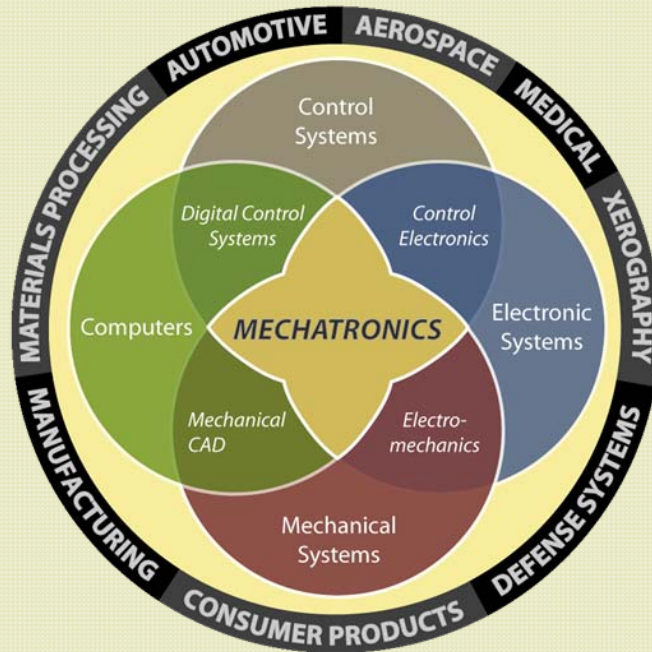


# Measurement Systems



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- References

- *Measurement Systems – Application and Design*
  - 5<sup>th</sup> Edition, Ernest Doebelin, McGraw Hill, 2004.
- *Control Sensors and Actuators*
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# Measurement System Topics

- Introduction
- Types of Applications of Measurement Instrumentation
- Generalized Configurations and Functional Descriptions of Measuring Instruments

# Introduction

- Measurement System

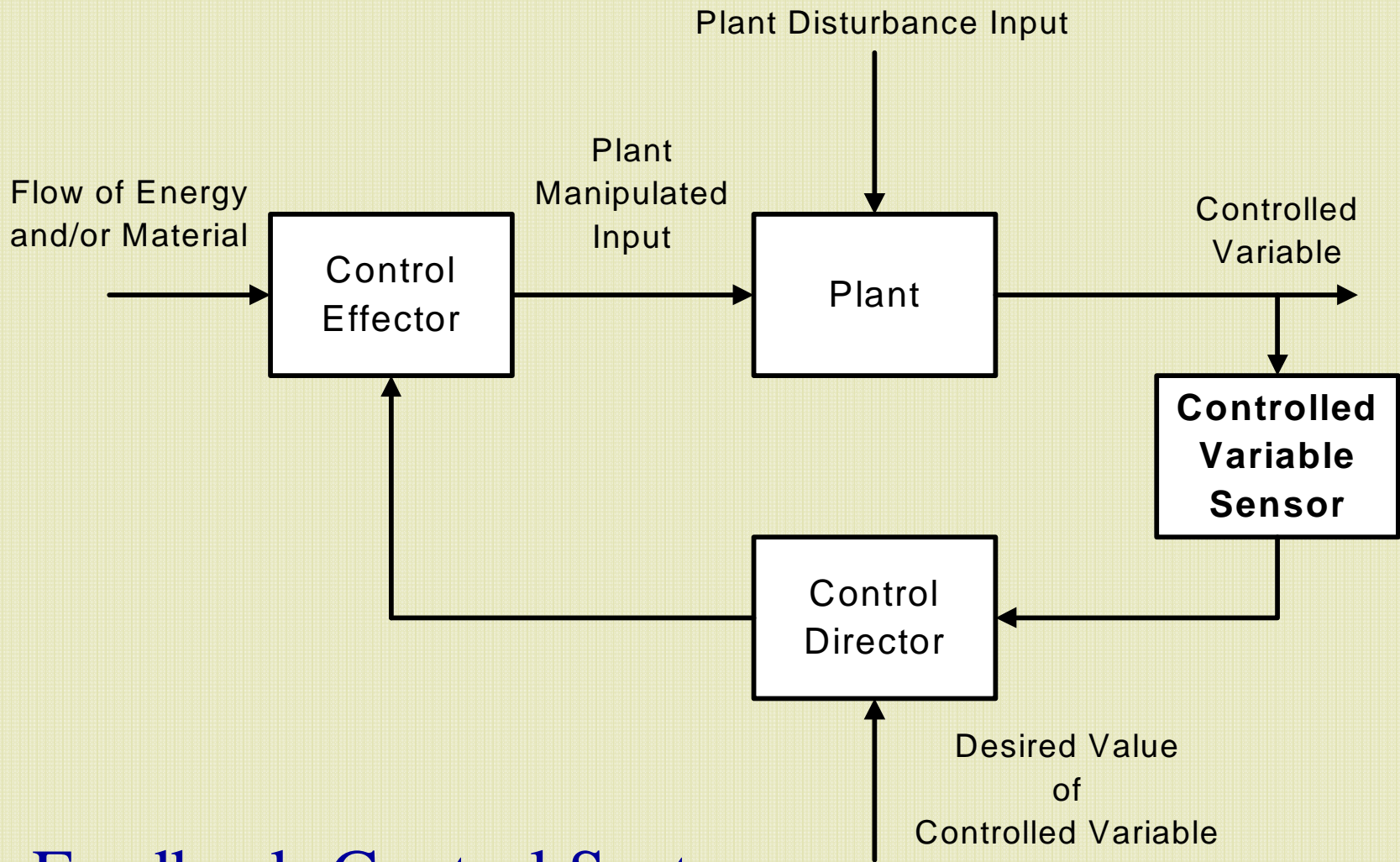
- This term measurement system includes all components in a chain of hardware and software that leads from the measured variable to processed data.
- In a modern automobile there are as many as 40 – 50 sensors (measuring devices) used in implementing various functions necessary to the operation of the car.
- Knowledge of the instruments available for various measurements, how they operate, and how they interface with other parts of the system is essential for every engineer.
- Modern engineering systems rely heavily on a multitude of sensors for monitoring and control to achieve optimum operation.

# Types of Applications of Measurement Instrumentation

- Every application of measurement, including those not yet invented, can be put into one of these three categories or some combination of them:
  - Monitoring of processes and operations
  - Control of processes and operations
  - Experimental engineering analysis
- Monitoring of Processes and Operations
  - Here the measuring device is being used to keep track of some quantity.

- Certain applications of measuring instruments may be characterized as having essentially a monitoring function, e.g., thermometers, barometers, and water, gas, and electric meters, automotive speedometer and fuel gage, and compass.
- Control of Processes and Operations
  - One of the most important classes of measurement application.
  - Sensors are used in feedback-control systems and many measurement systems *themselves* use feedback principles in their operation.
  - Sensors are used in feedback systems and feedback systems are used in sensors.

- So an instrument can serve as a component of a control system. To control any variable in a feedback control system, it is first necessary to measure it. Every feedback-control system will have at least one measuring device as a vital component.
- A single control system may require information from many measuring instruments, e.g., industrial machine and process controllers, aircraft control systems, automotive control systems (speed control, antilock braking, coolant temperature regulating, air conditioning, engine pollution, etc.).



# Feedback-Control System



- Experimental Engineering Analysis

- In solving engineering problems, two general methods are available: theoretical and experimental. Many problems require the application of both methods and theory and experiment should be thought of as complimenting each other.
- Features of Theoretical Methods
  - Often gives results that are of general use rather than for restricted application.
  - Invariably require the application of simplifying assumptions. The theoretically predicted behavior is always different from the real behavior, as a simplified physical/mathematical model is studied rather than the actual physical system.

- In some cases, may lead to complicated mathematical problems.
- Require only pencil, paper, computers, etc. Extensive laboratory facilities are not required.
- No time delay engendered in building models, assembling and checking instrumentation, and gathering data.

– Features of Experimental Methods

- Often gives results that apply only to the specific system being tested. However, techniques such as dimensional analysis may allow some generalization.
- No simplifying assumptions necessary if tests are run on an actual system. The true behavior of the system is revealed.

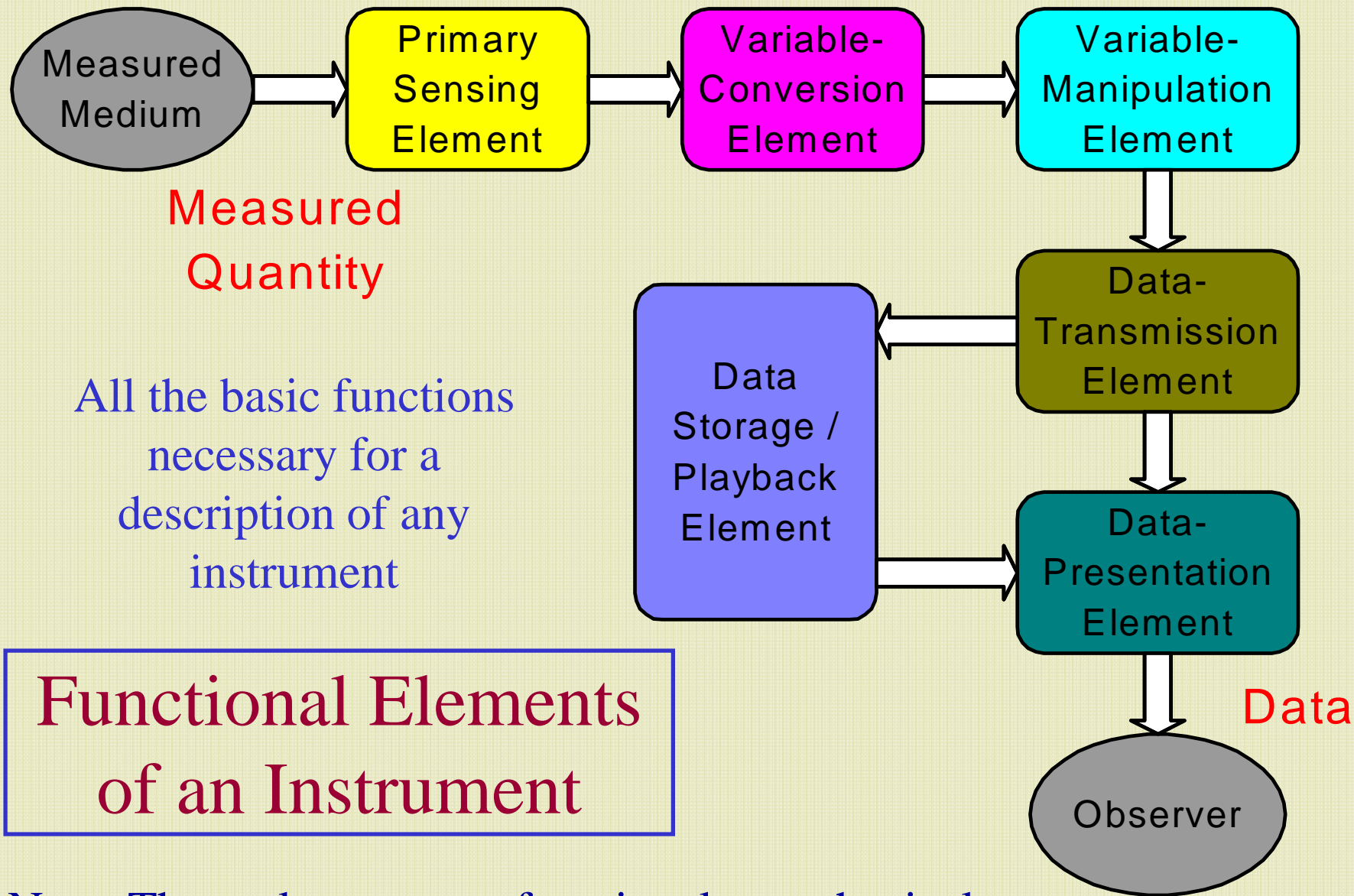
- Accurate measurements necessary to give a true picture. This may require expensive and complicated equipment. The characteristics of all the measuring and recording equipment must be thoroughly understood.
- Actual system or a scale model required. If a scale model is used, similarity of all significant features must be preserved.
- Considerable time required for design, construction, debugging of apparatus.

- Note

- The distinction among monitoring, control, and analysis functions is not clear-cut; the category decided on may depend somewhat on your point of view and the apparent looseness of the classification should not cause any difficulty.
- It is now extremely common for engineers to include in the design of a machine or process, as dedicated components, computers of various sizes. Computers are important, but the computer “component” of many machines and processes is often *not* the critical system element in terms of either technical or economic factors. Rather, components external to the computer, the actuators and sensors, are more often the limiting factors in the system design.

# Generalized Configurations and Functional Descriptions of Measuring Instruments

- It is desirable to describe both the operation and performance (static and dynamic) of measuring instruments and associated equipment in a generalized way without recourse to specific physical hardware.
- Here we focus on the operation which can be described in terms of the functional elements of an instrument or instrument system.
- By concentrating on these functions and the various physical devices available for accomplishing them, we develop our ability to synthesize new combinations of elements leading to new and useful instruments.



Note: These elements are functional, not physical.

- Primary Sensing Element

- This is the element that first receives energy from the measured medium and produces an output depending in some way on the measured quantity (measurand). The output is some physical variable, e.g., displacement or voltage. An instrument *always* extracts some energy from the measured medium. The measured quantity is *always* disturbed by the act of measurement, which makes a perfect measurement theoretically impossible. Good instruments are designed to minimize this loading effect.

- Variable-Conversion Element

- It may be necessary to convert the output signal of the primary sensing element to another more suitable variable while preserving the information content of the original signal. This element performs this function.

- Variable-Manipulation Element

- An instrument may require that a signal represented by some physical variable be manipulated in some way. By manipulation we mean specifically a change in numerical value according to some definite rule but a preservation of the physical nature of the variable. This element performs such a function.

- Data-Transmission Element

- When functional elements of an instrument are actually physically separated, it becomes necessary to transmit the data from one to another. This element performs this function.



- Data-Presentation Element

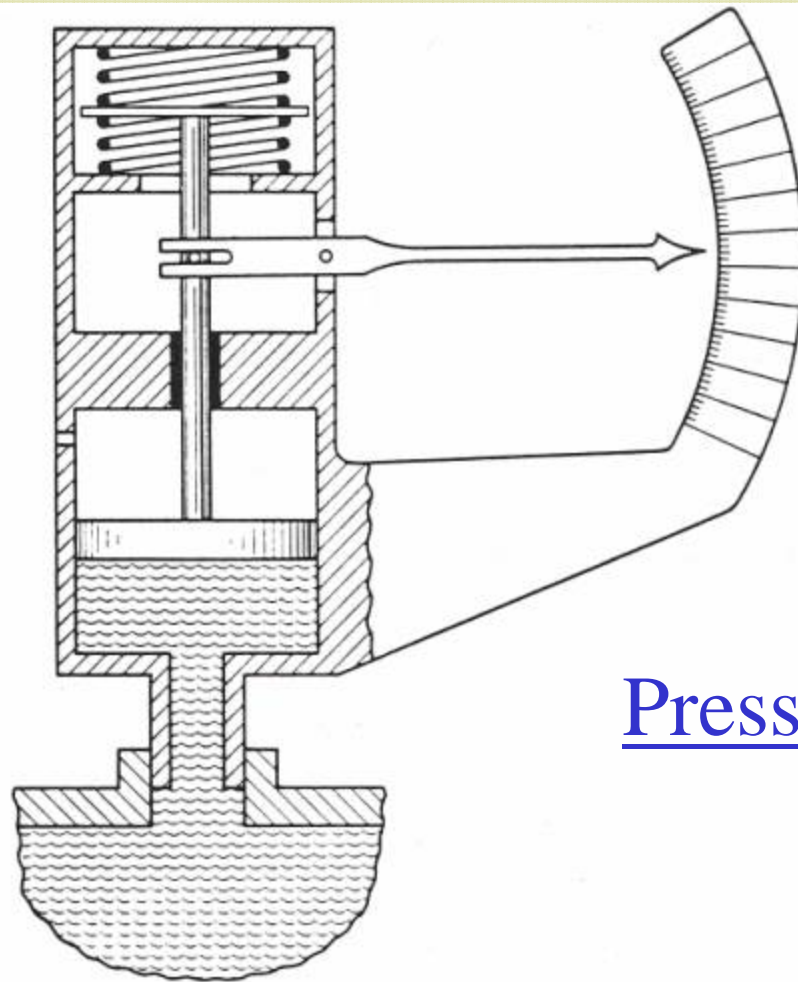
- If the information about the measured quantity is to be communicated to a human being for monitoring, control, or analysis purposes, it must be put into a form recognizable by one of the human senses. This element performs this “translation” function.

- Data Storage/Playback Element

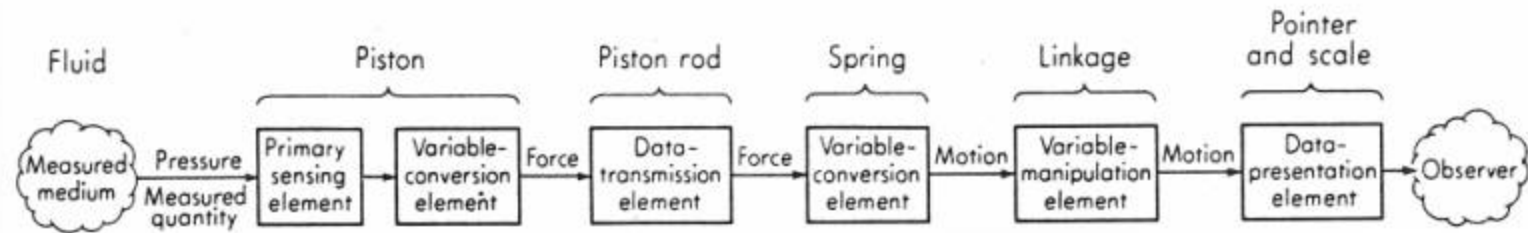
- Some applications require a distinct data storage/playback which can easily recreate the stored data upon command.

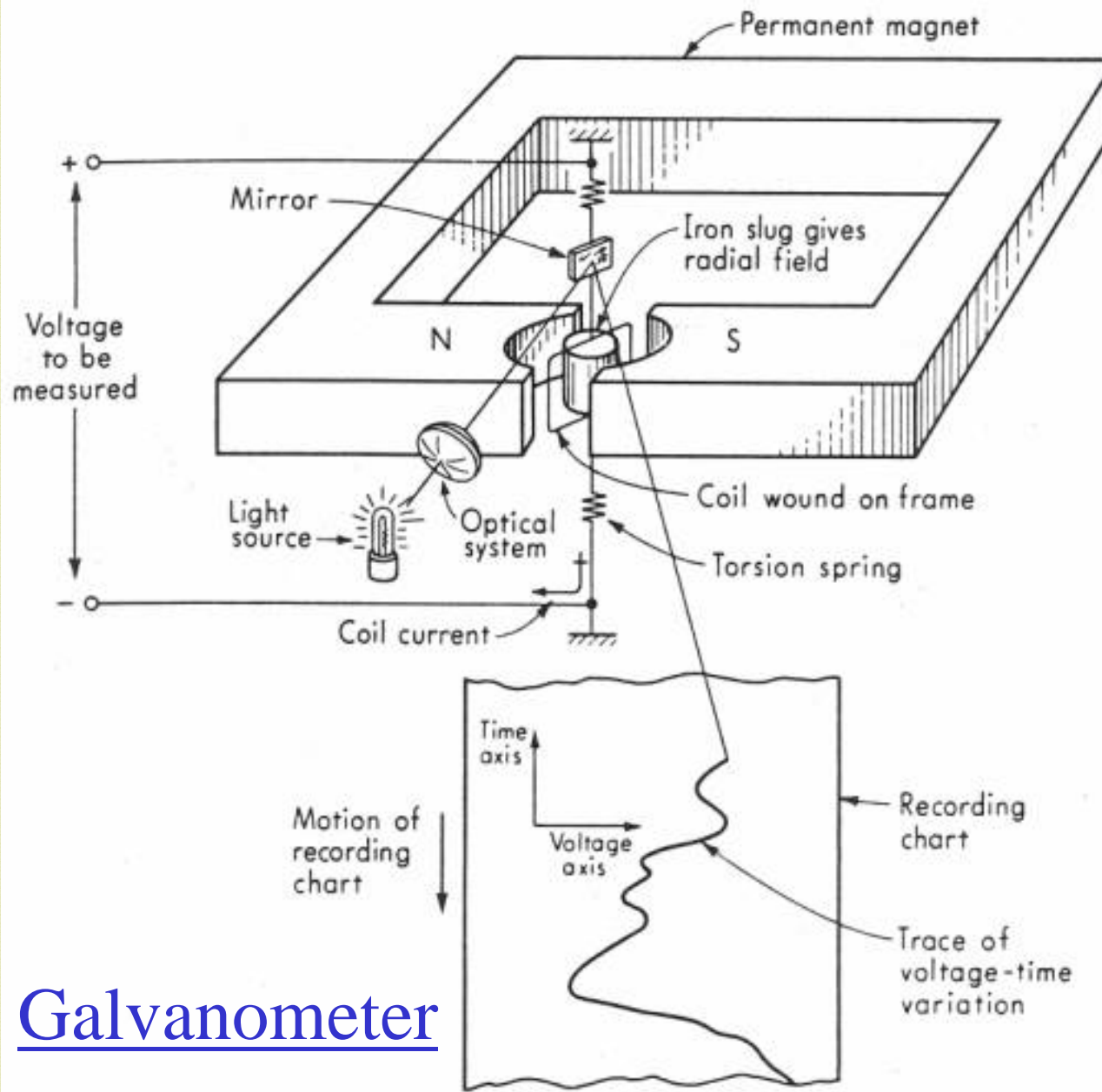
- Note

- A given instrument may involve the basic functions in any number, combination, or order. A given physical component may serve several of the basic functions.



## Pressure Gage





Can you recognize the basic functions necessary to the successful operation of this instrument?

# Galvanometer

- Active vs. Passive Transducers
  - In performing any of the general functions just discussed, a physical component may act as an active transducer or a passive transducer.
  - A component whose output energy is supplied entirely or almost entirely by its input signal is commonly called a *passive transducer*. The output and input signals may involve energy of the same form or there may be an energy conversion from one form to another.
  - An *active transducer* has an auxiliary source of power which supplies a major part of the output power while the input signal supplies only an insignificant portion. Again, there may or may not be a conversion of energy from one form to another.

- Analog vs. Digital Modes of Operation

- For analog signals, the precise value of the quantity (voltage, rotation angle, etc.) carrying the information is significant; the specific waveform of input and output signals is of vital importance.
- Digital signals are basically of a binary (on/off) nature, and variations in numerical value are associated with changes in the logical state (true/false) of some combination of switches.
  - +2 V to +5 V represents ON state
  - 0 V to +0.8 V represents OFF state
- In digital devices, it is simply the presence (logical 1) or absence (logical 0) of a voltage within some wide range that matters; the precise value of the signal is of no consequence.

- Digital devices are very tolerant of noise voltages and need not be individually very accurate, even though the overall system can be extremely accurate.
- When combined analog/digital systems are used (often the case in measurement systems), the digital portions need not limit system accuracy as there is no limit to the number of digits which can be carried accurately; these limitations generally are associated with analog portions and/or the analog/digital conversion devices.
- Since most measurement and control apparatus is of an analog nature, it is necessary to have both A/D converters and D/A converters, which serve as translators that enable the computer to communicate with the outside analog world.

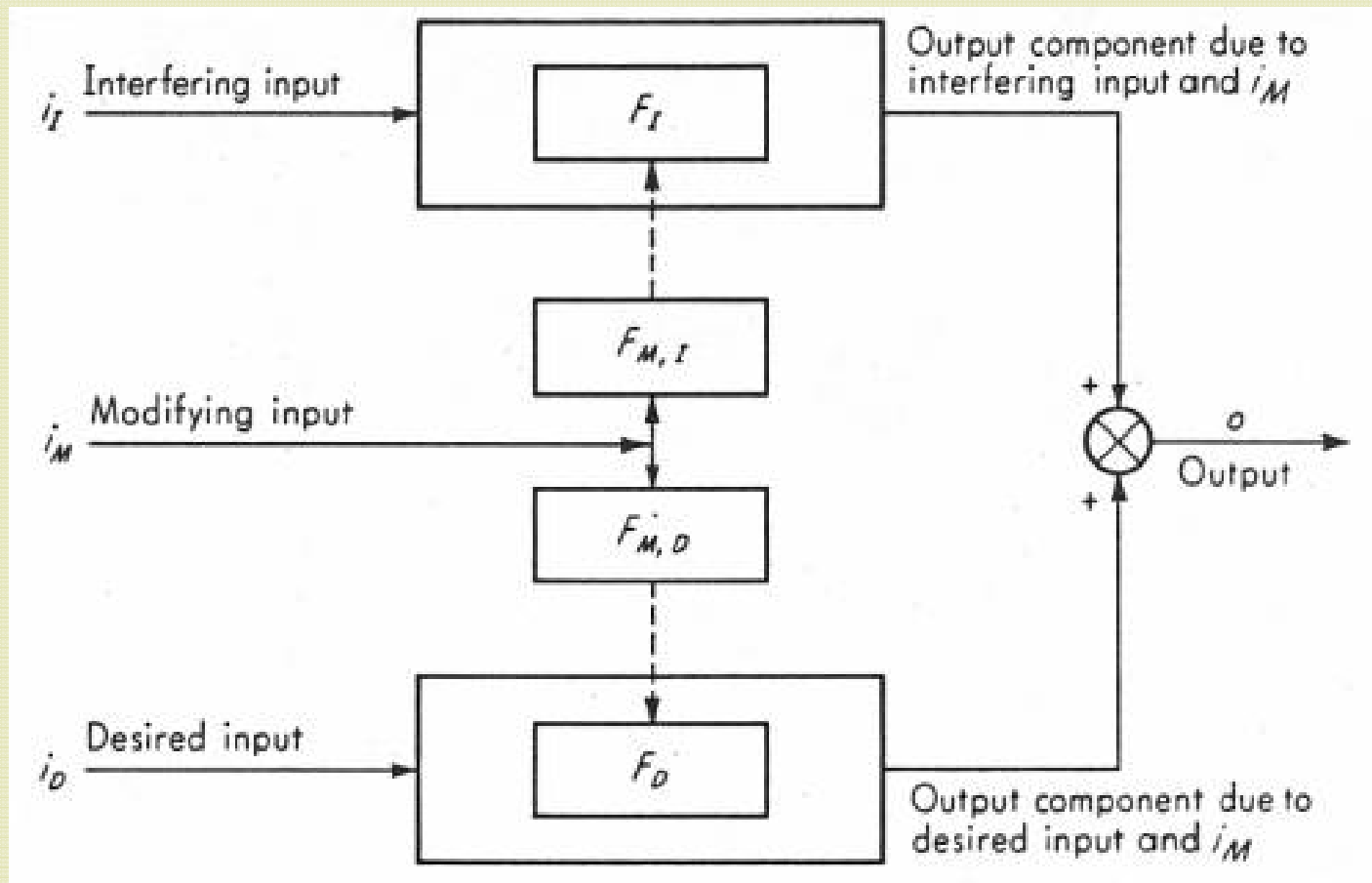
- Null and Deflection Methods

- Another useful classification separates devices by their operation on a null or a deflection principle.
- In a deflection-type device, the measured quantity produces some physical effect that engenders a similar but opposing effect in some part of the instrument. The opposing effect is closely related to some variable (usually a mechanical displacement or deflection) that can be directly observed by some human sense. The opposing effect increases until a balance is achieved, at which point the deflection is measured and the value of the measured quantity inferred from this.
- The pressure gage exemplifies this type of device.

- A null-type device attempts to maintain deflection at zero by suitable application of an effect opposing that generated by the measured quantity. Necessary to such an operation are a detector of unbalance and a means (manual or automatic) of restoring the balance. Since deflection is kept at zero (ideally), determination of numerical values requires accurate knowledge of the magnitude of the opposing effect.
- The accuracy attainable by the null method is of a higher level than that by the deflection method. Also, since the measured quantity is balanced out in the null method, the detector of unbalance can be made very sensitive because it need cover only a small range around zero. Also the detector need not be calibrated since it must detect only the presence and direction of unbalance, but not the amount. Null methods have difficulty in dynamic measurements.



- Input-Output Configuration of Instruments and Measurement Systems



- Input quantities are classified into three categories:
  - Desired Inputs
    - These are quantities that the instrument is specifically intended to measure.
  - Interfering Inputs
    - These are quantities to which the instrument is unintentionally sensitive.
  - $F_D$  and  $F_I$  are input-output relations, i.e., the mathematical operations necessary to obtain the output from the input. They represent different concepts depending on the particular input-output characteristic being described, e.g., a constant, a mathematical function, a differential equation, a statistical distribution function.

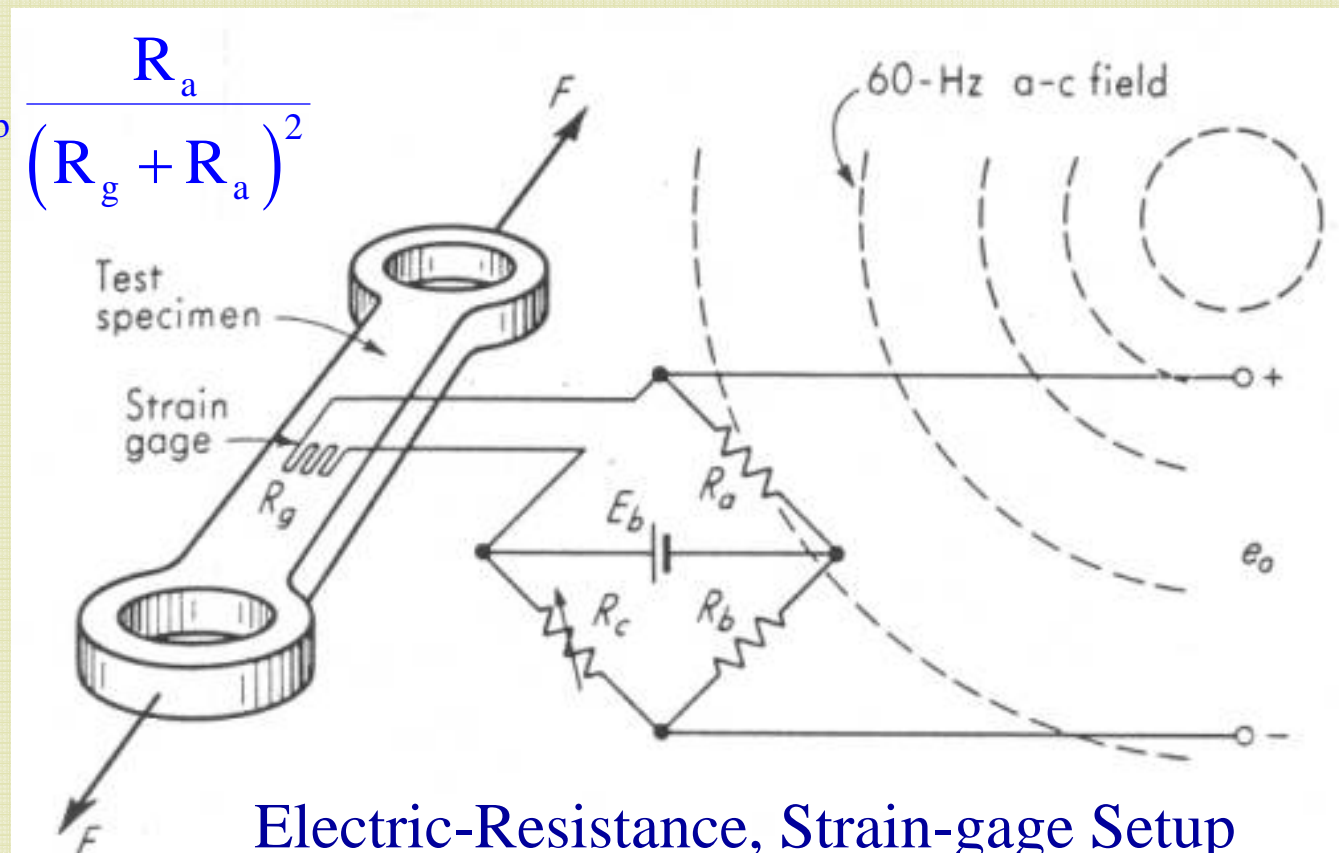
## – Modifying Inputs

- These are quantities that cause a change in the input-output relations for the desired and interfering inputs, i.e., they cause a change in  $F_D$  and/or  $F_I$ .  $F_{M,I}$  and  $F_{M,D}$  represent the specific manner in which  $i_M$  affects  $F_I$  and  $F_D$ , respectively.
- Note that the effects of both the desired and the interfering inputs may be altered by the modifying inputs.

## Example of Input Quantities

$$\Delta R_g = (GF) R_g \epsilon$$

$$e_o = - (GF) R_g \epsilon E_b \frac{R_a}{(R_g + R_a)^2}$$



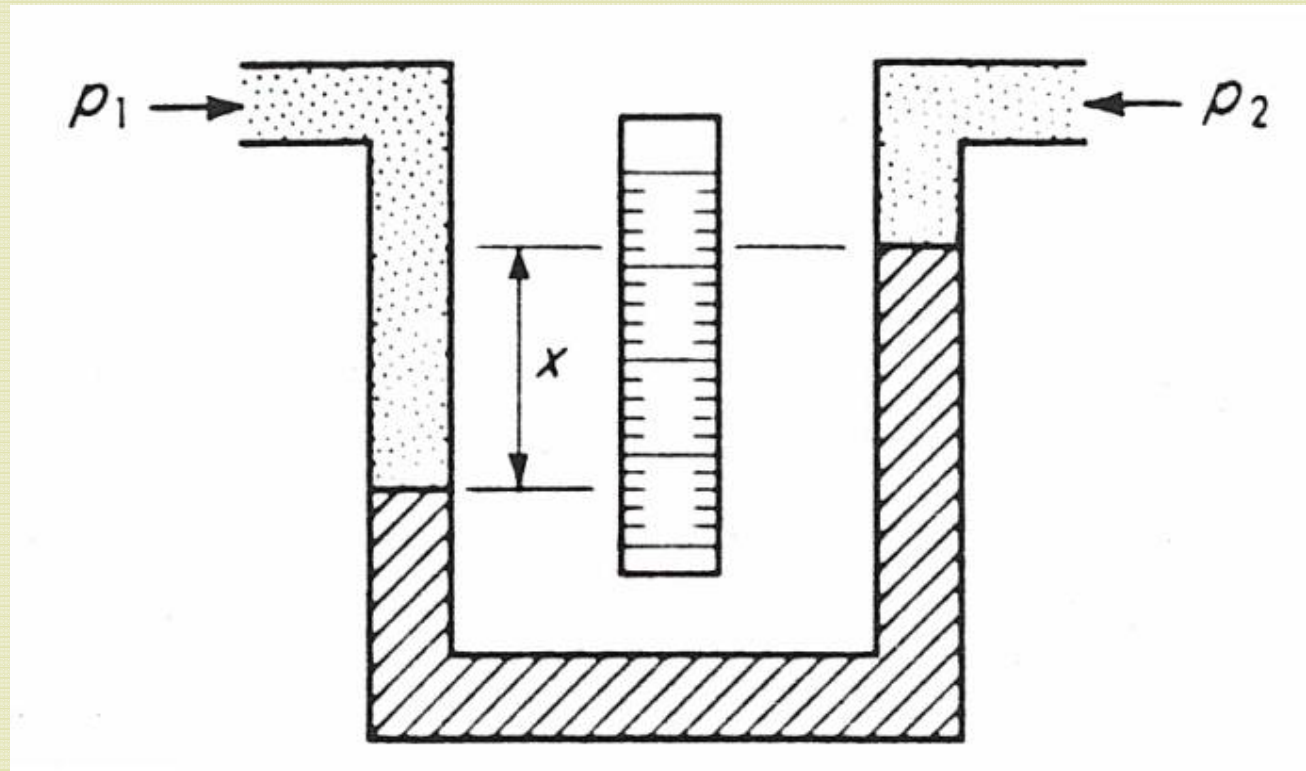
Electric-Resistance, Strain-gage Setup

Desired Input: strain

Interfering Inputs: 60-Hz magnetic field, gage temperature

Modifying Inputs: temperature, battery voltage  $E_b$

Example  
of  
Input Quantities



U-Tube Mercury Manometer for  
Differential-Pressure Measurement

Desired Inputs:  $p_1$  and  $p_2$

Interfering Inputs: acceleration, tilt angle

Modifying Inputs: ambient temperature, gravitational force, tilt angle

- Methods of Correction for Interfering and Modifying Inputs
  - Method of Inherent Sensitivity
  - Method of High-Gain Feedback
  - Method of Calculated Output Corrections
  - Method of Signal Filtering
  - Method of Opposing Inputs

- Method of Inherent Insensitivity

- This method proposes the sound design philosophy that the elements of the instrument should inherently be sensitive to only the desired inputs. This approach requires that somehow  $F_I$  and/or  $F_{M,D}$  be made as nearly equal to zero as possible. Thus, even though  $i_I$  and/or  $i_M$  may exist, they cannot affect the output.

- Method of High-Gain Feedback

- Suppose we wish to measure a voltage  $e_i$  by applying it to a motor whose torque is applied to a spring, causing a displacement  $x_o$ , which may be measured on a calibrated scale. For this properly designed open-loop system:

$$x_o = (K_{Mo} K_{SP}) e_i$$

- If modifying inputs  $i_{M1}$  and  $i_{M2}$  exist, they can cause changes in  $K_{M0}$  and  $K_{SP}$  that lead to errors in the relation between  $e_i$  and  $x_o$ . These errors are in direct proportion to the changes in  $K_{M0}$  and  $K_{SP}$ .
- Consider a closed-loop system. Here  $x_o$  is measured by a feedback device which produces a voltage  $e_o$  proportional to  $x_o$ . This voltage is subtracted from the input voltage  $e_i$ , and the difference is applied to an amplifier which drives the motor and thereby the spring to produce  $x_o$ :

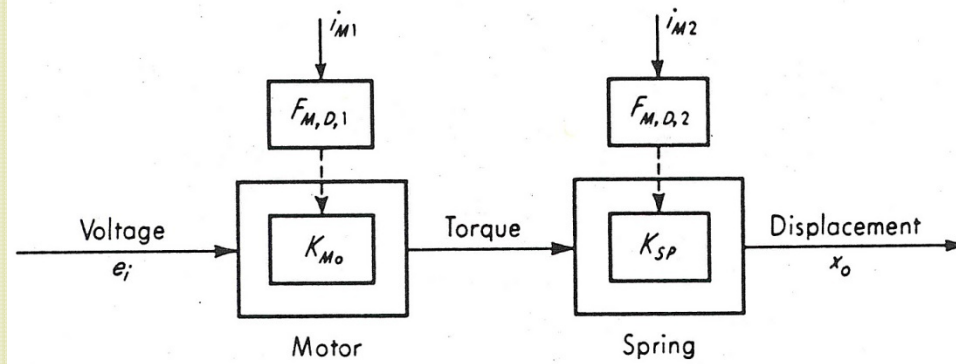
$$x_o = \frac{K_{AM} K_{M0} K_{SP}}{1 + K_{AM} K_{M0} K_{SP} K_{FB}} e_i$$

- Suppose we design  $K_{AM}$  to be very large (a “high-gain” system) so that  $K_{AM} K_{M0} K_{SP} K_{FB} \gg 1$ . Then  $x_o \approx \frac{1}{K_{FB}} e_i$

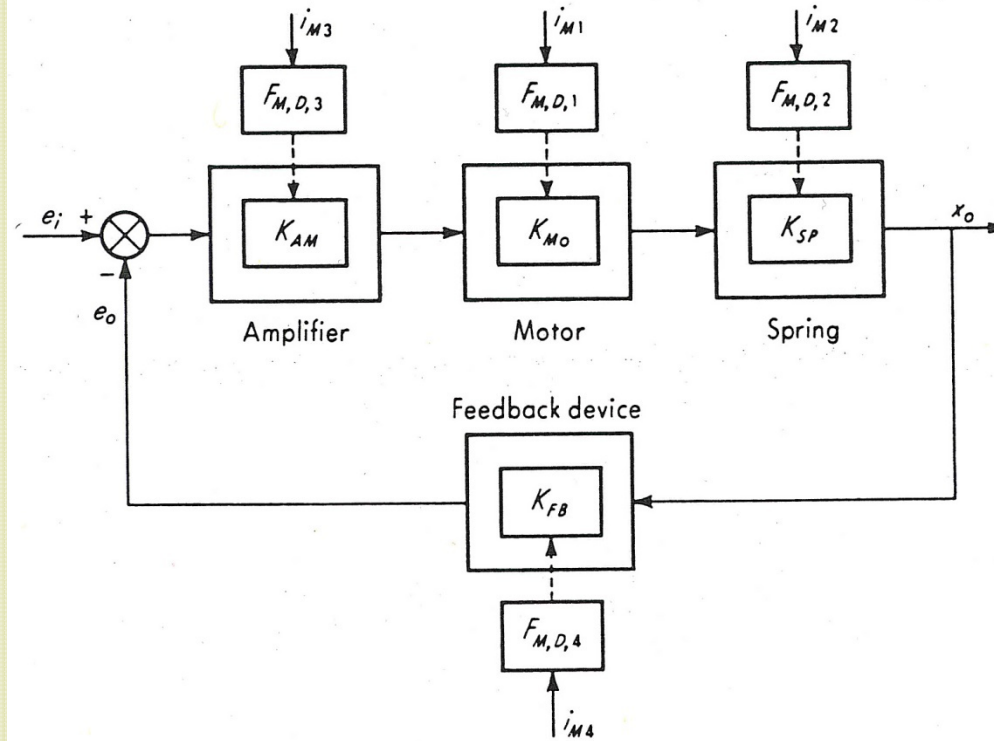


- The effects of variations in  $K_{AM}$ ,  $K_{SP}$ , and  $K_{M0}$  ( as a result of modifying inputs  $i_{M1}$ ,  $i_{M2}$ , and  $i_{M3}$ ) on the relation between  $e_i$  and output  $x_o$  have been made negligible. We now require only that  $K_{FB}$  stay constant (unaffected by  $i_{M4}$ ) in order to maintain constant input-output calibration. Since the amplifier supplies most of the power needed, the feedback device can be designed with low power-handling capacity which generally leads to greater accuracy and linearity in the feedback-device characteristics. Also, the input signal need carry only negligible power; thus the feedback system extracts less energy from the measured medium than the corresponding open-loop system, which results in less distortion of the measured quantity because of the presence of the measuring instrument.

# Method of High-Gain Feedback



(a) Open-loop system

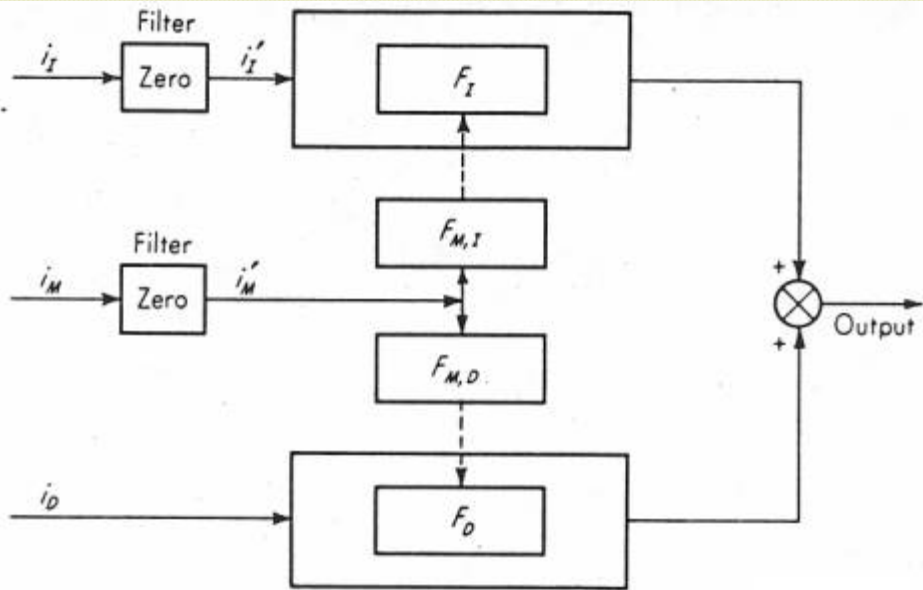


(b) Closed-loop or feedback system

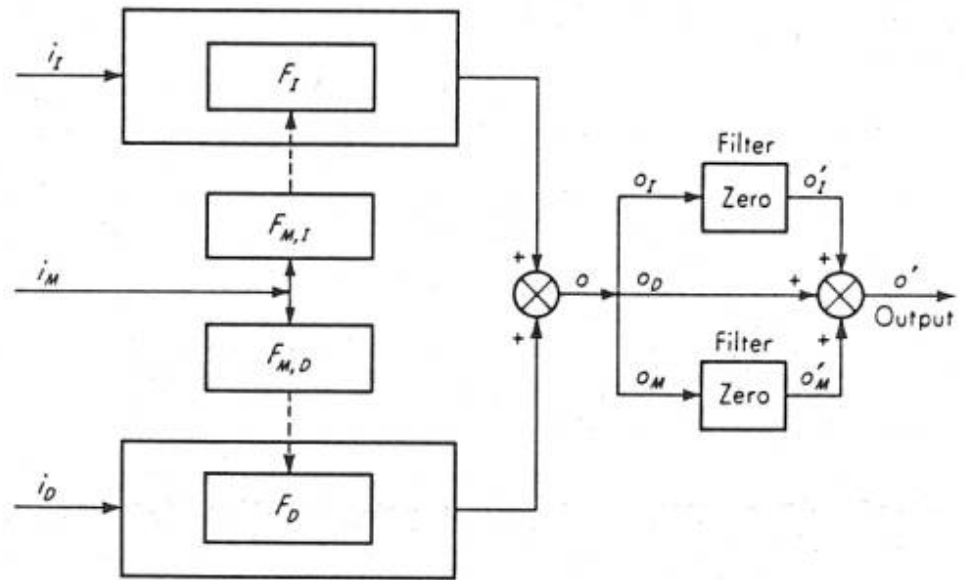
- Of course, feedback systems have the inherent problem of instability if there is an imbalance between strength of corrective action and system dynamic lags.
- Method of Calculated Output Corrections
  - This method requires one to measure or estimate the magnitudes of the interfering and/or modifying inputs and to know quantitatively how they affect the output. Then it is possible to calculate corrections which may be added to or subtracted from the indicated output so as to leave (ideally) only that component associated with the desired input.
  - Since most measurement systems today can afford to include a microcomputer to carry out various functions, if we also provide sensors for the spurious inputs, the microcomputer can implement the method of calculated output corrections on an automatic basis, giving a so-called smart sensor.

- Method of Signal Filtering

- This method is based on the possibility of introducing certain elements (“filters”) into the instrument which in some fashion block the spurious signals, so that their effects on the output are removed or reduced. The filter may be applied to any suitable signal in the instrument, be it input, output, or intermediate signal.
- The filters may take several forms. A filter can be designed (ideally) to block completely the passage of the signal. If the signal contains both desired and spurious components, the filter must be designed to be selective, i.e., it must pass the desired components essentially unaltered while effectively suppressing all others.



(a) Input filtering

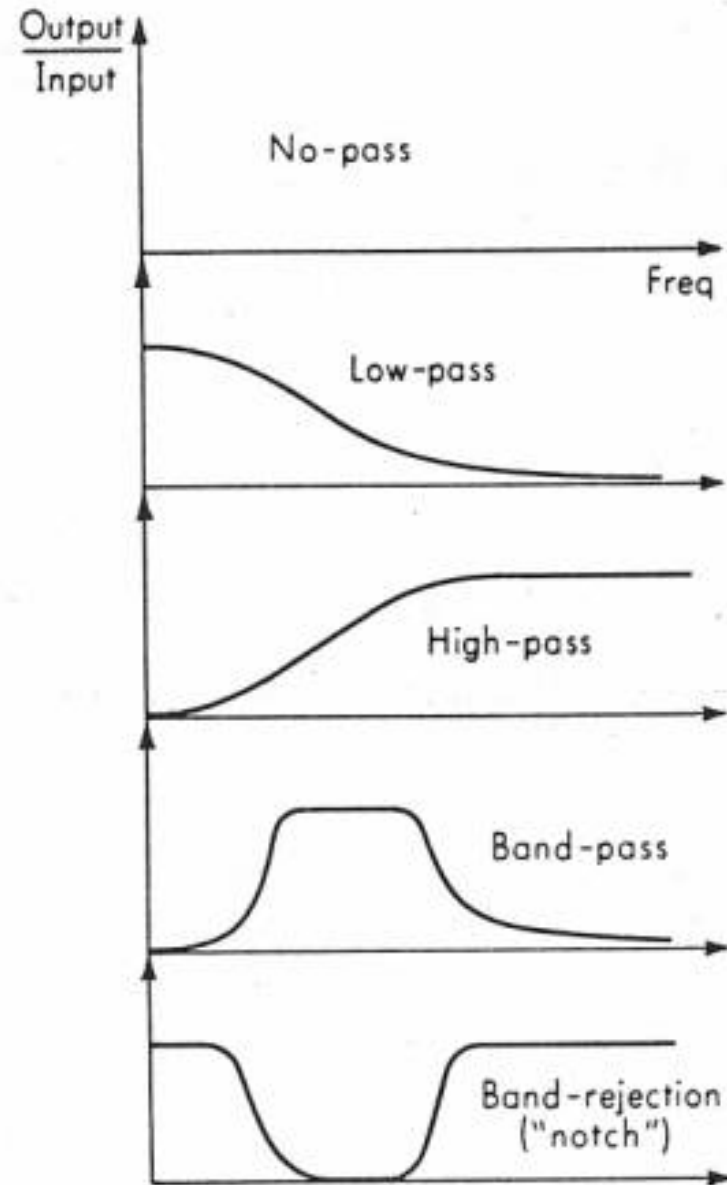


(b) Output filtering

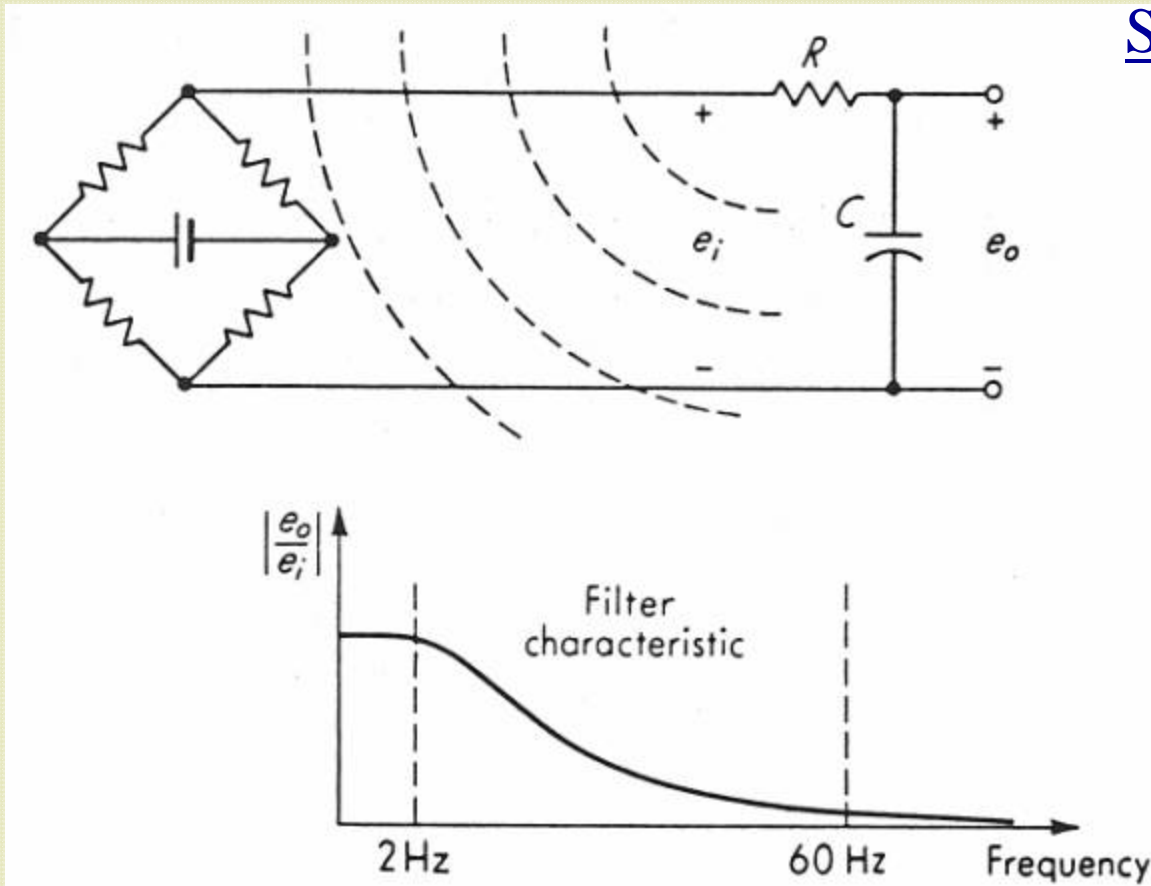
# Input and Output Filtering

## Basic Filter Types

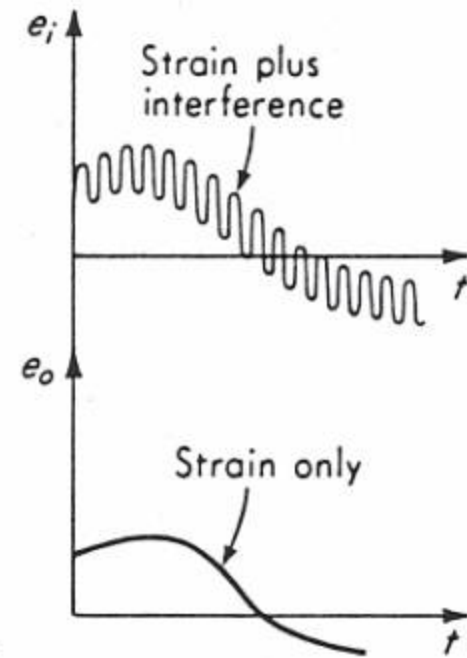
It is usually possible to design filters of mechanical, electrical, thermal, pneumatic, etc. nature which separate signals according to their frequency content in some specific manner.

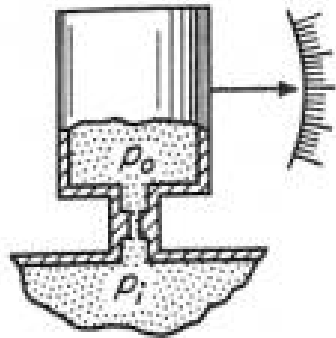


# Examples of Filtering

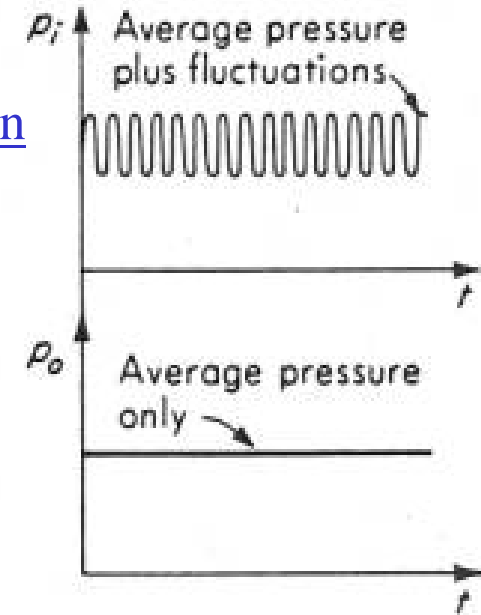
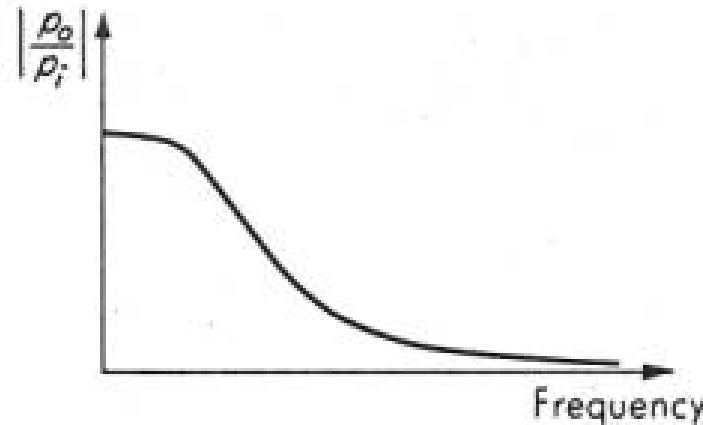


## Strain-gage Circuit





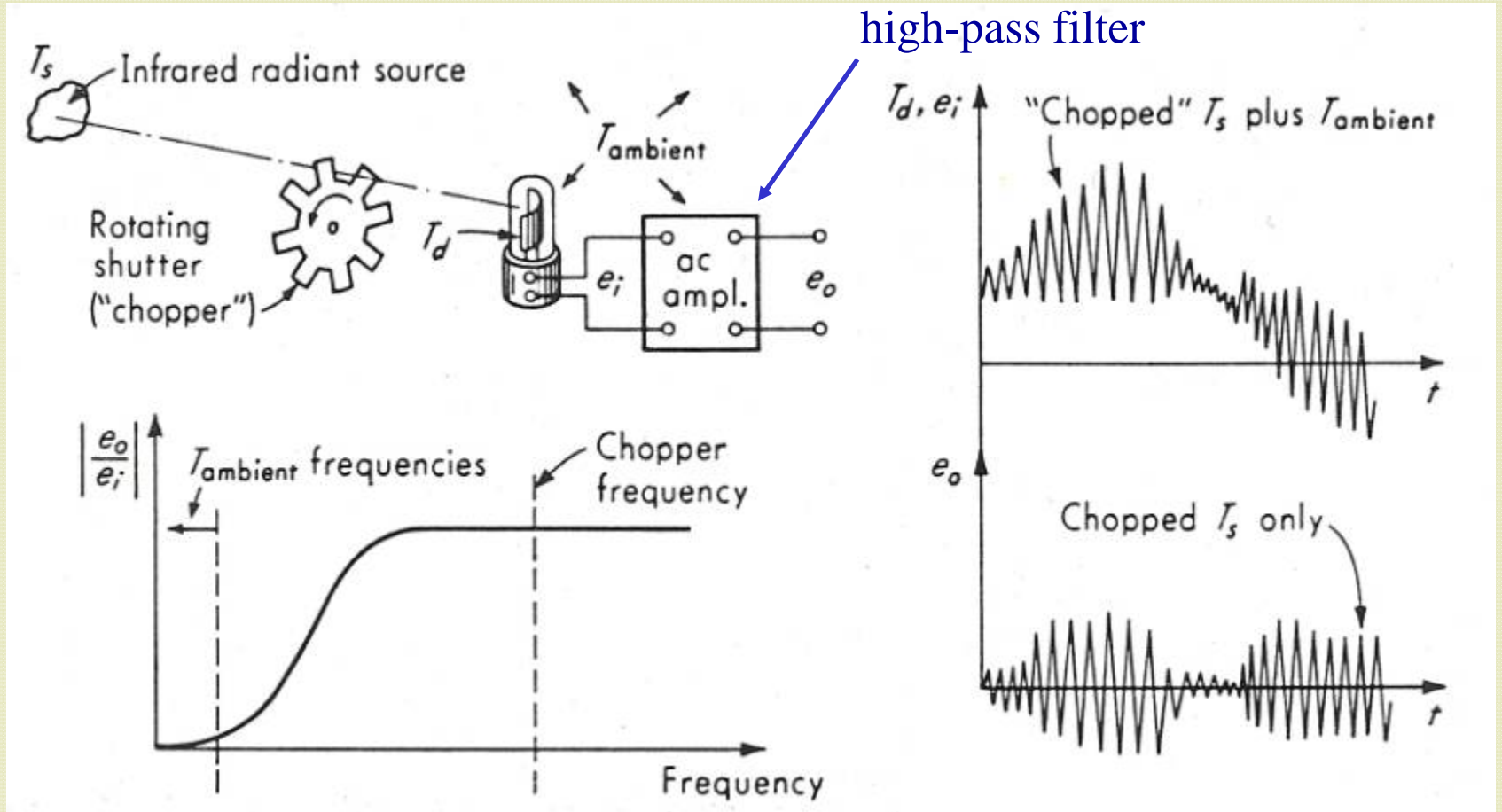
## Pressure Gage with Flow Restriction



Pressure gage modified by the insertion of a flow restriction (e.g., needle valve) between the source of the pressure and the piston chamber.

Pulsations in air pressure may be smoothed by the pneumatic filtering effect of the flow restriction and associated volume.



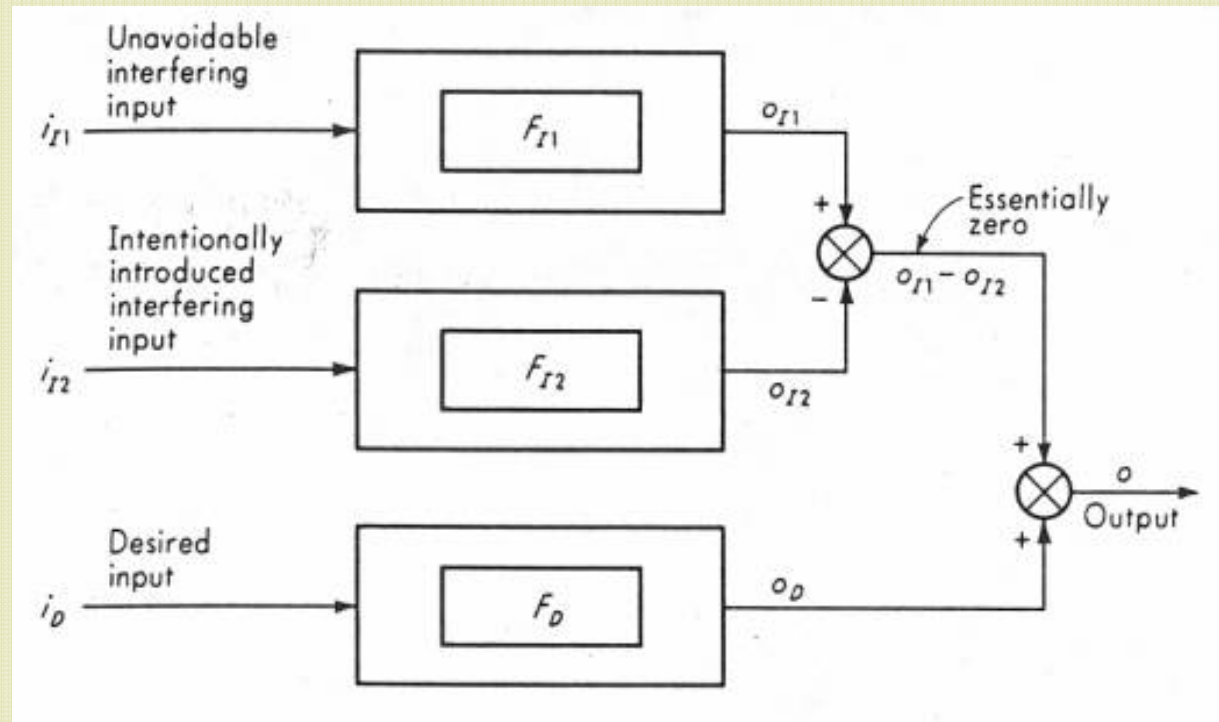


## Chopped Radiometer

- Method of Opposing Inputs

- This method consists of intentionally introducing into the instrument interfering and/or modifying inputs that tend to cancel the bad effects of the unavoidable spurious inputs.

Method applied to interfering inputs; extension to modifying inputs is obvious.



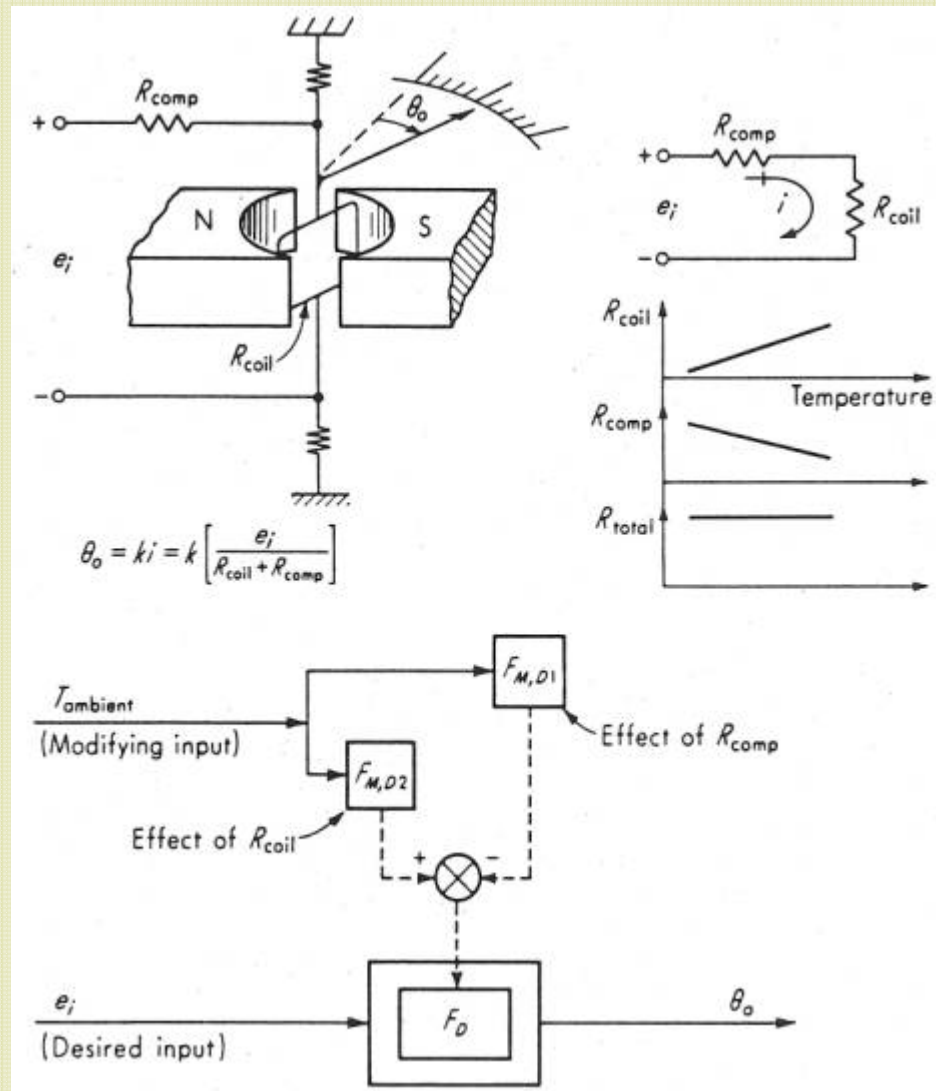
- The intentionally introduced input is designed so that the signals  $o_{I1}$  and  $o_{I2}$  are essentially equal, but act in opposite sense; thus the net contribution  $o_{I1} - o_{I2}$  to the output is essentially zero.
- This method might actually be considered as a variation on the method of calculated output corrections. However, the “calculation” and application of the correction are achieved automatically owing to the structure of the system, rather than by numerical calculation by a human operator.

# Examples of Method of Opposing Inputs

## Millivoltmeter

Millivoltmeter is basically a current-sensitive device whose scale can be calibrated in voltage as long as the total circuit resistance is constant.

Ambient temperature is a modifying input here.



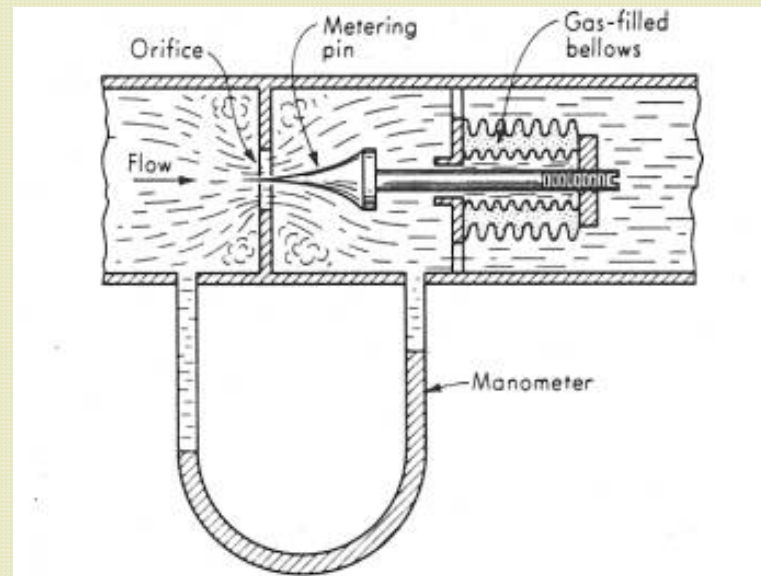
# Device for The Measurement of the Mass Flow Rate of Gases

Mass flow rate depends on the pressure drop across the orifice, but also on the density of the gas, which varies with pressure and temperature. Variations in gas temperature and pressure yield different mass flow rates for the same orifice pressure drop.

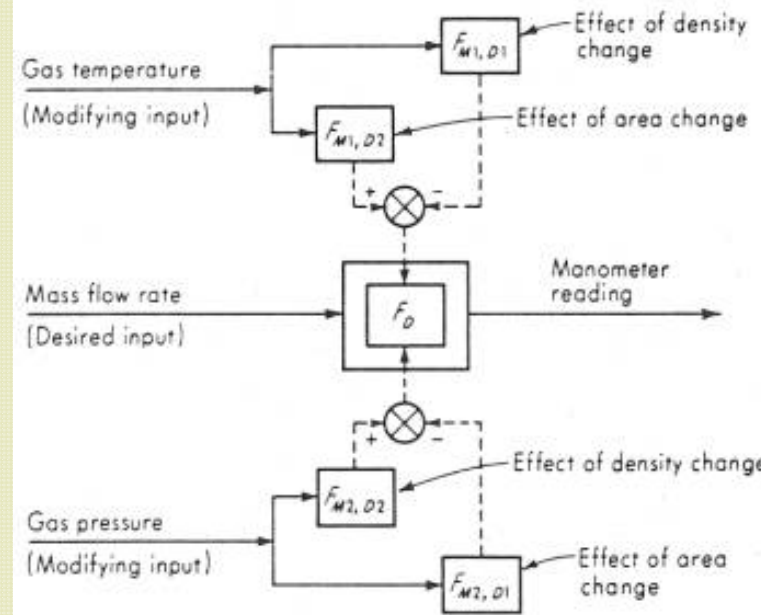
Flow rate through the orifice also depends on its flow area.

$$T \downarrow \Rightarrow \rho \uparrow, \dot{m} \uparrow \Rightarrow A \downarrow, \dot{m} \downarrow$$

$$p \uparrow \Rightarrow \rho \uparrow, \dot{m} \uparrow \Rightarrow A \downarrow, \dot{m} \downarrow$$

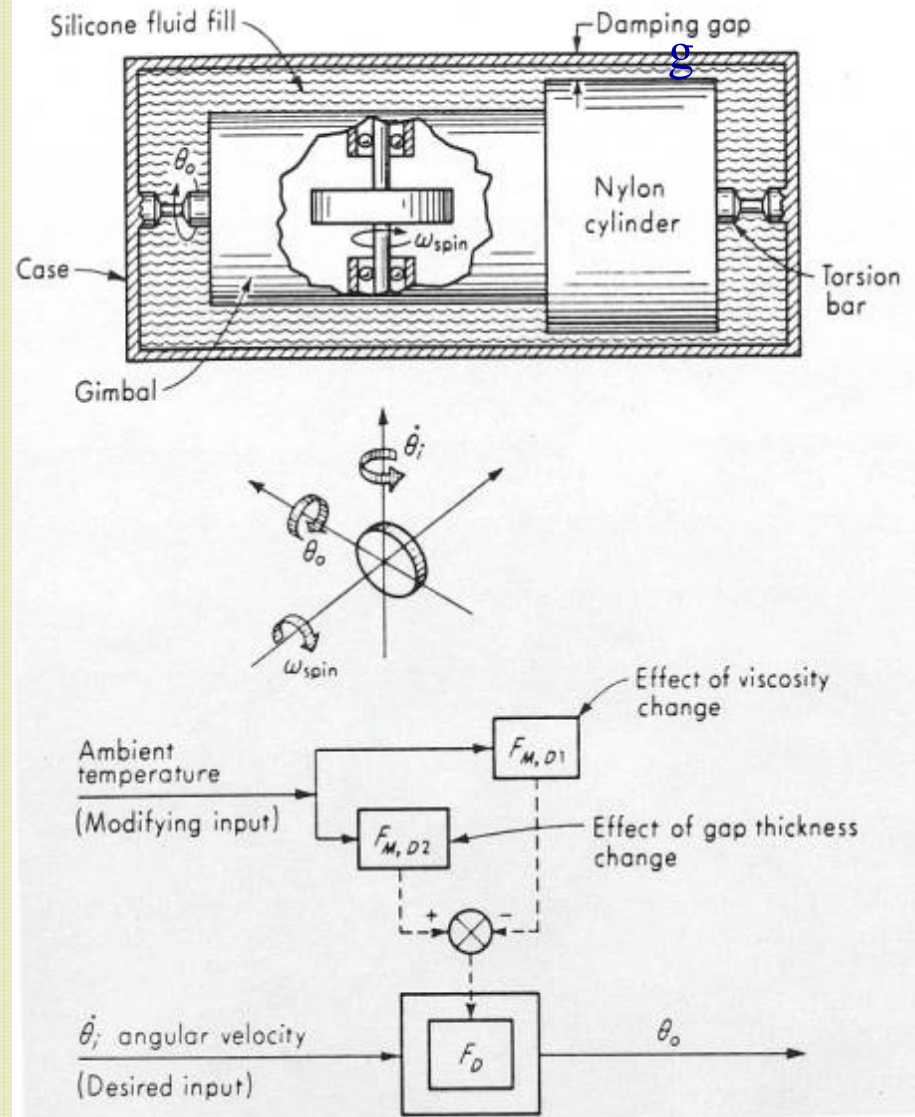


U-tube Manometer measures pressure drop across the orifice.



# Rate Gyroscope

To control unwanted oscillations, the gimbal rotation is damped by the shearing action of a viscous fluid in a narrow damping gap. The damping effect varies with the viscosity of the fluid and the thickness of the damping gap. Ambient temperature is a modifying input.



$T \uparrow \Rightarrow \mu \downarrow, \text{damping} \downarrow \Rightarrow \text{cylinder expands, } g \downarrow, \text{damping} \uparrow$

$T \downarrow \Rightarrow \mu \uparrow, \text{damping} \uparrow \Rightarrow \text{cylinder contracts, } g \uparrow, \text{damping} \downarrow$