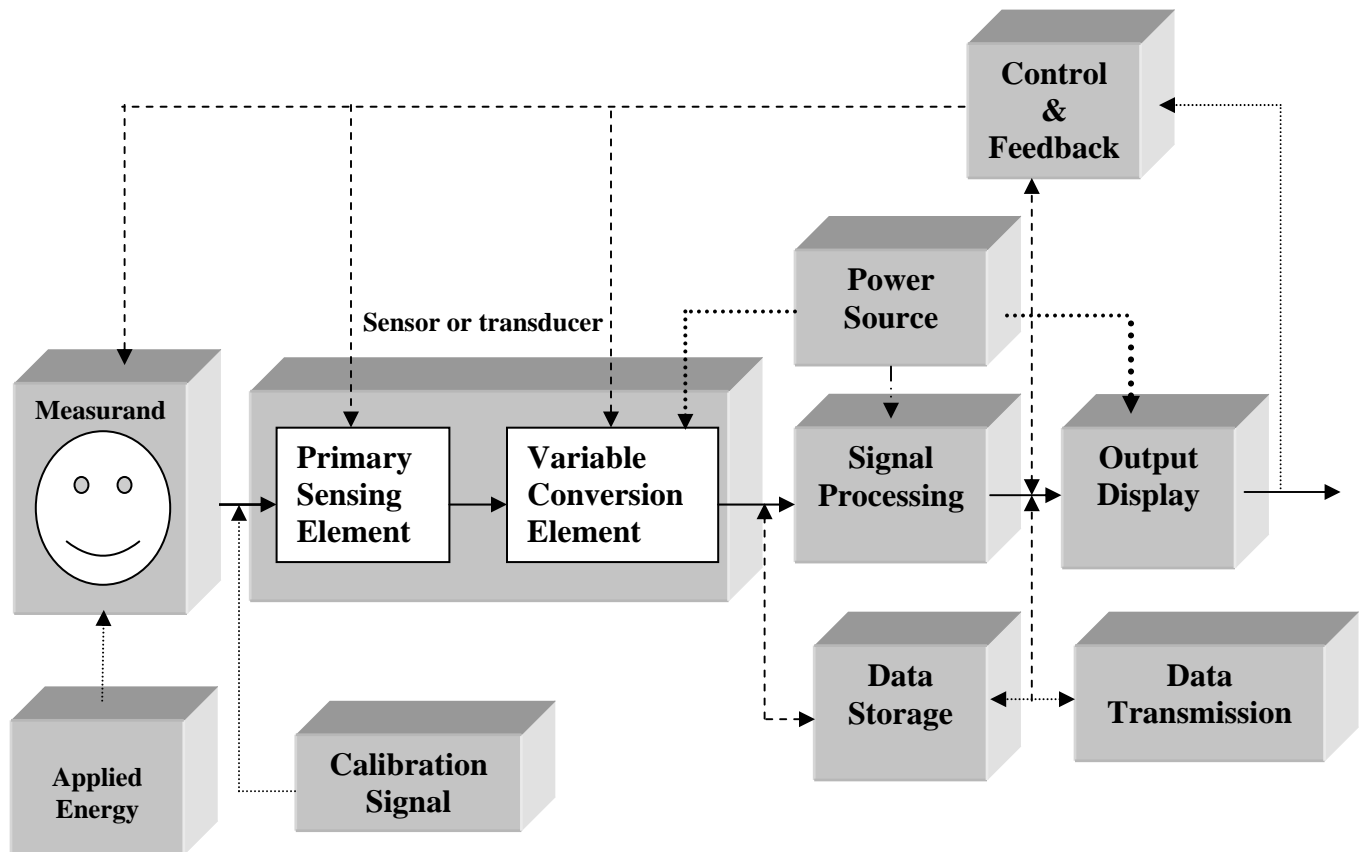


Basic Concepts of Medical Instrumentation

Generalized Medical Instrumentation system

- **Functional components of a typical medical instrumentation system**



Block diagram of a generalized medical instrumentation system

- **The major difference between this system and a conventional instrumentation system is:**

The source of the signals (measurand) is a living tissue or energy is applied to living tissue

Measurand

Physical quantity, property, or condition that is being measured by the system.

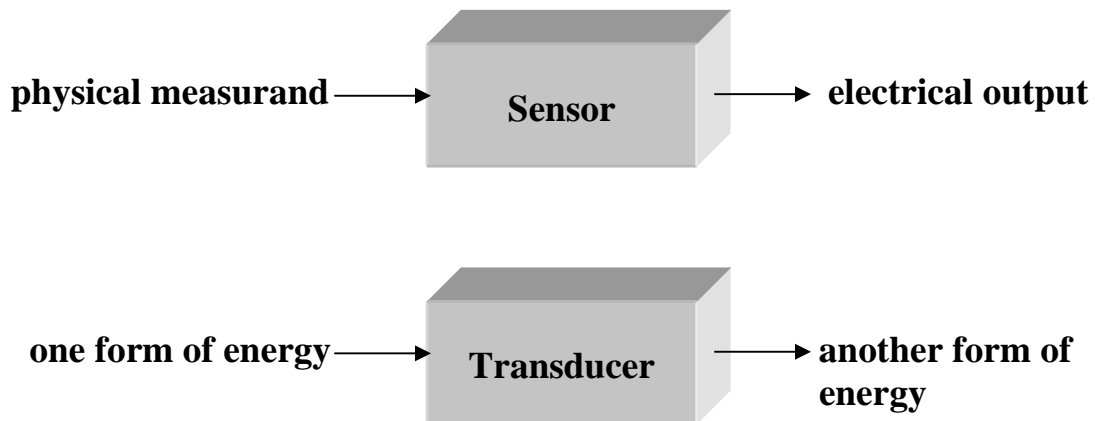
- * most important issue : accessibility
- internal (blood pressure), on body surface (ECG, EEG)
- emanate from the body (infra-red radiation)
- derived from a tissue sample (blood or biopsy)

Medically important measurands

- Biopotentials (ECG, EEG, EMG, EOG, etc.)
- Pressure, flow, dimensions (imaging)
- Displacement (velocity dx/dt , acceleration d^2x/d^2t , and force = md^2x/d^2t)
- Impedance, temperature and chemical concentration

The measurand may be localized to a specific organ or anatomical structure

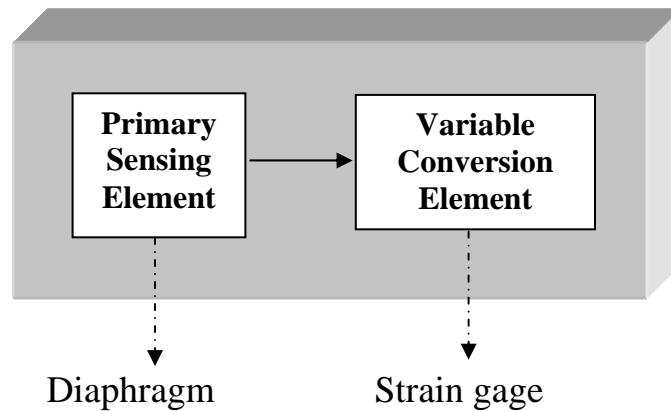
Sensor



* *The transducer or sensor should only **respond** to the **form of energy** present in the **measurand** to the exclusion of all others!*

* *The sensor should **interface** with the living system to **minimize the energy** extracted and being **minimally invasive**!*

Example of a sensor: pressure transducer



Pressure → displacement → electrical signal (voltage \propto pressure)

Sensitivity can be adjusted
over a wide range (p.s.e.)

usually need external
electrical power (v.c.e.)

Signal conditioning

Usually the sensor output can not directly drive the display, therefore signal processing or conditioning is required

Examples of signal processing:

1. Impedance matching
2. Amplification
3. Filtering
4. Mathematical mapping
5. Linearizing
6. Analog-to-digital conversion (ADC)
7. Digital-to-analog conversion (DAC)
8. Signal averaging to reduce noise (i.e. evoked response)
9. Transformation (time domain → frequency domain)
10. Compensation for undesirable sensor characteristics
11. Etc.

Output Display

Results must be displayed in a perceivable format for human operators

Examples of output displays:

1. Numerical
2. Graphical
3. Discrete
4. Continuous
5. Permanent or temporary

- *Most displays rely on our vision, but auditory sense is also sometimes used (for example, Doppler ultrasonic signals)*
- *User controls and output displays should conform to **human factors engineering** guidelines for the design of medical devices*

Auxiliary Elements

***Calibration signal** with the properties of the measurand should be applied to the sensor input or as early in the signal processing chain as possible

Many forms of **feedback (automatic or manual) may be required to elicit the measurand, to adjust the sensor and signal conditioner and to direct the flow of output (display, storage, transmission)

*****Data storage** for signal conditioning or examination of alarm conditions or implementation of different processing algorithms

**** **Data communication** → transmission of patient data to remote display at nurse's station and medical center

Operation Modes

1. **Direct and Indirect Modes**

- **Direct: Measurand directly to sensor**
 - readily accessible or
 - acceptable invasive procedure

For example: direct blood pressure measurement
- **Indirect: measurand not accessible**
 - Use another measurand with known relation to the desired one
 - Use some form of energy or material that interacts with the desired measurand to generate a new accessible one

For example:

Cardiac output (volume of blood pumped/min by the heart)

- Measurements of respiration & blood gas concentration
- Dye dilution
- Morphology of internal organs determined from X-rays

Pulmonary volume

- Determined from variations in thoracic impedance plethysmography (process of measuring volume changes)

For details refer to chapter 8 of your text or just be patient!

2. **Sampling or Continuous Modes**

- **Sampling: Parameters that change slowly do not require continuous measurements**

For example: body temperature, ionic concentrations, etc.

- **Continuous: Parameters that change fast enough to require continuous measurements**

For example: ECG, EEG, EMG, respiratory gas flow, etc.

Note: Frequency content of the measurand, the objective of the measurement, the condition of the patient and the potential liability of the physician influence how often data should be acquired

3. Generating and Modulating Sensors

- **Generating: Produce output from energy taken directly from measurand**

For example: photovoltaic cell (output voltage related to irradiation)

- **Modulating: Measurand changes flow of energy from an external source that affects the output of a sensor**

For example: photoconductive cell (apply external power to the sensor to measure changes in resistance with irradiation)

4. Analog and Digital Modes

- **Analog: Continuous (parameter takes on any value within the dynamic range)**

For example: Parameters that change fast enough to require continuous measurements: ECG, EEG, EMG, respiratory gas flow, etc.

- **Digital: Discrete (parameter takes on a finite number of different values)**

** Most sensors are analog (i.e., strain gages, thermistors, etc.)*

** Very few sensors are digital in nature (i.e., shaft encoders)*

Advantages of digital mode of operation:

- **Greater accuracy**
- **Repeatability**
- **Reliability**
- **Immunity to noise**
- **No need for periodic calibration**

** Therefore digital processing of signals has become very popular and we need Analog-to-digital Converters to interface analog sensors and displays*

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Advantages of analog displays:

Many clinicians prefer analog displays over digital ones when they are checking to see if a physiological variable is within certain limits and when they are looking at a fast changing parameter, for example: beat-to-beat heart rate → difficult to look at fast changing numbers indicating heart rate

5. Real-time and delayed-time Modes

Real-time: Sensors must acquire signals as they actually occur

- *Output is not always displayed immediately, because some types of signal processing (i.e. averaging, transformations, etc) require considerable amount of data before production of final results*

Delayed-time Often acceptable (short delays) unless urgent feedback & control depend on output

- *Cell cultures provide an example where several days of delay may be required before an output is obtained!*

Medical Measurement Constraints

- Medical instrumentation is designed to measure various medical & physiological parameters
- The amplitude and frequency ranges for each parameter are the major factors that affect the design of all instrument components
- Typical medical parameter measurement, frequency content, standard sensor or method used for measuring these parameters are: shown in Table1.1.

Table 1.1 Medical and physiological parameters

Parameter or measuring technique	Principal measurement range of parameter	Signal frequency range, Hz	Standard sensor or method
Ballistocardiography (BCG)	0–7 mg	dc–40	Accelerometer, strain gage
	0–100 μ m	dc–40	Displacement (LVDT)
Bladder pressure	1–100 cm H ₂ O	dc–10	Strain-gage manometer
Blood flow	1–300 ml/s	dc–20	Flowmeter (electromagnetic or ultrasonic)
Blood pressure	10–400 mm Hg	dc–50	Strain-gage manometer
		dc–60	
Direct (arterial)			
Indirect (Venous)	25–400 mm Hg	dc–60	Cuff, auscultation
		dc–50	
Strain gage			
Blood gases			
P_{O_2}	30–100 mm Hg	dc–2	Specific electrode, volumetric or manometric
P_{CO_2}	40–100 mm Hg	dc–2	Specific electrode, volumetric or manometric
P_{N_2}	1–3 mm Hg	dc–2	Specific electrode, volumetric or manometric
P_{CO}	0.1–0.4 mm Hg	dc–2	Specific electrode, volumetric or manometric
Blood pH	6.8–7.8 pH units	dc–2	Specific electrode
Cardiac output	4–25 liter/min	dc–20	Dye dilution, flowmeter
Electrocardiography (ECG)	0.5–4 mV	0.01–250	Skin electrodes
Electroencephalography (EEG)	5–300 μ V	dc–150	Scalp electrodes
(Electrocorticography and brain depth)	10–5000 μ V	dc–150	Brain-surface or depth electrodes
Electrogastrography (EGG)	10–1000 μ V	dc–1	Skin-surface electrodes
	0.5–80 mV	dc–1	Stomach-surface electrodes
Electromyography (EMG)	0.1–5 mV	dc–10,000	Needle electrodes
Eye potentials			
EOG	50–3500 μ V	dc–50	Contact electrodes
ERG	0–900 μ V	dc–50	Contact electrodes
Galvanic skin response (GSR)	1–500 k Ω	0.01–1	Skin electrodes
Gastric pH	3–13 pH units	dc–1	pH electrode; antimony electrode
Gastrointestinal pressure	0–100 cm H ₂ O	dc–10	Strain-gage manometer

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Table 1.1 (Continued)

Parameter or measuring technique	Principal measurement range of parameter	Signal frequency range, Hz	Standard sensor or method
Gastrointestinal forces	1–50 g	dc–1	Displacement system, LVDT
Nerve potentials	0.01–3 mV	dc–10,000	Surface or needle electrodes
Phonocardiography (PCG)	Dynamic range 80 dB, threshold about 100 μ Pa	5–2000	Microphone
Plethysmography (volume change)	Varies with organ measured	dc–30	Displacement chamber or impedance change
Circulatory	0–30 ml	dc–30	Displacement chamber or impedance change
Respiratory functions Pneumotachography (flow rate)	0–600 liter/min	dc–40	Pneumotachograph head and differential pressure
Respiratory rate	2–50 breaths/min	0.1–10	Strain gage on chest, impedance, nasal thermistor
Tidal volume	50–1000 ml/breath	0.1–10	Above methods
Temperature of body	32–40°C 90–104°F	dc–0.1	Thermistor, thermocouple

SOURCE: Revised from *Medical Engineering*, C. D. Ray (ed.). Copyright © 1974 by Year Book Medical Publishers, Inc., Chicago. Used by permission.

Things to note in this table are:

Nearly all biomedical measurements depend on some form of energy being applied to the living tissue or to the sensor, for example:

- *X-ray, ultrasonic imaging and electromagnetic or Doppler ultrasonic blood flowmeters depend on externally applied energy interacting with living tissue*
- *Safe level of applied energy is an important consideration*

Additional constraints on medical instruments used in medical environment:

- **Reliable**
- **Simple to operate**
- **Withstand physical abuse and exposure to corrosive chemicals**
- **Electrical safety (minimize electric shock hazard)**

BI Lecture Series

9

Classification of Biomedical Instruments

There are **four** approaches to classification:

1. Quantity being sensed:

- Pressure, flow, temperature, potential, etc.

Advantage: *easy comparison of different methods for measuring any quantity*

2. Principle of transduction:

- Resistive, capacitive, inductive, ultrasonic or electrochemical

Advantages:

- a. different applications of each principle can be used to strengthen understanding of each concept*
- b. newer applications readily apparent*

3. Measurement technique for each physiological system:

- Cardiovascular, pulmonary, nervous, endocrine

Advantage: *isolates all important measurements for specialists*

Disadvantage: *considerable overlap of quantities sensed and the principles of transduction used*

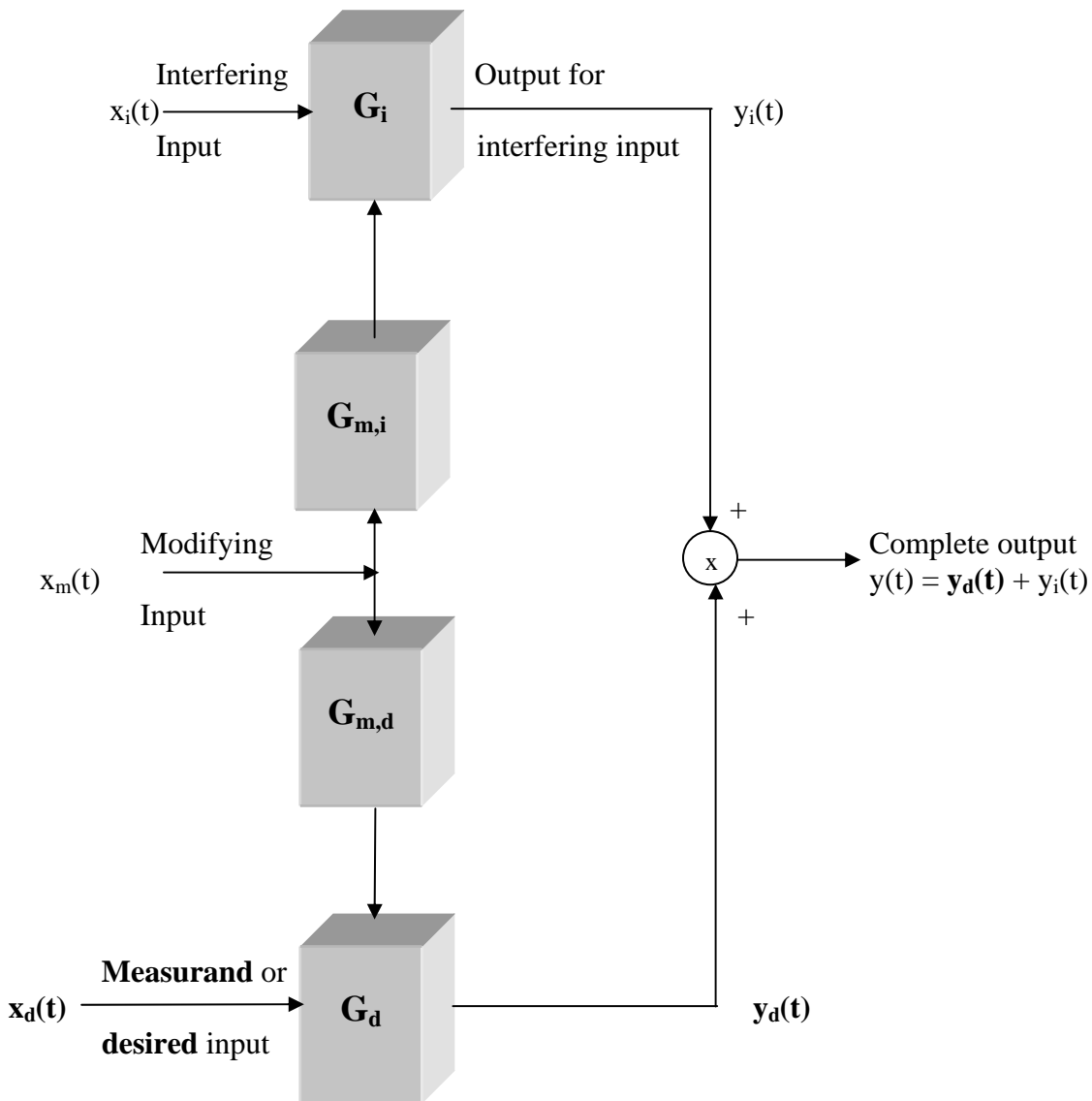
4. Clinical medicine specialties:

- Pediatrics, Obstetrics, Cardiology, Radiology, etc.

Advantage: *valuable for medical personnel interested in specialized instruments*

Interfering and Modifying Inputs

A general block diagram for classifying desired and undesired inputs to instruments is shown below:



Generalized Input-output diagram

Desired input: *the measurand that the instrument is designed to isolate and measure*

Interfering inputs: *quantities that inadvertently affect the instrument as a consequence of the principles used to acquire & process the desired inputs*

Modifying inputs: *undesired quantities that indirectly affect the output by altering the performance of the instrument itself*

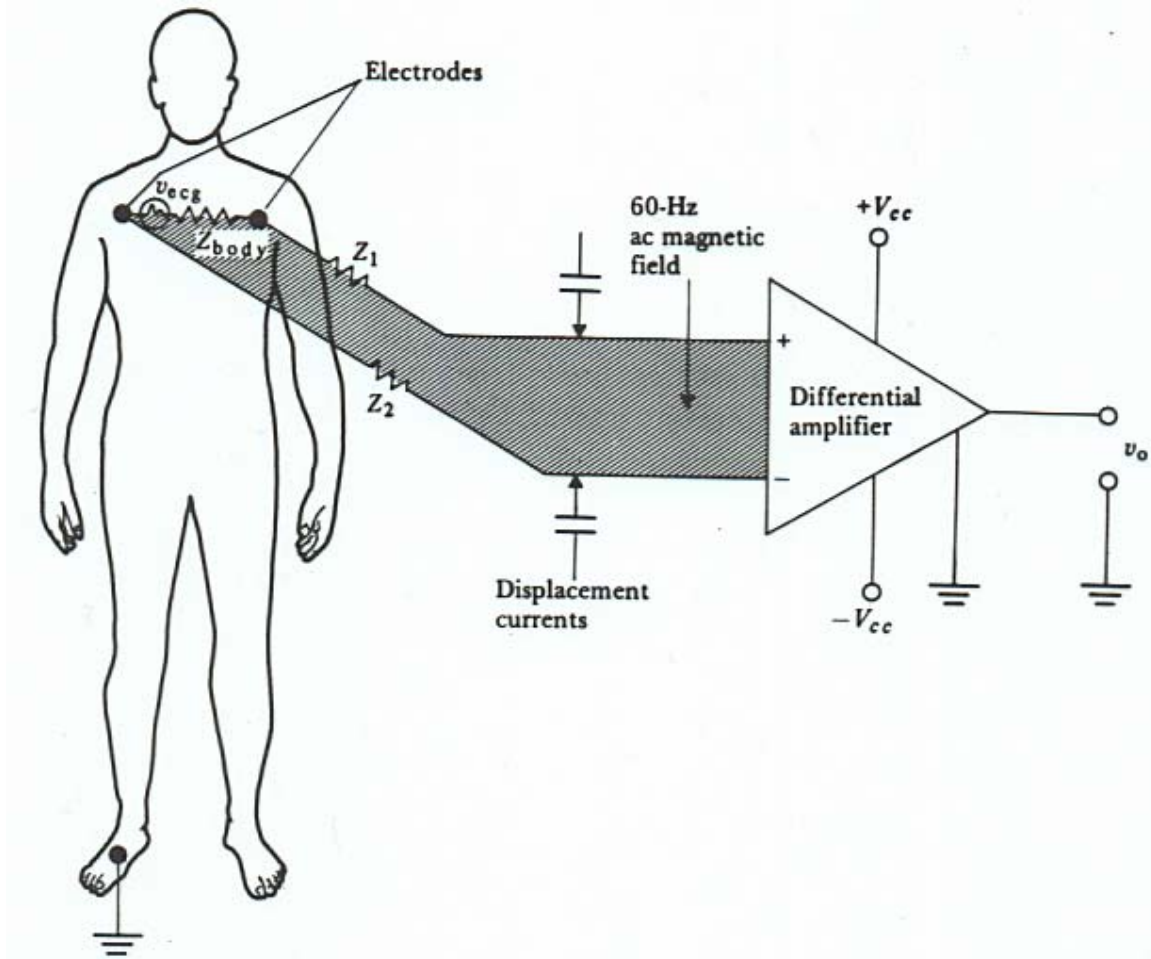
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- **Modifying inputs can affect processing of either desired or interfering inputs**
- **Some undesirable quantities can act as both a modifying input and an interfering input**
- **G_d represents the I/O relationship (a mapping function) between the desired input and output. It may be:**
 1. **A linear amplification [output = $K \times$ input] - remember Linear Electronics!**
 2. **A non-linear equation [output = $f(\text{input})$],**
i.e. $y_d(t) = x^3(t) + 27x_d^2(t) + 12$
Some non-linear sensor or processor
 3. **A dynamic relation that may be time varying (differential equation)**
 4. **A non-deterministic relationship with random or stochastic components (statistical distribution function)**
- **G_i may be the same as G_d**
- **$G_{m,d}$ and $G_{m,i}$ represent mechanisms by which modifying inputs affect the operation G_d and G_i**

Note: Variations to this scheme are possible as this is a generalized I/O diagram

Example

A simplified ECG recording system provides a good example. See Figure 1.3 in your text. Detailed analysis of such a system takes place in Chapter 6 of Webster.



Simplified electrocardiographic recording system

In this recording system:

- The **desired** input is: v_{ecg} –electrocardiographic voltage between 2 electrodes (RA & LA)
- The **interfering** inputs are:
 1. 50 Hz or 60 Hz (powerline) noise voltage induced in the shaded loop by ac magnetic fields

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Note: *The desired and interfering voltages are in series and both appear at the input of the differential amplifier*

2. Difference between capacitively coupled displacement currents flowing through Z_{body}
 3. Voltage drop across Z_1 and Z_2 due to displacement currents
- The **modifying** input is:
Orientation of patient cables
 - Plane parallel to magnetic field → zero input
 - Plane perpendicular to magnetic field → maximum input
 - The **modifying** inputs **affecting G_d and G_i** are:
 1. Time-dependent changes in electrode impedance (more details in Chapter 5, when we study biopotential electrodes)
 2. Electrode motion

To reduce or eliminate the effects of most interfering and modifying inputs we have **two** alternatives:

1. **Alter the design of essential instrument components (preferred, but hard to achieve)**
2. **Add new components to offset the undesired inputs**
3. **The second alternative is more feasible and we call them compensation methods**

Compensation methods

There are **four** different types of compensation methods:

1. Inherent sensitivity

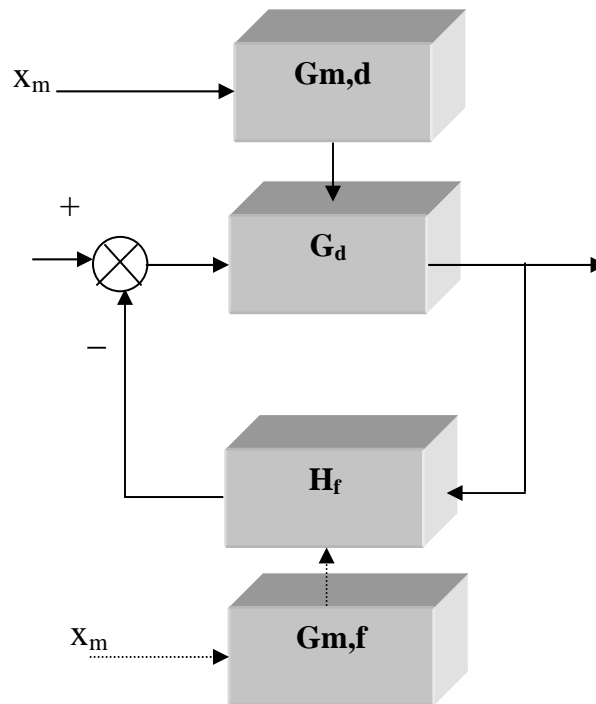
- All components only respond to desired inputs \rightarrow make G_i and $G_{m,d} = 0$ in the figure for generalized Input-output presented above

In the ECG recording problem, Figure 1.3 of Webster:

- twist the electrode wires \rightarrow this makes $G_i \rightarrow 0$
(remember from Physics:
 $v_{int} \sim B$ (magnetic field density). A (area subtended by the mag. field). n (number of wire turns)
By twisting the wires we make $A \rightarrow 0!$ Therefore $v_{int} = 0!$)
- Minimize electrode motion \rightarrow this makes $G_{m,d} \rightarrow 0$

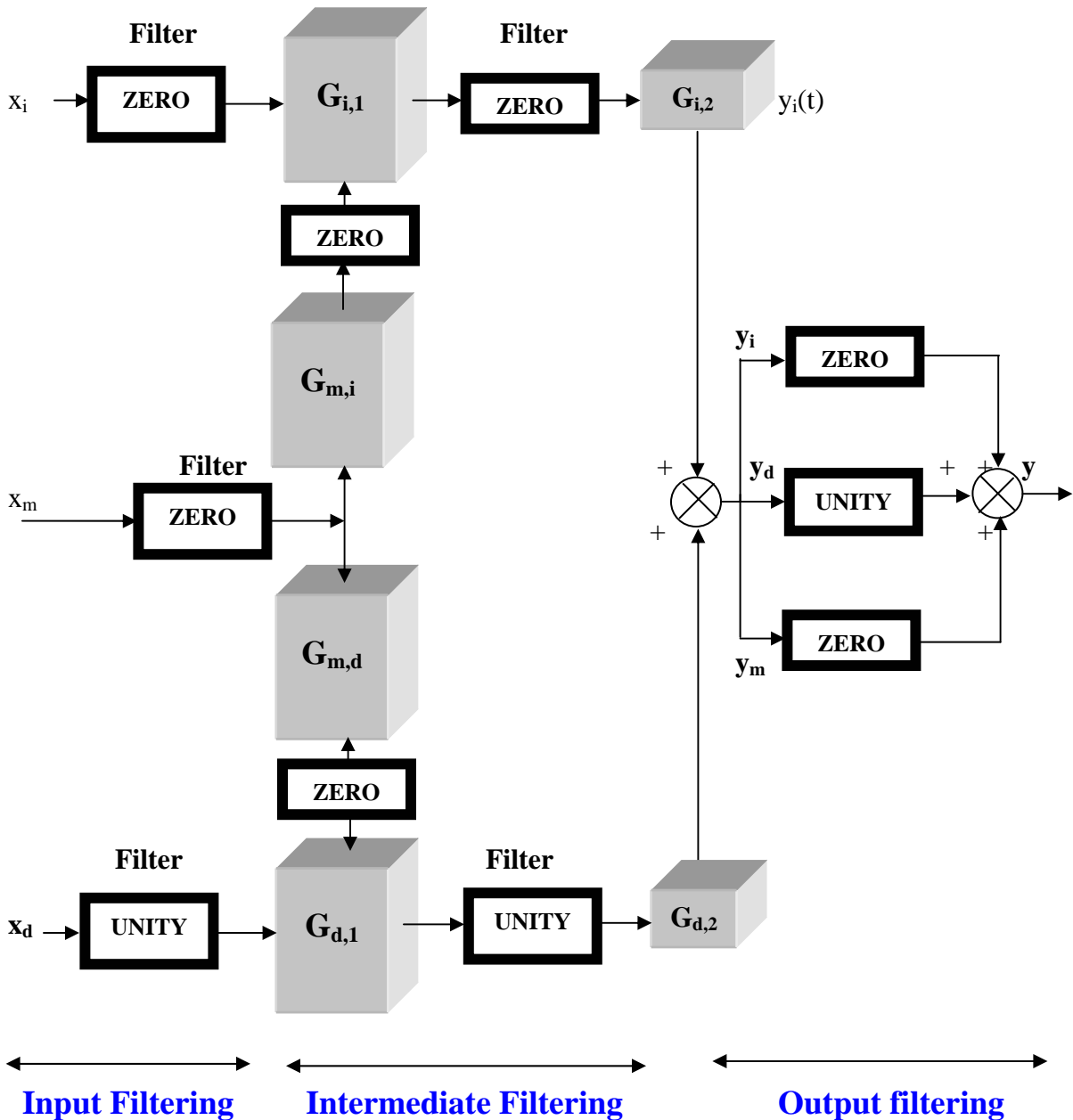
2. Negative feedback

- Use negative feedback to minimize the effect of modifying inputs on the performance of the instrument (comprehensive study of feedback methods takes place in Electronics and Control topics)



Negative Feedback Compensation Method

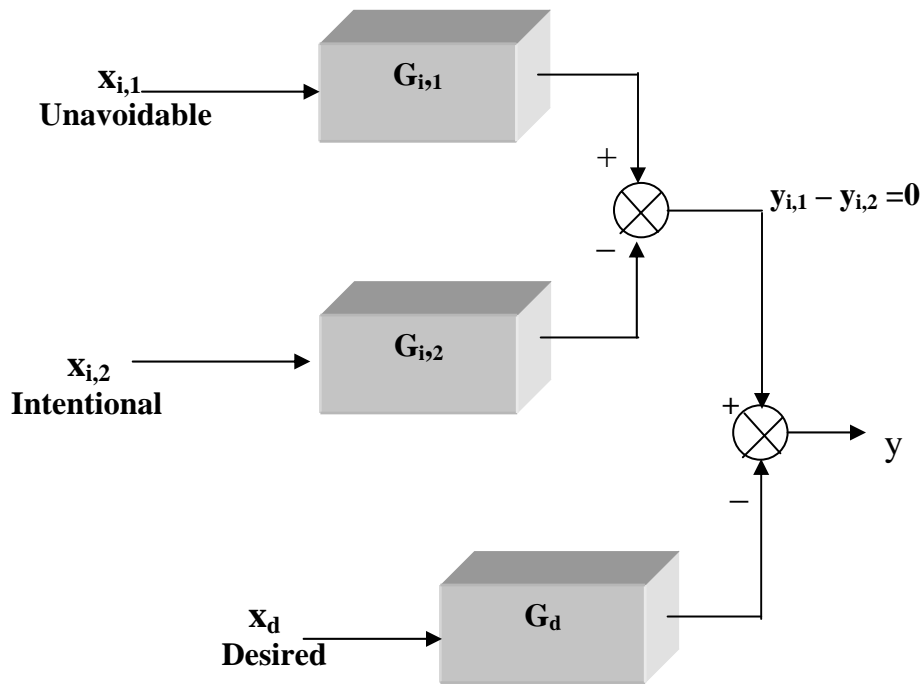
3. Signal filtering



Signal Filtering Compensation Method

- Filters may be inserted at the input, intermediate or output stages. Study the different filtering methods in your text carefully and note that all filters are not necessarily electrical, but designers use mechanical, pneumatic, thermal or electromagnetic filters to block out undesired environmental inputs. Also note which stage qualifies for what type of filter(s) best.

4. Opposing inputs



Opposing Inputs Compensation Method

- **Introduce extra intentional inputs such that:**

$$\begin{array}{ccc}
 \mathbf{x}_{i,1} \cdot \mathbf{G}_{i,1} & \approx & \mathbf{x}_{i,2} \cdot \mathbf{G}_{i,2} \\
 \text{Unavoidable} & & \text{Intentional}
 \end{array}$$