BENG 186B: Principles of Bioinstrumentation Design

# Lecture 4

# Other Sensors and Control Elements

## References

Webster, Ch. 2 (Sec. 2.5-2.9).

http://en.wikipedia.org/wiki/Linear_variable_differential_transformer

http://en.wikipedia.org/wiki/Piezoelectric_sensor

http://en.wikipedia.org/wiki/Switch

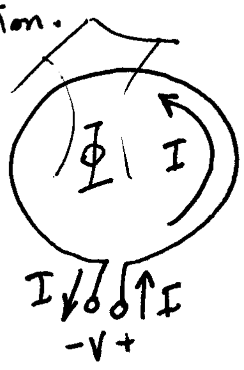
http://en.wikipedia.org/wiki/Relay

http://en.wikipedia.org/wiki/Potentiometer

## – Inductive sensors (displacement)

A bit antiquated, but inductors themselves (in particularly mutual inductors) are widely and increasingly used in wireless bioinstrumentation.

- Coil



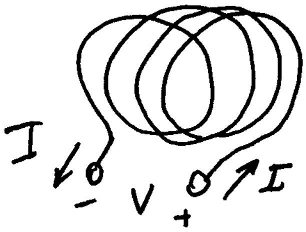
– current I generates magnetic flux $\Phi$:

$$\Phi = L . I$$

– derivative flux $\frac{d\Phi}{dt}$ induces voltage V

$$V = \frac{d\Phi}{dt} = L \cdot \frac{dI}{dt}$$

- Multiturn coil : n turns (windings) ⇒

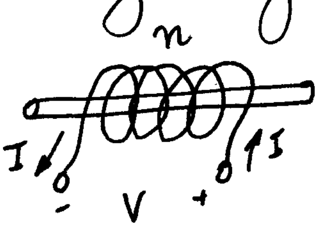


– n times larger flux for same current

– n times larger voltage for same derivative flux

$$\Rightarrow \times n^2$$

- Coil with ferromagnetic core : permeability $\mu = \underset{\text{VACUUM}}{\mu_0} . \underset{\text{MATERIAL SPECIFIC (relative perm.)}}{\mu_r} \Rightarrow$



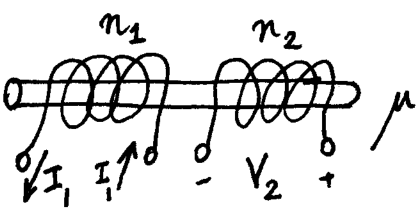
– $\mu_r$ times larger flux for same current

– no change in voltage for given derivative flux

$$\Rightarrow \times \mu$$

$$\Rightarrow V = \underset{\text{INDUCTANCE}}{L} \frac{dI}{dt} \quad \text{with } L = \underset{\text{NUMBER OF WINDINGS (TURNS)}}{n^2} . \underset{\text{GEOMETRY FACTOR}}{G} . \underset{\text{EFFECTIVE PERMEABILITY}}{\mu}$$

- Mutual inductance between magnetically coupled coils:



  - current $I_1$ generates magnetic flux ($\times \mu n_1$)
  - derivative flux induces voltage $V_2$ in second coil ($\times n_2$)

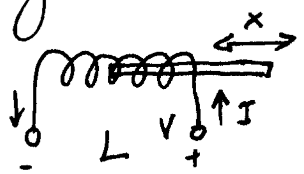
$$\Rightarrow V_2 = \underset{\text{MUTUAL INDUCTANCE}}{M_{12}} \cdot \frac{dI_1}{dt} \quad \text{with} \quad M_{12} = n_1 n_2 \cdot G \cdot \mu$$

This is the basis of a TRANSFORMER, and WIRELESS TELEMETRY

- Coil(s) with displaceable ferromagnetic core ⇒ INDUCTIVE SENSOR

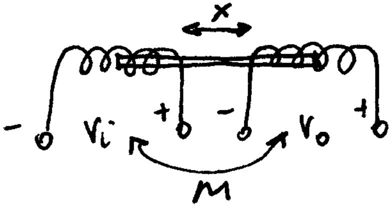
Effective permeability $\mu$ changes with displacement of the core $x$.

- Self-inductance:



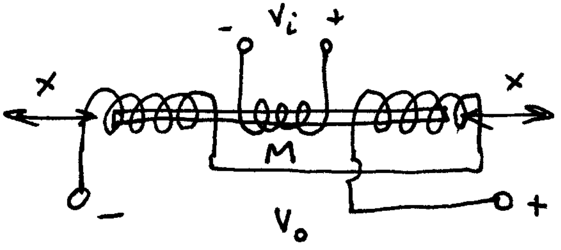
$\Delta L \propto \Delta x$ for small $\Delta x$

- Mutual inductance (transformer):



$\Delta M \propto \Delta x$ for small $\Delta x$

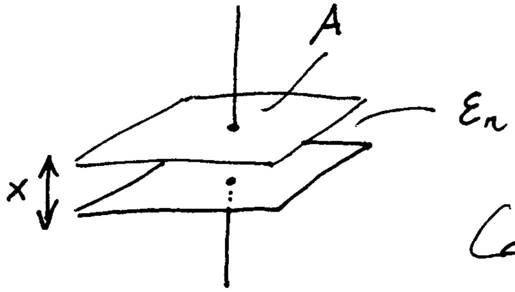
- Linear variable differential transformer (LVDT):



$M \propto x$ for larger $x$

  - more linear, zero offset
  - requires a diode-rectifier bridge for decoding of phase

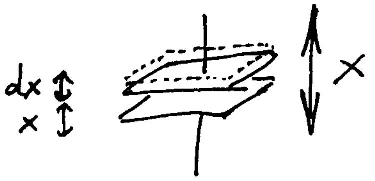
## — Capacitive sensors (displacement):



dielectric constant : $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$
(permittivity)
VACUUM RELATIVE PERMITTIVITY

Capacitance between plates:

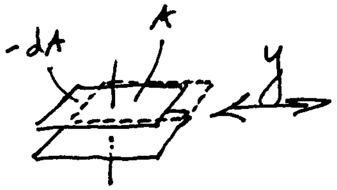
$$C = \varepsilon \cdot \frac{A}{x} = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{x}$$



Transversal displacement

$\Rightarrow$ SENSITIVITY : $\frac{dC}{C} = -\frac{dx}{x}$

or $\frac{dC}{dx} = -\frac{C}{x} = -\varepsilon \frac{A}{x^2}$



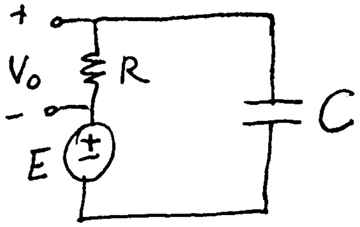
Lateral displacement

$\Rightarrow$ SENSITIVITY : $\frac{dC}{C} = +\frac{dA}{A} = -\frac{dy}{y}$

or $\frac{dC}{dy} = -\frac{C}{y} = -\varepsilon \frac{A}{xy}$

Measurement of $\frac{dC}{C}$ : e.g (as in condenser microphone):

$$x \approx \underset{DC}{x_0} + \underset{AC}{\delta x(j\omega)} \qquad (\delta x \ll x_0)$$



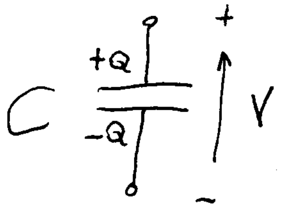
$$\Rightarrow \frac{V_0(j\omega)}{\delta x(j\omega)} = \underbrace{\frac{E}{x_0}}_{\text{CONSTANT}} \cdot \underbrace{\frac{j\omega\tau}{1+j\omega\tau}}_{\approx 1 \text{ for } \omega > \frac{1}{\tau}} \; ; \; \tau = R C_0$$

$$\Rightarrow \delta x \approx \frac{x_0}{E} \cdot V_0 \quad \text{for } \omega > \frac{1}{\tau} \qquad \text{(HIGHPASS)}$$

# Microphonics in capacitive sensing:

- DC (static) charge on a capacitor:

$$Q = C\cdot V$$



- AC charge flow (current) through the capacitor:

$$I = \frac{dQ}{dt} = C\cdot\frac{dV}{dt} + \frac{dC}{dt}\cdot V$$

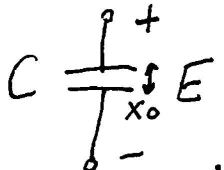
$$\frac{dC}{C} = -\frac{dx}{x}$$

$$= C\cdot\underset{\substack{\downarrow\\ \text{electronics}}}{\frac{dV}{dt}} - C\frac{V}{x}\cdot\underset{\substack{\downarrow\\ \text{microphonics}}}{\frac{dx}{dt}}$$

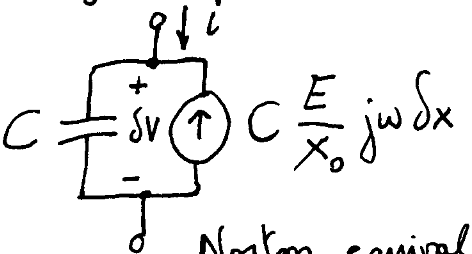
⇒ For small AC signals and large DC bias:

$$\begin{cases} x = x_0 + \delta x\,, & \delta x \ll x_0 \\ V = \underset{\substack{\downarrow\\ DC}}{E} + \underset{\substack{\downarrow\\ AC}}{\delta V}\,, & \delta V \ll E \end{cases}$$

DC:



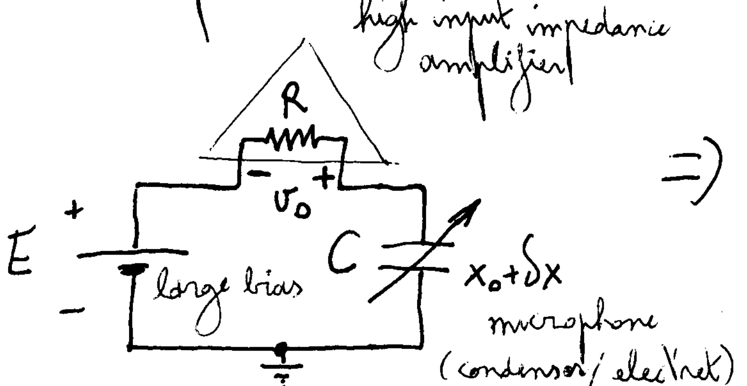
AC:



Norton equivalent:

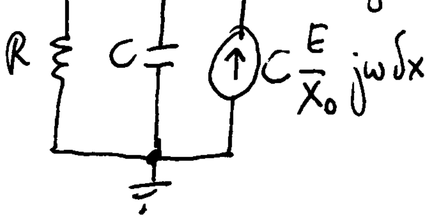
$$i(j\omega) = \underset{\substack{\downarrow\\ \text{electronics}\\ \text{admittance}}}{j\omega C\,\delta V} - \underset{\substack{\downarrow\\ \text{microphonics}\\ \text{Source}}}{C\frac{E}{x_0}j\omega\,\delta x}$$

Example: condensor/electret microphone:



$$v_0 = \frac{R\cdot\frac{1}{j\omega C}}{R+\frac{1}{j\omega C}}\cdot C\frac{E}{x_0}j\omega\,\delta x$$

⇒



## — Piezoelectric sensors (displacement, and force):

PIEZOELECTRIC CRYSTALS are electromechanical SENSORS and ACTUATORS:

- applied force (displacement) induces charge (voltage);
- applied voltage (charge) induces displacement (force).

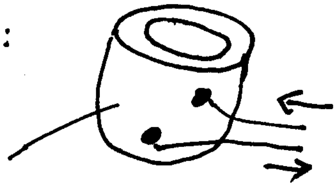
| DISPLACEMENT | ⟷ | FORCE | ⟷ | CHARGE | ⟷ | VOLTAGE |
|---|---|---|---|---|---|---|
| $x$ | $E$<br>YOUNG'S MODULUS | $f$ | $k$<br>PIEZOELECTRIC CONSTANT | $q$ | $C$<br>CAPACITANCE | $v$ |

$$E = \frac{\sigma}{\varepsilon} = \frac{f/A}{x/L} \qquad q = k \cdot f \qquad q = C \cdot v$$

Typical use:

- Micro-balance : sensitive, compact weight measurement
- Audio / ultrasonic : microphone AND speaker for active acoustics

**Example:**



← Vin : SPEAKER : activate acoustic wave

→ Vout : MICROPHONE : sense acoustic wave

2 crystals

Speaker-microphone pair allows to measure TRANSIT TIME which gives an indirect, sensitive measure of DISTANCE between two points on the cardiac muscle surface (assuming speed of sound does not change with muscle contraction.)

- Other sensors, e.g. TEMPERATURE : same principle
  - Thermocouple : junction of 2 different metals creates a voltage dependent on temperature
    - Common (K-type) : sensitivity ≈ 40 $\mu V / ^\circ C$
    - Need a temperature reference and a second, matched thermocouple to measure absolute rather than change in temperature.
  - Thermistor : ceramic material with resistance dependent on temperature
    - $\frac{\Delta R}{R} = \alpha \cdot \Delta T$ or $R = R_0 (1 + \alpha \Delta T)$

      where temperature coefficient $\alpha$ depends on the material ($\alpha > 0$, or $\alpha < 0$), and on temperature (nonlinear!).
    - Can be differentially embedded in a Wheatstone bridge for accurate T measurement.

# BASIC CONTROL ELEMENTS : Switches, relays, turnpots

- Switches:

on/off toggle

or

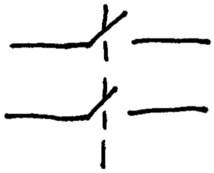
(same)

or

2 positions

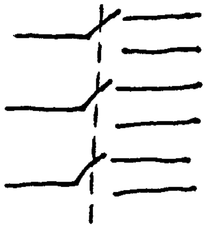
"DOUBLE THROW"

Can join two switches with single control (both move together):

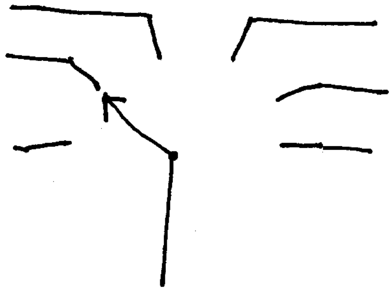


"DOUBLE POLE"

Multi-throw, multi-throw combinations, e.g.:



"3P2T"
3 pole, 2 throw



"1P6T"
1 pole, 6 throw

e.g.: 6 lead ECG measurements, selected by switch

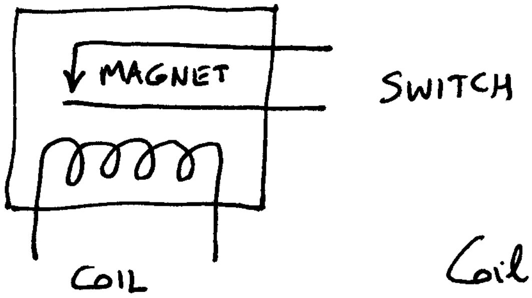
Push buttons:

N.O.
"normally open"

N.C.
"normally closed"

(NOTE: "closed" means conducting; connected; "open" means non-conducting, disconnected)

– Relays : electrically (magnetically) activated switches



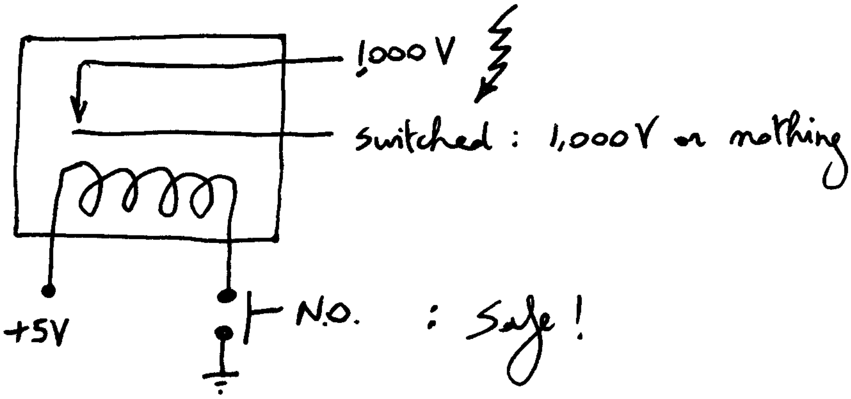
Coil closes (or opens) switch when a voltage is applied

Voltage → current in coil → magnetic field → magnet pulling action → switch closes or opens

Why needed ?

→ electronic and software control of a switch, rather than mechanical (manual) input

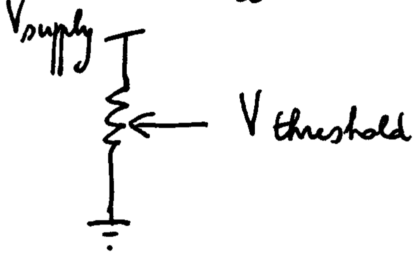
→ safety with high voltages, e.g. :



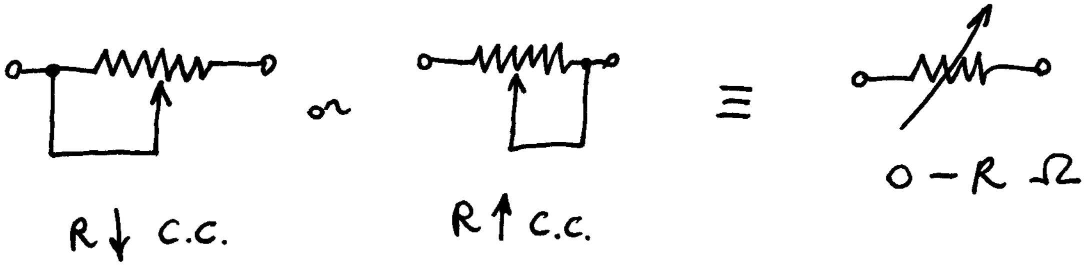
- Turn potentiometers (or TURNPOTS):

  analog control of circuit parameters with the turn of a knob.

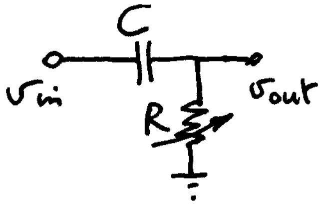
- Threshold, offset, bias control:



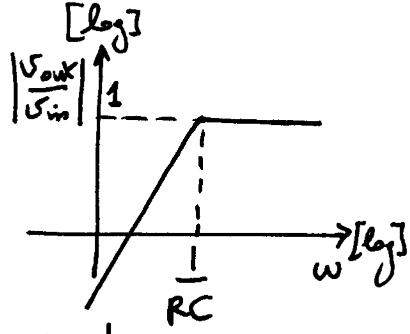
- Variable resistor: turnpot with two terminals:



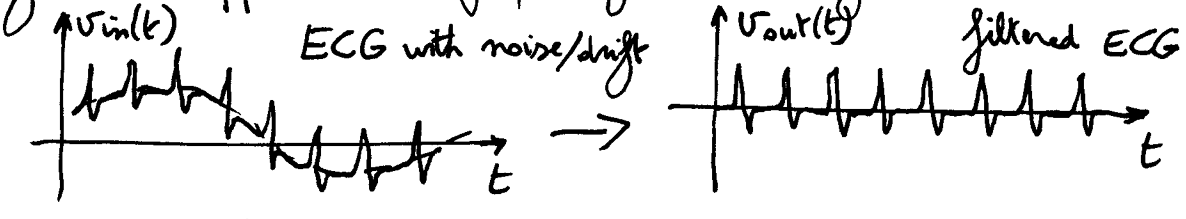
<u>Example</u>: HIGHPASS FILTER with VARIABLE CUTOFF FREQUENCY:



$$\frac{v_{out}(j\omega)}{v_{in}(j\omega)} = \frac{R}{\frac{1}{j\omega C} + R} = \frac{j\omega RC}{1 + j\omega RC}$$



Useful to suppress low-frequency noise/drift in the sensor/signal:



Turning the $R$ knob trades noise/drift rejection vs. signal fidelity.