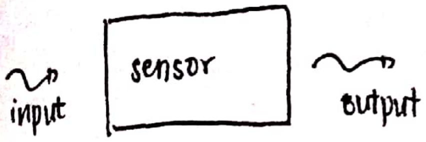
APPLIED PHYSICS 185

01-17-2019

Sensors

→ ANS Def: A device w/c provides a usable output in response to a specified measurand.



→ acquires a physical parameter & converts it into a signal suitable for processing
→ active element: transducer
  ∘ microphone, loud speaker, biological senses

Transducer

→ converts one form of energy to another
→ when input ~~electrical~~ is physical & output is electrical ⇒ sensor
→ input is electrical & output is physical
  ⇒ actuator

Detectable Phenomenon

Stimulus	Quantity ⤳ responses
Acoustic	Wave
Biological/Chemical	Fluid conc.
Electric	Charge, voltage, current, E-Field
Magnetic	Magnetic field
Optical	Refractive index, reflectivity
Thermal	Temp., flux, specific heat
Mechanical	Position, velocity, force

Physical Principles

∘ Ampere's Law
∘ Curie-Weiss Law
∘ Faraday's Law of induction
∘ Photoconductive effect

• sensors are omnipresent.

How to choose sensors?

Environmental Factors:	Temp. range, humidity effects, corrosion, size, raggedness, power consumption
Economic Factors:	cost, Availabity, Lifetime
Sensor Characteristics:	sensitivity, range, stability, error, repeatability, linearity, response time, frequency response

∘ Temperature sensors → read

• Accelerometer
  → used to measure along one line of axis

Physical computing

• sensing & ~~computing~~ controlling the physical world w/ computers
• "computers"
• low cost, open source hardware

01-22-2019

Sensors, Signals, & Systems

∘ sensor – device that receives a stimulus and responds with an electrical signal
• input physical property (stimulus) & converts to electrical signal
  - output voltage, current, or charge.
  - amplitude, frequency, phase, or digital code: output signal format

ex. Motion sensor
  → time of flight (sound) (?) sensor
  → does not directly measure distance or motion
  → sends out pulse/echo to detect distance
  → microphone + speaker system

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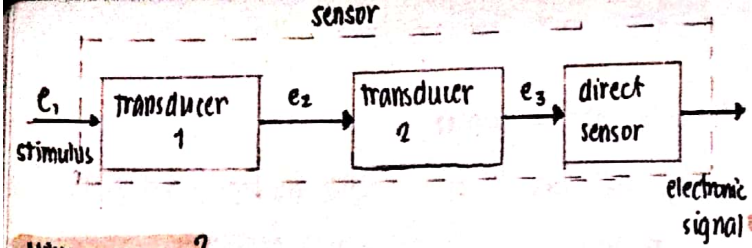


Why sensors?

→ to create a more accurate/precise observations of physical quantities
→ information (that you can use)

- Any sensor is an energy converter
- Landauer's Principle: kT ln2 to flip a bit

1 1 1 1 1 1 1 0 1

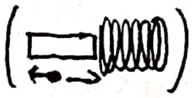
↳ new information (not expected)

- Sensors are impt in gathering new info.
  - ↳ transferring max. amt of information to the signal.

Sensors vs. Transducer

- Transducer converts one type of energy into another. Sensor converts any type of energy to electrical.
- Fundamental rule of transducer: measuring device/method should not alter the event being measured
- Rule of thumb: Energy drawn from system should be ≤1/100 measuring energy

Direct vs. Indirect

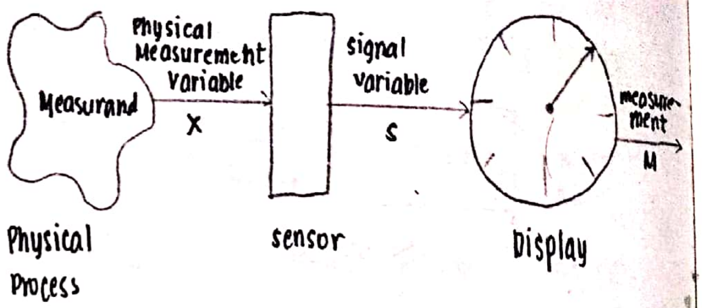
- direct energy conversion into electrical signal generation or modification.
- ex. of direct sensors
  - induction/emf experiment ()

Create thermometer
→ make repeatable measurements
→ scale

Units of measurement

→ important

Simple Instrument Model



- sensors tend to have their own response.
- S is a function of time (may or may not change)
- X also is a fcn of time
- expanding S, X, & M into Taylor series, terms should have same form (not always True)

accuracy: how close the value measured to the theoretical value.

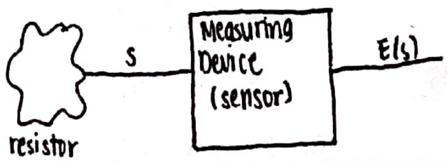
error: difference of theoretical & measured
- systematic error
- random error

precision: how close the measured values are to each other

resolution: how detailed the given data / figure is

threshold: limit / cap
ex. threshold is 0. if reading is non-0, the reading is <u>biased</u>. ⇝ not additive or can be additive

01-24-2018



Focus of 185: Physics of measuring device not the physics of the physical material being measured

	"Standard" Values	Measured
E_1	S_1	$S_M \cdot F(E)$
E_2	S_2	
E_3	S_3	

→ can be called a calibration table

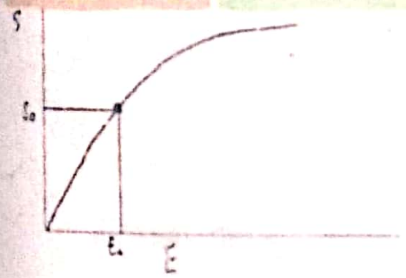
• Given $E = f(s)$ (measured) → $s = f^{-1}(E) = F(E)$ (unknown)

• To find fcn F: ① use lookup table
② plot points & find trend curve
③ interpolate data

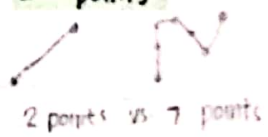
$V = IR$ → can use best fit line IF R is constant.
But $R = \frac{\rho L}{A} = \frac{\rho_0(1+\alpha\Delta T)L}{A}$. R changes over time.

• Finding the fcn is important to find s. This function 'converting' s to E(s) is called the transfer function.

• calibration curve → a mirror of the transfer fcn.



• more data points = better calibration curve
↳ in order to describe what happens bet. 2 points.



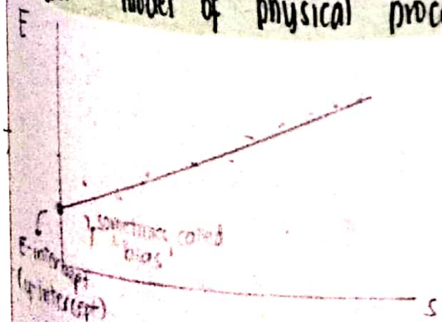
• For Taylor series to be precise, the highest no. of degree allowed is 1 or 2 or whatever precision you want.

• Problems w/ polynomial fit: function passing through 0.

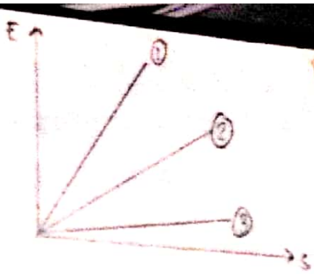
• Types of fits:
- linear
- nonlinear
- polynomial
- trigonometric
- exponential
- logarithmic
- special fcns. (ex. fourier)

• 2D calibrator: calibration sheet/manifold

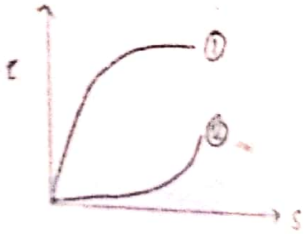
• Model → model of physical processes or model of data



$E = A + Bs$
↓ E_0 ; sensor ↳ sensitivity (slope)



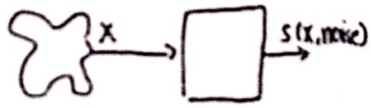
Which is better to use making sensors?
① → high sensitivity
→ small change in S, big change in E (good readings)



① → better to measure small s values
② → better to measure large s values
• to measure the entirety of s, use a combination of ① & ②

01-31-2018

... continue lesson



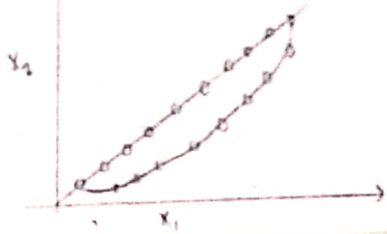
• is the sensor:
› sensitive?
› calibrated?

Problems of sensor:
• sensitivity
• noise
• linearity
• range

E12 Resistance (?)
10 ⟶ 100 (Ω)
→ multiply with 1/12 (?)

~~Hysteresis~~ Hysterisis / hysteresis → difference in forward & reverse measurements

ex. incandescent bulb, magnetic systems, oil price

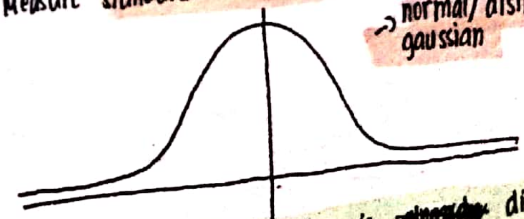


• some systems have additive noise (no signal, may noise)
and some have multiplicative noise (no signal, no noise)

• If noise = 0 : $S(x,\text{noise}) = S(x,0) = S(x)$

• Taking multiple measurements & averaging it (mean) "characterizes" the noise (but not really)

• Measure standard deviation



- it is assumed that noise is ~~[illegible]~~ distributed in a gaussian/normal curve.

• Don't assume noise in normal w/out good foundations!

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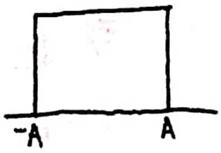
central-limit theorem

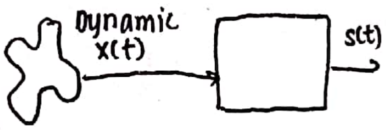
- makes it okay to assume noise is normal
- after repeated measurements (until $t \to \infty$), every signal, including noise, will appear to have a gaussian distribution

- poisson distribution → exponential
- uniform distribution:



- signals (& noise): combination of normal & uniform distribution

- when signals are dynamic, sensors should have a dynamic response



laplace

$$L\left(x(t) = a_k\frac{d^k y}{dt^k} + \dots + a_2\frac{d^2y}{dt^2} + a_1\frac{dy}{dt} + a_0 y\right)$$

$$X(s) = (a_k s^k + \dots + a_2 s^2 + a_1 s + a_0)Y(s)$$

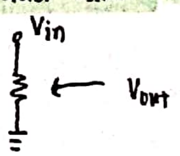
to see how much of Y is in X

$$\frac{Y(s)}{X(s)} = \frac{1}{a_k s^k + \dots + a_1 s + a_0} = G(s)$$

→ transfer function

0's in denominator: poles

ex. of 0 order sensor: (0 poles) (resistor measurer)

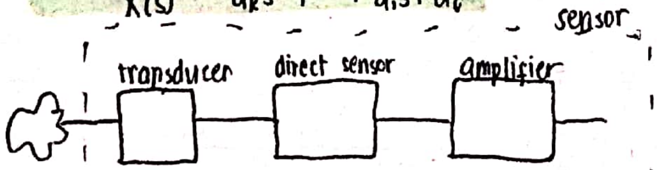


02-07-2019

Transfer Function, G(s)

$$G(s) = \frac{Y(s)}{X(s)} = \frac{1}{a_k s^k + \dots + a_1 s + a_0}$$

Ex.



$\frac{k}{\tau s+1}$ (tau) $\qquad \frac{k_d}{\frac{s^2}{w_0^2}+\frac{2\zeta s}{w_0}+1} \qquad k_a$

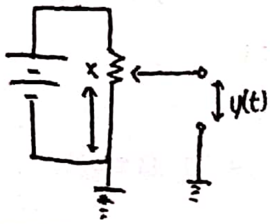
Transfer fcn of the complex sensor: $\frac{k k_d k_a}{(\tau s+1)\left(\frac{s^2}{w_0^2}+\frac{2\zeta s}{w_0}+1\right)}$

0-order sensor: no poles

$y(t) = k\,x(t)$

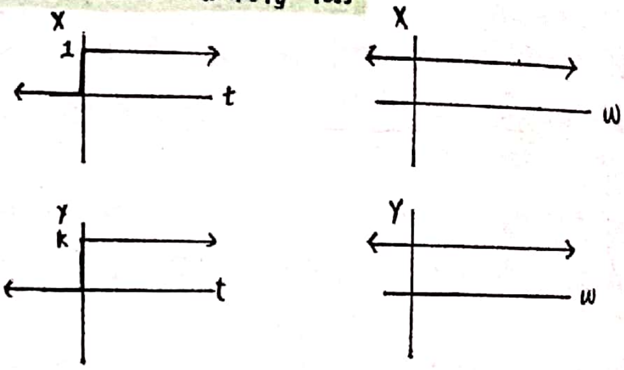
$\boxed{G(s) = k} = \frac{Y(s)}{X(s)}$ — no capacitors

- y(t) & x(t) have same freq (diff. amplitude)
- no delays, infinite bandwidth



→ k = 1

- sometimes called memory-less



- Physically: no energy storage, high impedance

1st order sensor

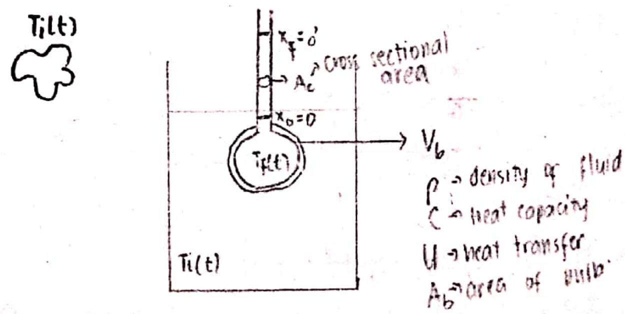
$x(t) = a_1\frac{dy}{dt} + a_0 y$

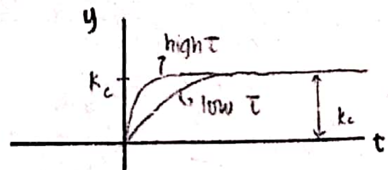
$$G(s) = \frac{Y(s)}{X(s)} = \frac{1}{a_1 s + a_0} = \boxed{\frac{k}{\tau s + 1}}$$

k: state sensitivity; τ: time constant

- at least 1 energy/information storage
- problem: energy dissipation

consider: measure Temperature (T(t))





→ x(t) is a step fcn

$\rightarrow U A_b T_i = U A_b T_f + V_b \rho \frac{dT_f}{dt} C$

↳ energy absorbed by fluid

$X_o = \frac{K_{ex} V_b T_f}{A_c}$

combining the 2 equations above:

$$\frac{\rho C A_c}{K_{ex}} \frac{dX_o}{dt} + \frac{U A_b A_c}{K_{ex} V_b} X_o = U A_b T_i$$

sensitivity $k = \frac{K_{ex} V_b}{A_c}$ time constant $\tau = \frac{\rho C V_b}{U A_b}$

2nd order

Now, let's look at:

$$a_2 \frac{d^2y}{dt^2} + a_1 \frac{dy}{dt} + a_0 y = x(t)$$

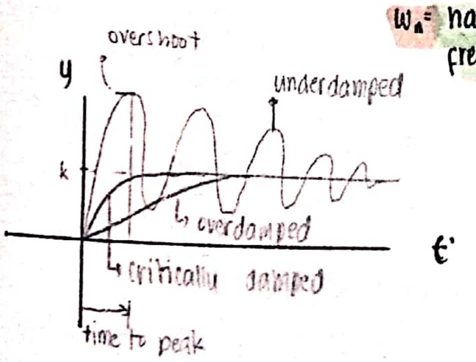
$$G(s) = \frac{1}{a_2 s^2 + a_1 s + a_0} \quad \rightsquigarrow \text{2nd order}$$

$$= \boxed{\frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}}$$

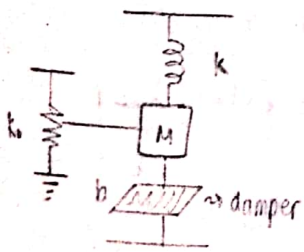
k = static gain $\left(\frac{1}{a_0}\right)$

ζ = damping coefficient $\left(\frac{a_1}{2\sqrt{a_0 a_1}}\right)$

ω_n = natural frequency $\left(\sqrt{\frac{a_0}{a_2}}\right)$

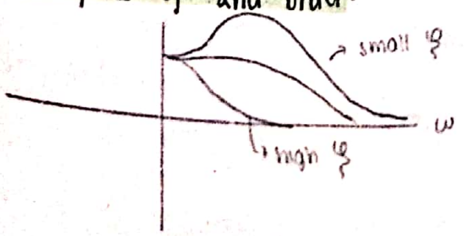


Ex.



⇝ seismometer / accelerometer

Frequency response of 2nd order:

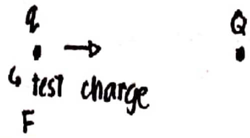


*For underdamped systems you will have extra frequencies. For overdamping, it introduces extra signals & attenuates the system.

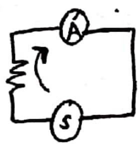
Electrical sensors 02-12-2019

- charge → measured by counting no. of electrons
- counting electrons = measuring current

$$I = \frac{\text{no. of electrons}}{\text{time}}$$

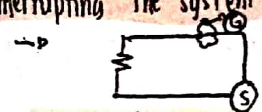


- instead of using a field detector, we can use a flux detector instead
- current I
  - move along conductors
  - KVL (Kirchhoff's Voltage Law): $\sum_{closed} V = 0$
  - KCL (Kirchhoff's Current Law): $I_{out} = \sum I_{in}$
  - ammeter connected in series to measure current.



Ⓐ → has internal resistance
→ uses power

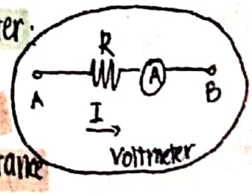
How to measure I w/o interrupting the system?



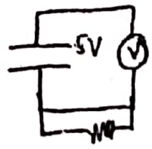
→ use wire around the circuit, use Galvanometer to measure induced EMF. (no internal R)

→ Problem: sensitivity

- voltage V
  - amount of work needed to move a unit charge from A to B; ⇝ not easy to measure
  - Ohm's Law: $V = IR$
  - Problems in making a voltmeter:
    - ⇝ requires a working ammeter
    - ⇝ requires a known resistance
    - ⇝ changes the internal resistance of a system.



- can be measured using capacitors: $C = Q/V$
  → need the value of Q



$\tau = \frac{1}{RC}$ → measure from observing the behaviour of the capacitor (when the capacitance drops to $\frac{1}{e}C$)

- largest C that you can get is from the longest sampling rate that you have

$C_{max} = \frac{4096}{R}$ [Arduino]

•Resistivity, ρ
→ dependent on the geometry of the material
• $\rho(T)$ ⇒ ~~JE~~ dependent on J & E

•Resistance R
• measure L, A & know its resistivity ρ

$$R = \rho \frac{L}{A}$$

•Polarization
•Capacitance

02-14-2019

•load cell → used in bathroom scales

Resistance

$$R = \rho\left(\frac{L}{A}\right)$$
→ geometric factor

$$\rho = \rho_0(1+\alpha\Delta T)$$
normalized
↳ $\frac{T-T_0}{T_0}$ (?)

Ways to deform a material: Stress & Strain
•Stress - Force is in the same direction w/ the deformation → unit: Young's modulus F/a
•Strain - not the same direction

Young's modulus

$$E = \frac{F}{A}$$

Deformation

$$e = \frac{dl}{l}$$

•Stress $\sigma = \frac{F}{A} = E\frac{dl}{l} = Ee$
↳ strain
↓ Young's modulus

• we know that the volume of the cylinder is
$$V = \frac{A}{A} A l$$

So, $R = \rho\frac{L}{A} = \rho\frac{l^2}{V}$

$$\frac{dR}{dl} = \frac{2\rho l}{V}$$

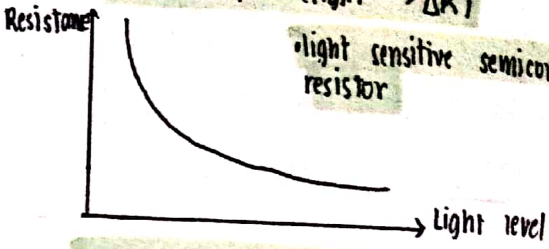
→ longer resistor is better than a shorter one (change in R is dependent on the length)
• has a maximum
→ smaller volume is better

$$\frac{dR}{R} = S_e e$$
↳ gauge sensor (dependent on the material)

Primary Transducers

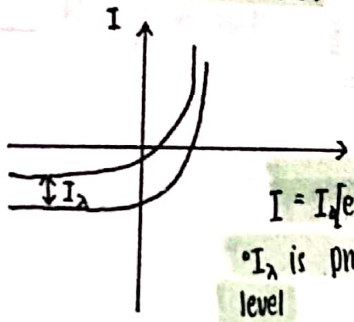
02-26-2019

•Light sensor
> photoconductor (light → ΔR) → another name for LDR



•light sensitive semiconductor resistor

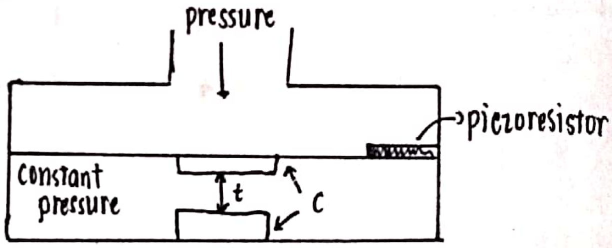
> photodiode (light → ΔI)



$$I = I_s[e^{eV/kT}-1] - I_\lambda$$

• I_λ is proportional to the light level

> membrane pressure sensor
resistive (pressure → ΔR)
capacitive (pressure → ΔC)



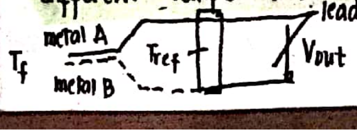
$$C = \varepsilon A/t$$

Displacement Measurements
• measurements of size, shape & position utilize

(ν) Poisson's ratio - ratio of tranverse contraction strain & longitudinal extension strain
(GF) Gauge factor - strain factor $\left(1+2\nu+\frac{\Delta\rho/\rho}{e}\right)$

Temperature sensor
• Resistance Temperature Detector (RTD) → platinum sensor
•Thermistors (thermally sensitive resistors)
• observe R changes: $R_T \approx R_0[1+\alpha T_1]$
↳ very small
$R_T = R_0 \exp\left[B\left(\frac{1}{T}-\frac{1}{T_0}\right)\right]$
↳ relatively large

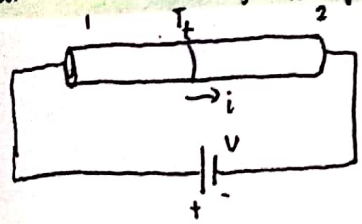
•Thermocouples
•based on the seebeck effect: dissimilar metals at different temperatures → signal



- Different types of thermocouple
- usual thermocouple used: K-type (Chromel +, Alumel −)
  - ↳ cheap

Fiber Optic Temperature Sensor
- can be made small enough for biological implantation

Peltier effect
- temperature change in a conductor
- can produce heat or cold depending on the direction of electric current through the junction.



- concerns the reversible absorption of heat which usually takes place when an electric current crosses a junction between 2 dissimilar metals.

Touch sensor ⇝ refridgerator, keyboard press, switches

Tilt sensors ⇝ measure tilting position wrt. gravity

Encoders
- count no. of rotations
- important spec: Number of counts / revolution

Bend sensor
- resistant changes as it bends (V = IR)
- assuming constant ~~voltage~~ current, voltage changes w/ resistance

MEMS = micro-electro-mechanical system
- ↳ miniature transducers created using IC fabrication processes

Microaccelerometer
- ↳ cantilever beam
- ↳ suspended mass

Rotation
- ↳ gyroscope

Passive Sensor Readout Circuit
- Photodiode circuits
- Thermistor Half-bridge
- Wheatstone bridge

Basic OP-amp config
- Voltage comparator - digitize input
- Voltage follower - buffer
- Non-inverting & Inverting Amplifier
- Summing Amplifier $V_{out} = -(V_1 R_f/R_1 + \ldots V_N R_f/R_N)$
- Differential Amplifier
- Integrating Amp
- Differentiating Amp

Converting configuration
- current-to-voltage $V_{out} = -I_{in} R$
- voltage-to-current $I_L = V_{in}/R$

Instrumentation Amplifier
- Robust differential gain amplifier
- Input stage - ↑ input impedance (buffers gain stage)
  - no common mode gain
  - can have differential gain
- Gain stage - differential gain
  - ↓ input impedance
- Overall
  - ↳ amplifies only the differential component
    - high common mode rejection ratio
  - ↳ high input impedance suitable for biopotential electrodes w/ high output impedance

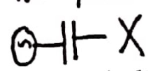
03-07-2019

Sensor

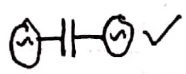
Input characteristics
- Impedance → similar to resistor ('impedes')
  - → ~~involves~~ relevant when you have signals not static in time
  - → purely resistive: no effect at low & high frequencies (R) (no imaginary part)
  - → complex term: reactance (reactive element)

AC

capacitive reactance:
- at low frequencies: (ex. DC)

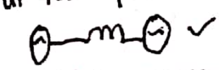


  - ↳ will act as a capacitor
- at high frequencies: better transmission (capacitor)

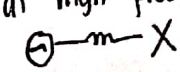


  - → ~~hig~~ for capacitors: low frequencies will ~~attenuate~~ remove than at high frequencies

inductive reactance (—m—)
- at low frequencies: (pass through) → acts like a wire



- at high frequencies: (not pass through) ⇝ magnetic field → back EMF
  - ↳ attenuate signal



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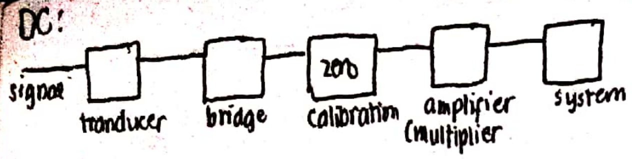
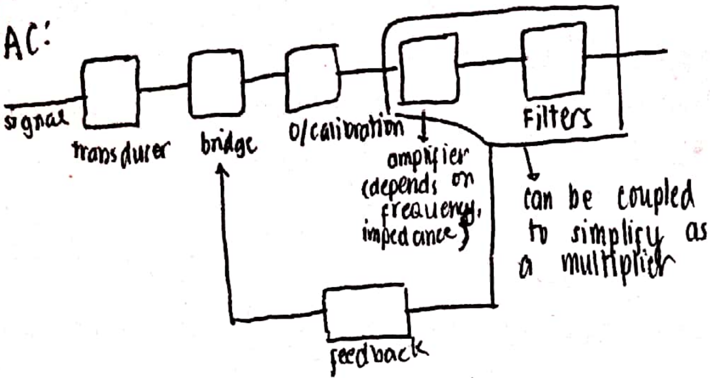
DC:



AC:



• adding more components makes the sensor more expensive.

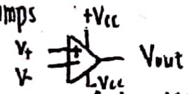
amplification:
- increase level to ADC level
- improve sencitivity
- resolution

filtering
- reject noise
- aliasing → distortion

isolation

03-12-2018

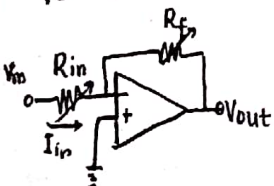
op-amps



Gain ≈ 100 K

Golden rules
- $V_+ = V_-$
- high impedance

~~(non-inverting)~~



(inverting)

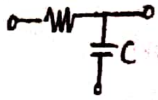
$I_{in} = \frac{V_{in}}{R_{in}}$

$V_{out} = -I_{in} R_f$

$\boxed{V_{out} = -V_{in} \frac{R_f}{R_{in}}}$

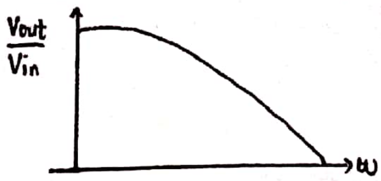
non-inverting: gain = $\left(1 + \frac{R_f}{R_{in}}\right)$

LPF -
- low pass filter
- something that does not ~~include~~ let in fast changing ~~frequency~~ fluctuations
- ex. capacitor



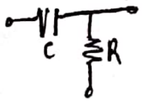
example of low-pass filter

- allows 'low' signals to pass through



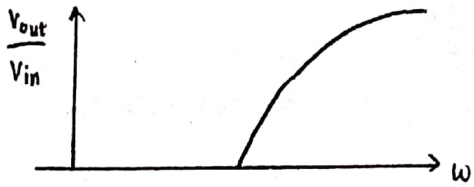
- $\frac{V_{out}}{V_{in}} = \frac{1}{1 + j\omega RC}$
- when to use low-pass filters?
  - removal of high-frequency noise

HPF
- high pass filter

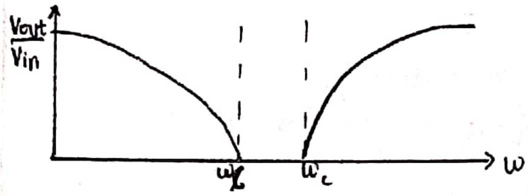


→ draws down power

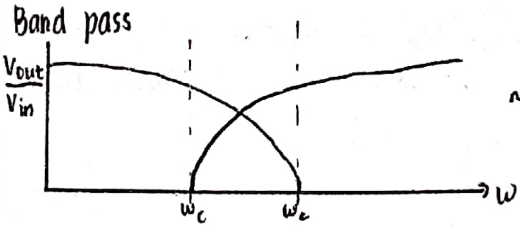
- DC can't pass through



LPF + HPF = Band cut

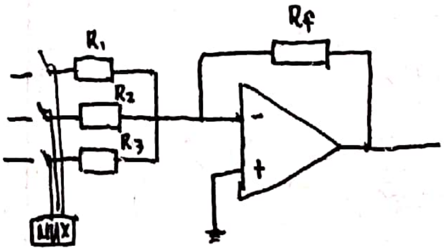


Band pass



→ overlapping LPF & HPF

03-14-2019



(summing amplifier)

→ "poor man's multi-input amplifier"

for selecting w/c resistors to use ~~[illegible]~~

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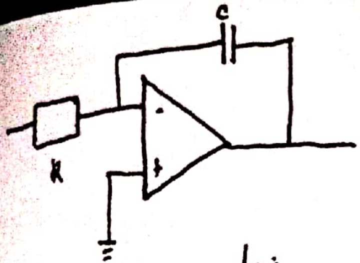
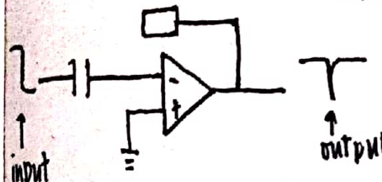


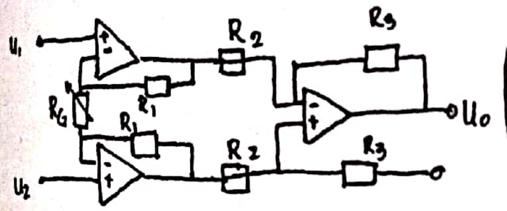
(integrator)

↳ sums up the input signals
↳ "moving average



(differentiator)

↳ getting derivative



(3 Op-Amp instrumentation amplifier)

↳ getting diff of u_1 & u_2, amplify the difference, & multiply by a gain.
↳ very sensitive amplifier
↳ $u_o = (u_1 - u_2)\left(1 + \frac{2R_1}{R_G}\right)$

$(u_1 - u_2)G$

↳ not adjustable
↳ constant gain

Filters

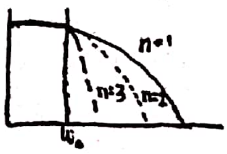
$$\left|\frac{O(w)}{I(w)}\right|^2 = \frac{1}{1 + \left(\frac{w}{w_o}\right)^n}$$

→ transfer function

"Butterworth filter"

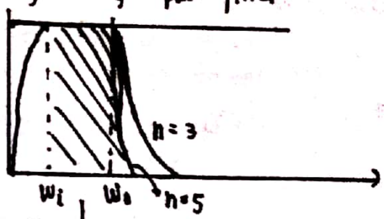
order n=0: not useful, allows everything to pass through

n=1: RC circuit



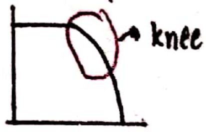
→ to get a sharper slope, increase order of Butterworth filters → maximally (?) flat pass band

adding a high pass filter



↳ 'rectangle' pass band

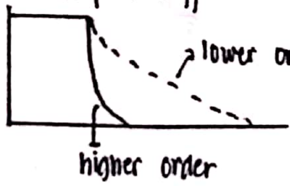
- nonlinear response
- "smooth transition"
- not sharp



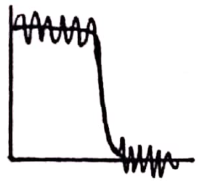
- higher orders make thinner rectangle pass band

Chebyshev filter
→ sharp cutoff

→ notch filter

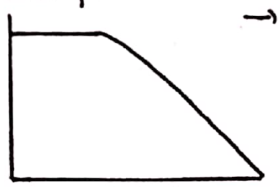


- Elliptic filter
→ allows ripples



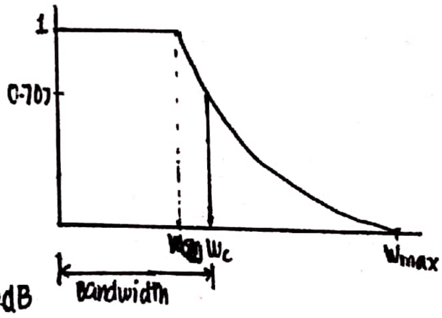
- Bessel filters

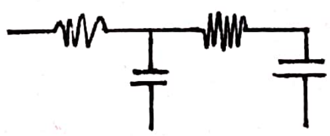
→ linear response



Bandwidth
→ where values of transfer fcn is greater than 0.707

Break point
→ when signals gone down by -3 dB
→ $\left[-10 \log\left(\frac{W_{out}}{W_{in}}\right)\right]$ dB
↓
definition of decibel.





: problem → attenuates signal because of multiple resistors

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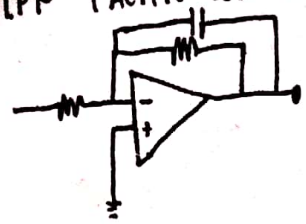
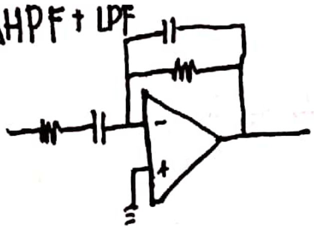
ALPF (Active Low Pass Filter)

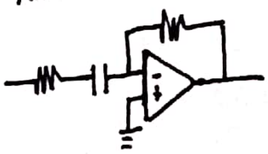


- also an integrator
- 1st order
- how to make 2nd order?
  - attach another op-amp
  - attach 2nd order LPF to op-amp

AHPF + LPF



AHPF



* ~~Salen-Key~~ Sallen-Key

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