that determines the precision of the captured signal—the more bits used to record the value of the sampled signal, the higher its resolution and the better its sound when played back.
- However, the more bits used, the more disk space is required for storage or bandwidth for transmission. For example, one minute of sampling at 44.1 kHz using 16 bits per sample requires 5.292 MB of disk space.

- The telephone companies convert analog voice to digital at their central offices for transmission across trunk lines to other central offices or to long-distance systems. Voice converted to digital requires a 64-kbit/sec channel.
- ADCs are used in a variety of information-processing applications. Information collected from analog phenomena such as sound, light, temperature, and pressure can be digitized and made available for digital processing.
- A codec (coder/decoder) is the device that transforms the analog signals to digital signals. The process involves sampling, quantizing, and digitizing. The amplitude of a signal is measured at various intervals. The tighter these intervals, the more accurate the recording.

ADC



The analog signal is sampled at a discrete time-interval or period, τ_s

The sampling frequency is given by the equation

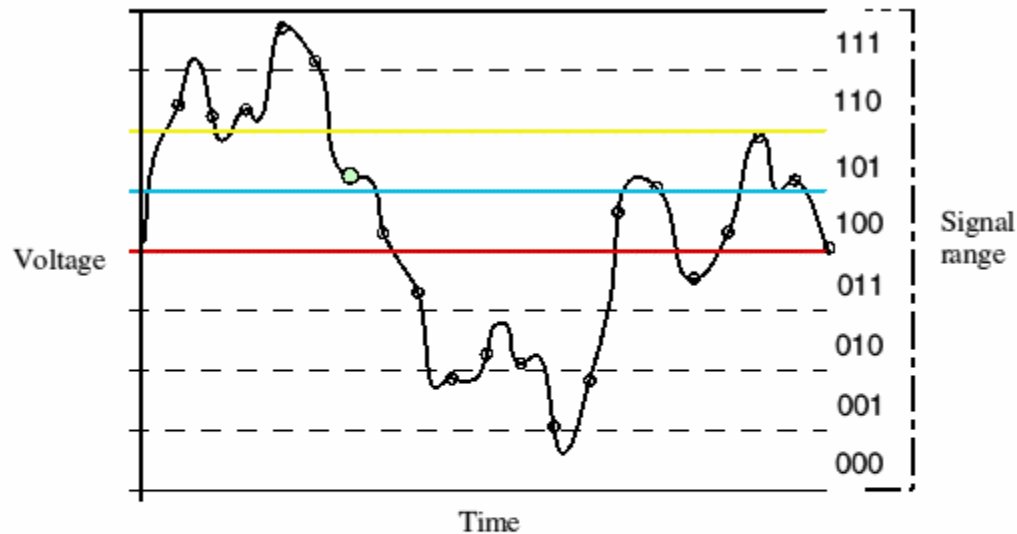
$$f_s = \frac{1}{\tau_s} \quad [\text{samples/sec}]$$

The sampled value is held until the next sample is taken.

The held value is converted to a digital number.

Sampling Theorem

ADC samples analog signals at regular intervals and convert these values to binary words. The sampling rate should be at least twice that of the highest frequency in the analog signal that the sample gives the original signal. This criterion is known as the Nyquist Criterion or Shannon's sampling theorem.

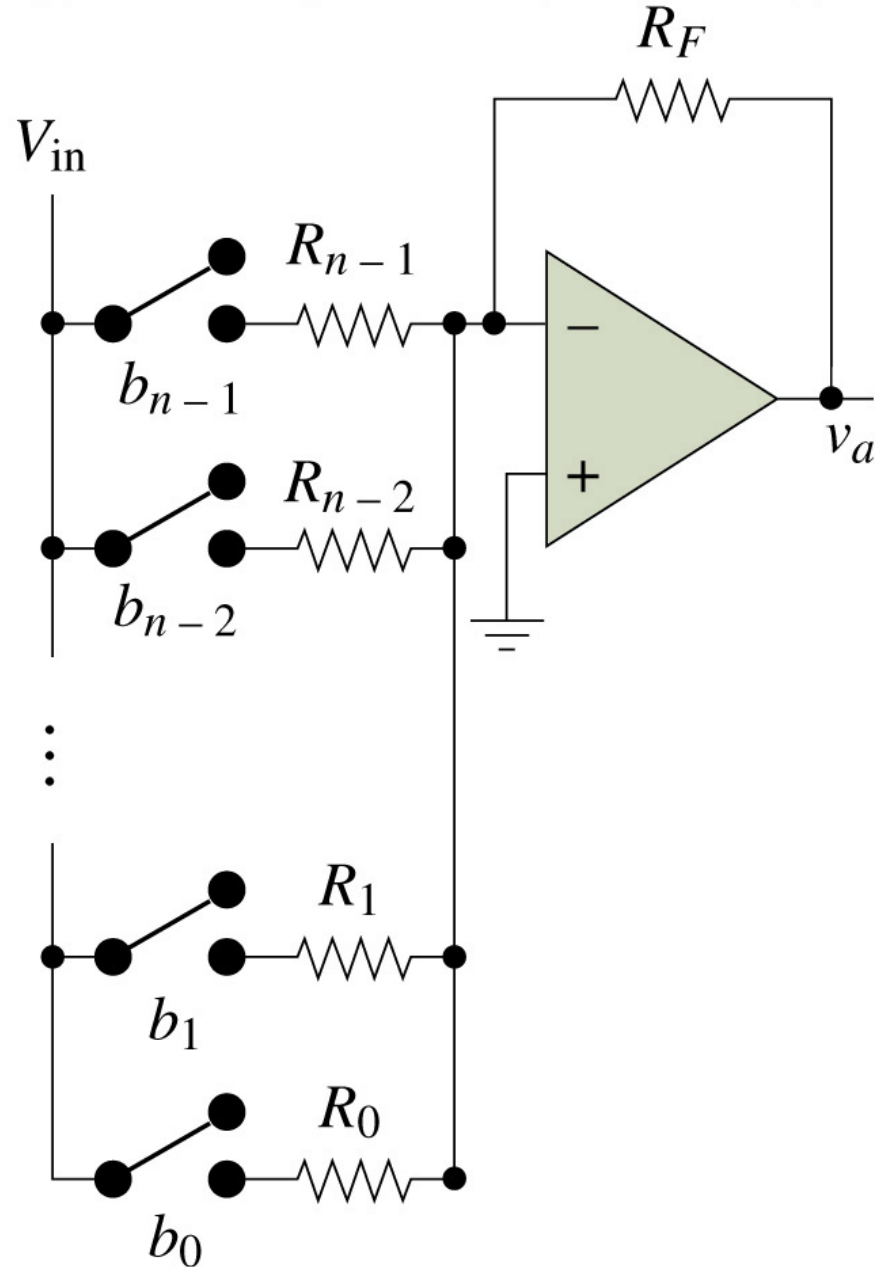


Turning analog waves into digital signals.

1011011011111101100011001010010001001100101011100101101100.

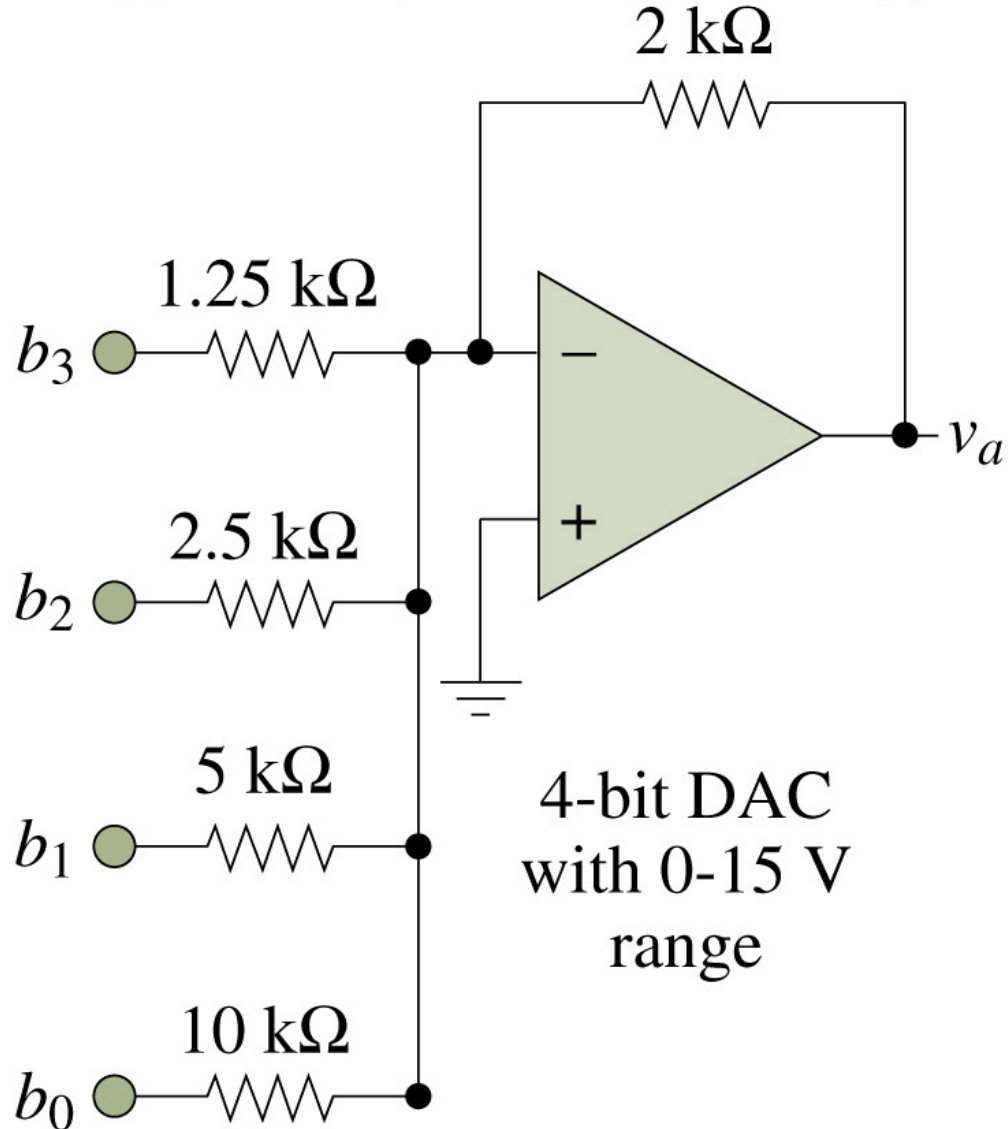
An n -Bit Digital-to-Analog Converter

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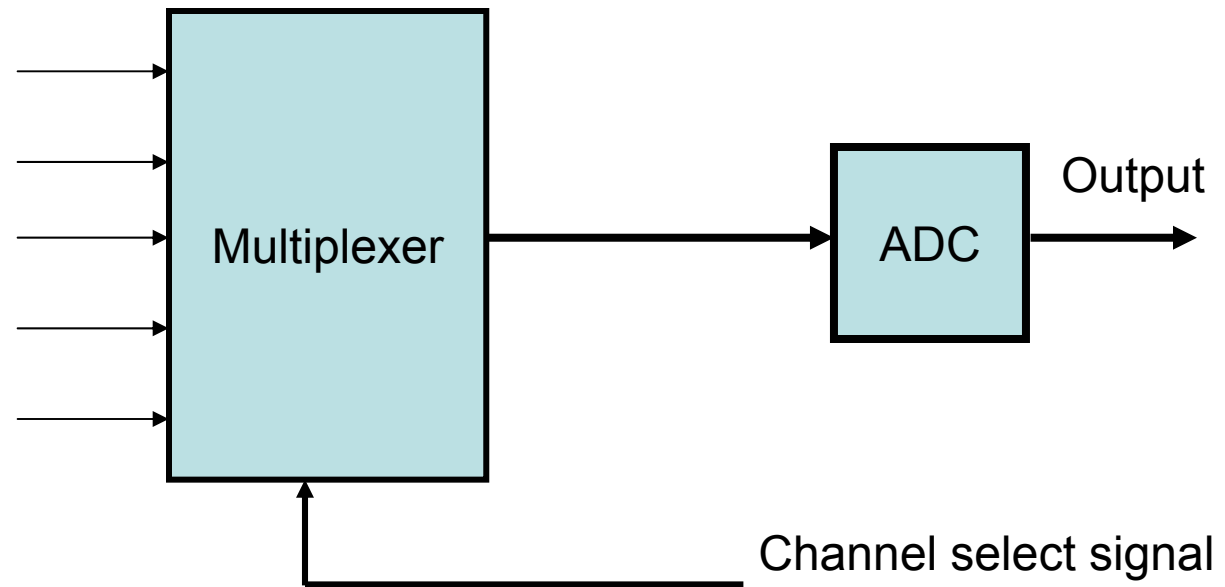
A 4-bit DAC

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Multiplexers

- Several analog channels are processed sequentially through a multiplexer, which is a digitally controlled switch. The multiplexer accepts parallel inputs from several channels and provides one analog output at a time for conversion to digital form.



Data Acquisition System

The term data Acquisition or DAQ is used for the process of taking data from sensors and moving them into a computer for processing. The sensors are connected via signal conditioning to data acquisition board which is plugged into the back of a computer.

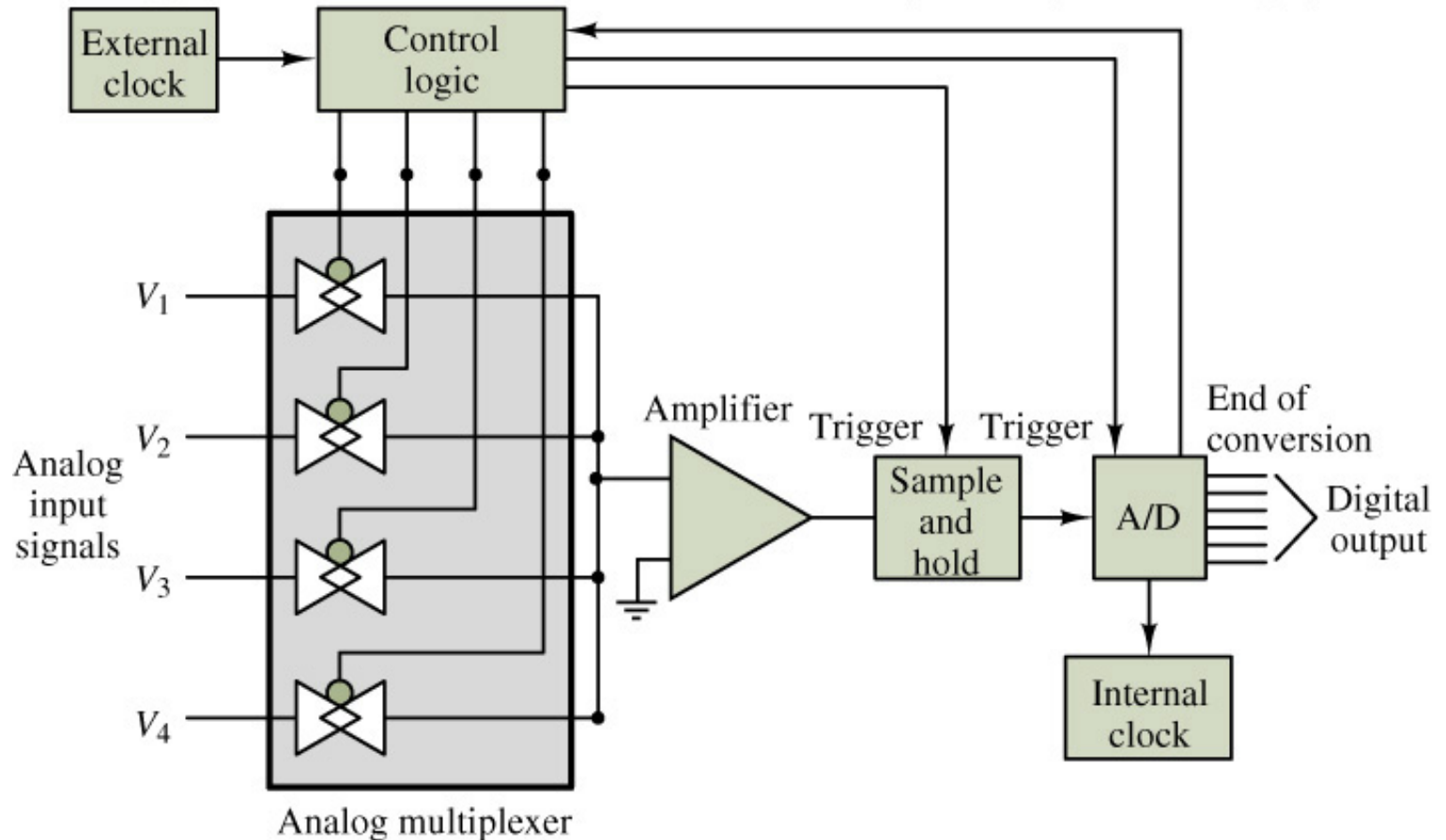
The DAQ board is a printed circuit board that, for analog inputs, basically provides a multiplexer, amplification, ADC, register, and control circuit so that the sampled digital signals are applied to the computer system.

Computer software is used to control the acquisition of data via the DAQ board. When the program requires an input from a particular sensor, it activates the board by sending a control word to the control and status register. Such a word indicates the type of operation the board has to carry out. As a consequence the board switches the multiplexer to the appropriate input channel. The signal from the sensor will move via the amplifier to ADC, data register and then processed by the computer.

In brief, data Acquisition means storing data from sensors using a microprocessor or a computer.

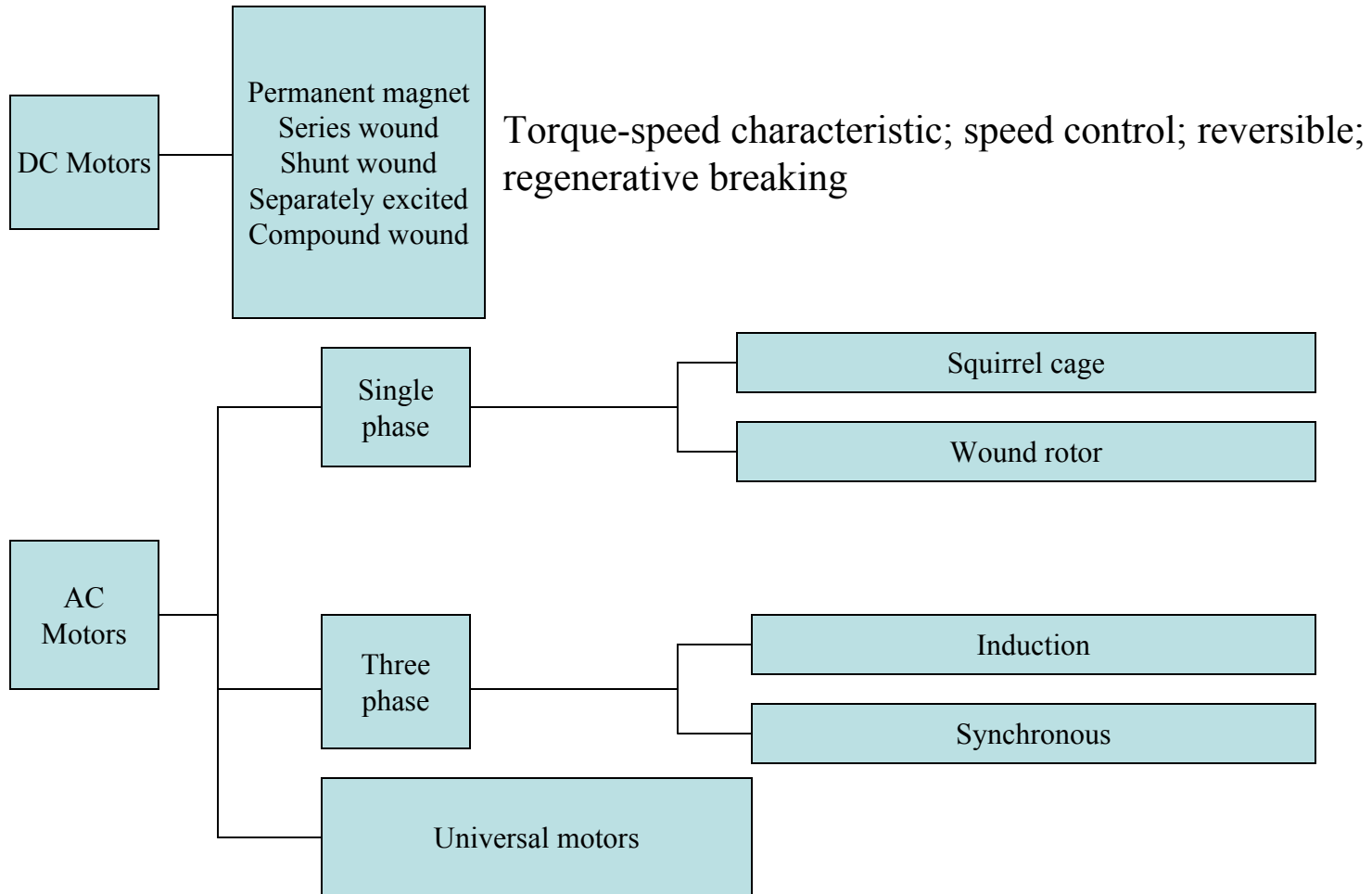
DAQ

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Actuators

Relays and Motors



List of Mechatronic Systems

- Air bag safety, antilock break system; remote automatic door locks; cruise control, etc.
- Copy machines, fax machines, dcanners.
- MRI equipment; ultrasonic probes; and other medical equipment.
- Autofocus cameras; VCRs; CD players; camcoders; and other consumer products.
- Welding robots; automatic guided vehicles.
- Flight control actuators; landing gear system; and cockpit control system.
- Washing machines; dishwashers; automatic ice makers.
- Garage door openers; security system; and other home support systems.
- Variable speed drills; digital torque wrenches.
- Factory automation system.
- More!