BENG 186B: Principles of Bioinstrumentation Design

Lecture 1

Introduction: Bioinstrumentation Systems

References

Webster, Ch. 1 (Sec. 1.2, 1.3, 1.5, 1.8, 1.9).
http://en.wikipedia.org/wiki/Accuracy
http://en.wikipedia.org/wiki/Electrical_impedance

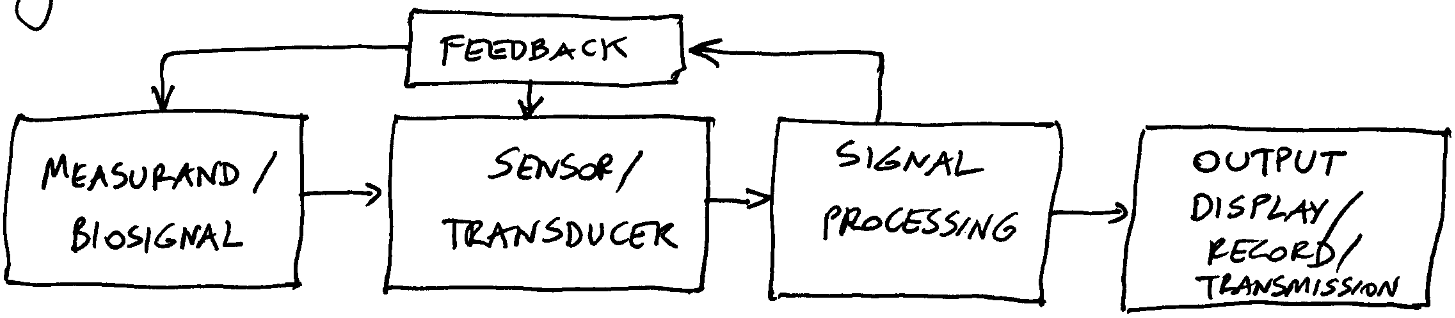
INTRO TO BIOINSTRUMENTATION

Webster, Chap. 1

- Bioinstrument:
  - Sensor or actuator (or both) used in medicine or biological research
  - Usually directly connected to a living system
  - Processes, displays or transmits biological data
- Areas of biomedical engineering that use these instruments:
  - Bioelectronics (e.g. cardiac monitoring)
  - Biomechanics (e.g. tissue testing)
  - Biooptics (e.g. screening for biomarkers, radiation therapy)
  - Biomaterials (e.g. biocompatibility testing)
  - Biosystems (e.g. properties of cells)
  - Medical imaging (e.g. MRI, PET)

  etc.
- Key to successful engineering of a bioinstrument:
  - → understand the physiology of the system
  - → know the variables to be measured
  - → know the function and limitations of the components

- General bioinstrument:



e.g. pressure, temperature, flow, chemical concentration, voltage/current

converts one form of signal to another, typically to voltage

amplify weak signals; filter out noise; extract signal

typically wireless transmission for an implant

- Operational modes:
  - Direct vs. indirect measurement
    → if possible, direct is better (for the signal, not necessarily for the patient)

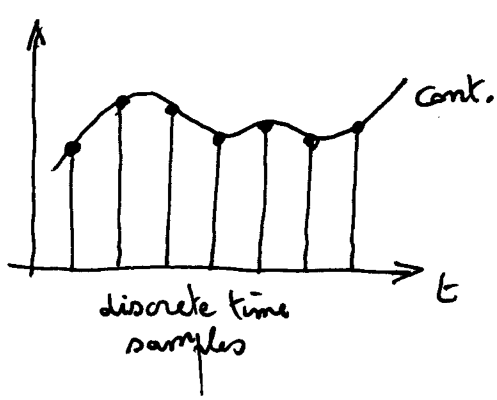
    e.g.: microelectrode array (direct neural, invasive) vs.
    fMRI (indirect neural BOLD signal, non-invasive)

  - Sampled vs. continuous data aquisition

    Sampled ↓ DIGITAL — continuous ↓ ANALOG

    DIGITAL: discrete-time, discrete-level amplitude

Most sensors are analog, then signal is converted to digital for processing or transmission



NYQUIST criterion: any continuous signal of frequency bandwidth f_{BW} can be fully reconstructed from its discrete-time samples at sampling rate $2 f_{BW}$.

⇒ guideline : use anti-alias lowpass filter at $\leq f_{BW}$ cut-off frequency prior to sampling at $2 f_{BW}$.

— Real-time vs. delayed

→ Real-time signal processing is essential for bioinstruments with feedback

→ Some delay is acceptable for output display / transmission systems.

THROUGHPUT is more important than LATENCY
(typ. Msps, or 10^6 samples/s) (typ. ms)

- Performance characteristics : quantifying the quality of the measurement or the signal processing

Static instrument characteristics :

— Accuracy : the difference between the "true" value and the mean of the measured values

Sometimes expressed in %: (for positive measurands)

$$\frac{\text{true value} - \text{mean measured}}{\text{true value}} \times 100\%$$

→ can vary with time, frequency, etc.

→ with this definition, smaller is better !

— Precision : degree of reproducibility or repeatability
standard deviation of the measured values

Precision and accuracy are not the same thing!

e.g. : Bull's eye :

ACCURATE, NOT PRECISE — PRECISE, NOT ACCURATE

The best instrument is both accurate, and precise.

It is common to express accuracy and/or precision with significant figures, e.g.

value = 30 μV
value = 32.578 μV

— Resolution : smallest increment that can be resolved in the measurement.

For digital outputs, it is one LSB (least significant bit)

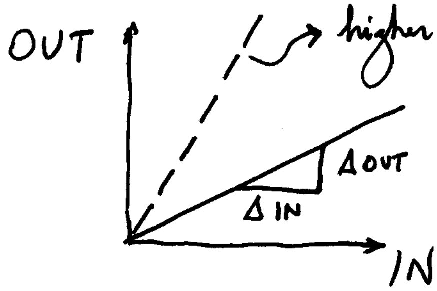
e.g.: 8-bit over 2.56 V range gives a resolution of 1 LSB = 10 mV.

These are performance characteristics of measured outputs.

For systems, we also consider performance from input to output:

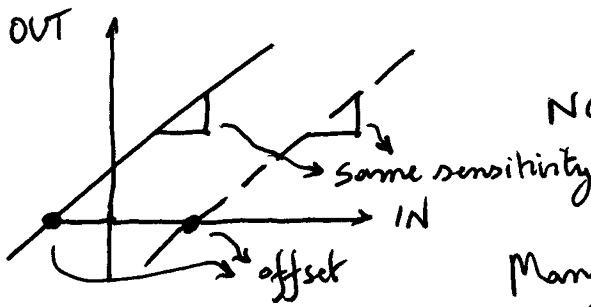
- Sensitivity : gain of a system $= \dfrac{\Delta \text{ OUT}}{\Delta \text{ IN}}$

= slope of input – output relationship :



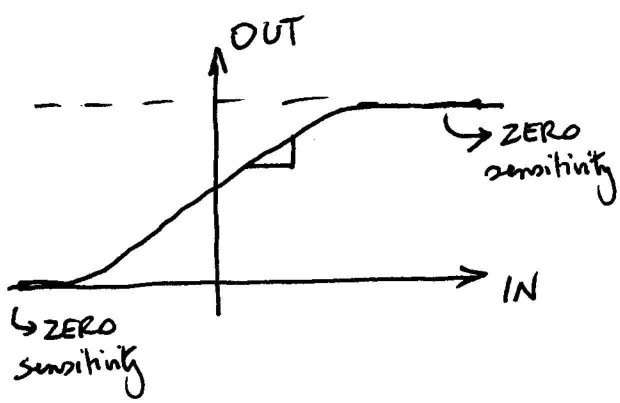
→ higher sensitivity is typically better.

For linear systems, sensitivity is constant.



NOTE: Offset does not affect sensitivity.

Many instruments have two knobs : gain (sensitivity), and offset control

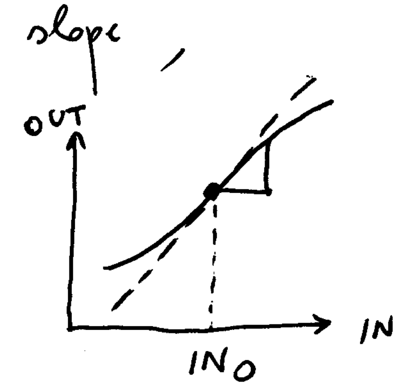


Instruments almost always saturate in low and high input regimes. It is desirable to operate them in their region of highest sensitivity.

In general, for nonlinear systems :

$$\text{Sensitivity} = \left.\frac{d\,\text{OUT}}{d\,\text{IN}}\right|_{\text{IN}_0} = \text{local slope}$$

where IN_0 is the operating point.



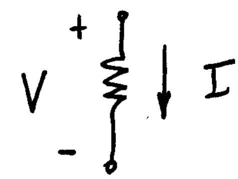
- Input impedance and output impedance:

These describe how the static or dynamic variables of a system (such as a circuit) interact with those of the inputs and the outputs it connects to.

For circuits, the variables are voltage and current.

For a resistor, impedance is simply resistance:

$$Z = R = \frac{V}{I}$$



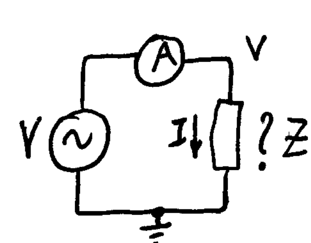
More generally,

$$\text{Impedance } Z = \frac{\text{effort variable}}{\text{flow variable}}$$

where effort variable = voltage, pressure, temperature, ...
flow variable = current, flow, heat, ...

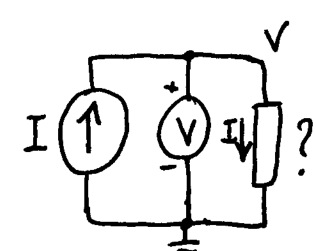
For a general circuit, impedance is still:

$$Z = \frac{V}{I}$$ → can be calculated, or measured:



VOLTAGE SOURCE
+ AMMETER

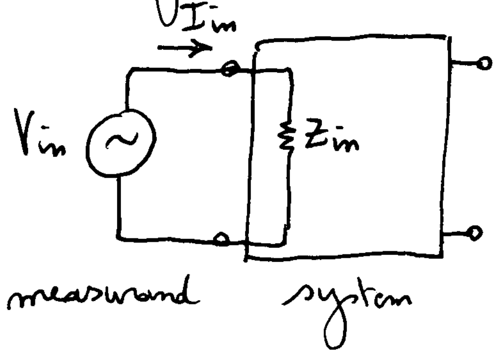
, or



CURRENT SOURCE
+ VOLTMETER

Input impedance is the impedance of a circuit (system) at its input, as seen from the outside:

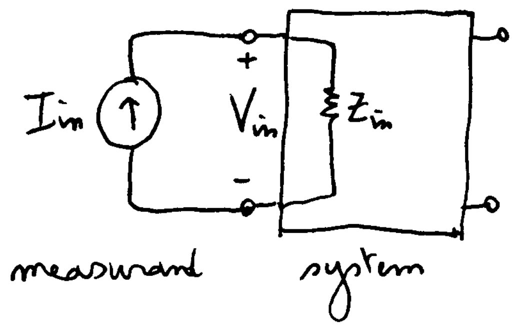
$$Z_{in} = \frac{V_{in}}{I_{in}}$$



(Z_{in} may not be an actual resistor in the box, it is the Thevenin equivalent of what is inside.)

If the measurand is voltage, then large Z_{in} is good! Little current is taken from the measurand by the system.

If the measurand is current, then large Z_{in} is not good. Large Z_{in} would mean a large voltage even for small current, which may disturb the current supplied by the measurand:

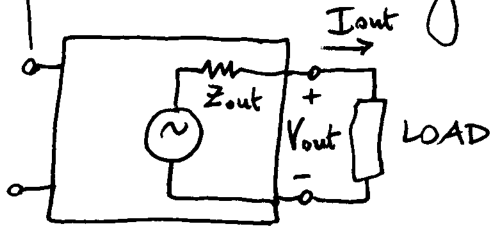


Ideally, we should have:

- $Z_{in} \approx \infty$ ($I_{in} = 0$ for all V_{in}) for VOLTAGE MEASURANDS as for an ideal VOLTMETER
- $Z_{in} \approx 0$ ($V_{in} = 0$ for all I_{in}) for CURRENT MEASURANDS as for an ideal AMMETER

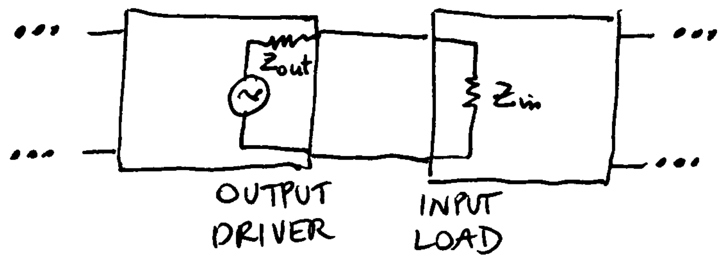
Output impedance is the impedance at the system's output:

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



(The Thevenin equivalent shown in the box)

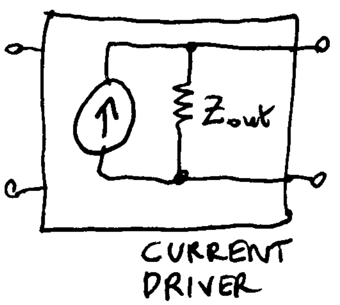
It is equally important as input impedance when multiple systems are cascaded together:



For good modular design, we want a system not to be loaded by its inputs, and its outputs to be unaffected by the loads.

Ideally, we should have:

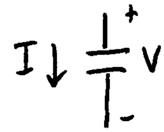
- $Z_{out} \approx 0$ $\left(\Delta V_{out} = 0 \text{ for all } \Delta I_{out}\right)$ for VOLTAGE DRIVERS as for an ideal voltage source
- $Z_{out} \approx \infty$ $\left(\Delta I_{out} = 0 \text{ for all } \Delta V_{out}\right)$ for CURRENT DRIVERS as for an ideal current source



(Norton equivalent shown in the box)

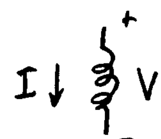
Dynamic characteristics :

- Input and output impedance are functions of frequency f, or angular frequency $\omega = 2\pi f$

e.g.: C : 

$C \frac{dV}{dt} = I$, or $j\omega C V = I$

$$\Rightarrow Z = \frac{V}{I} = \frac{1}{j\omega C}$$

L : 

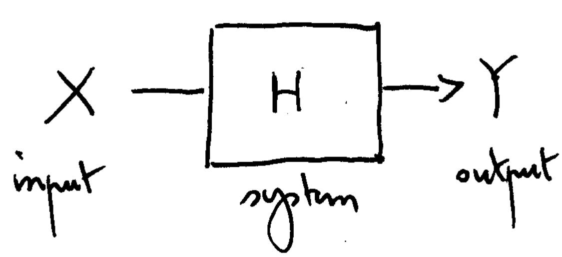
$L \frac{dI}{dt} = V$, or $j\omega L I = V$

$$\Rightarrow Z = \frac{V}{I} = j\omega L$$

circuits with R, L, C, and dependent/independent voltage/current sources $\longrightarrow$ complex functions of $j\omega$

- Accuracy, precision, and sensitivity are functions of frequency as well.

- Transfer function $\frac{Y(j\omega)}{X(j\omega)}$ is a dynamic measure of sensitivity.



$$Y(j\omega) = H(j\omega) \cdot X(j\omega)$$

OUTPUT = TRANSFER FUNCTION · INPUT