NANYANG TECHNOLOGICAL UNIVERSITY

School of Mechanical & Aerospace Engineering

Design, Machine, Control, Intelligence

MA4822

Measurement and Sensing Systems

Xie Ming, PhD (France)

mmxie@ntu.edu.sg

http://personal.ntu.edu.sg/mmxie

Outline

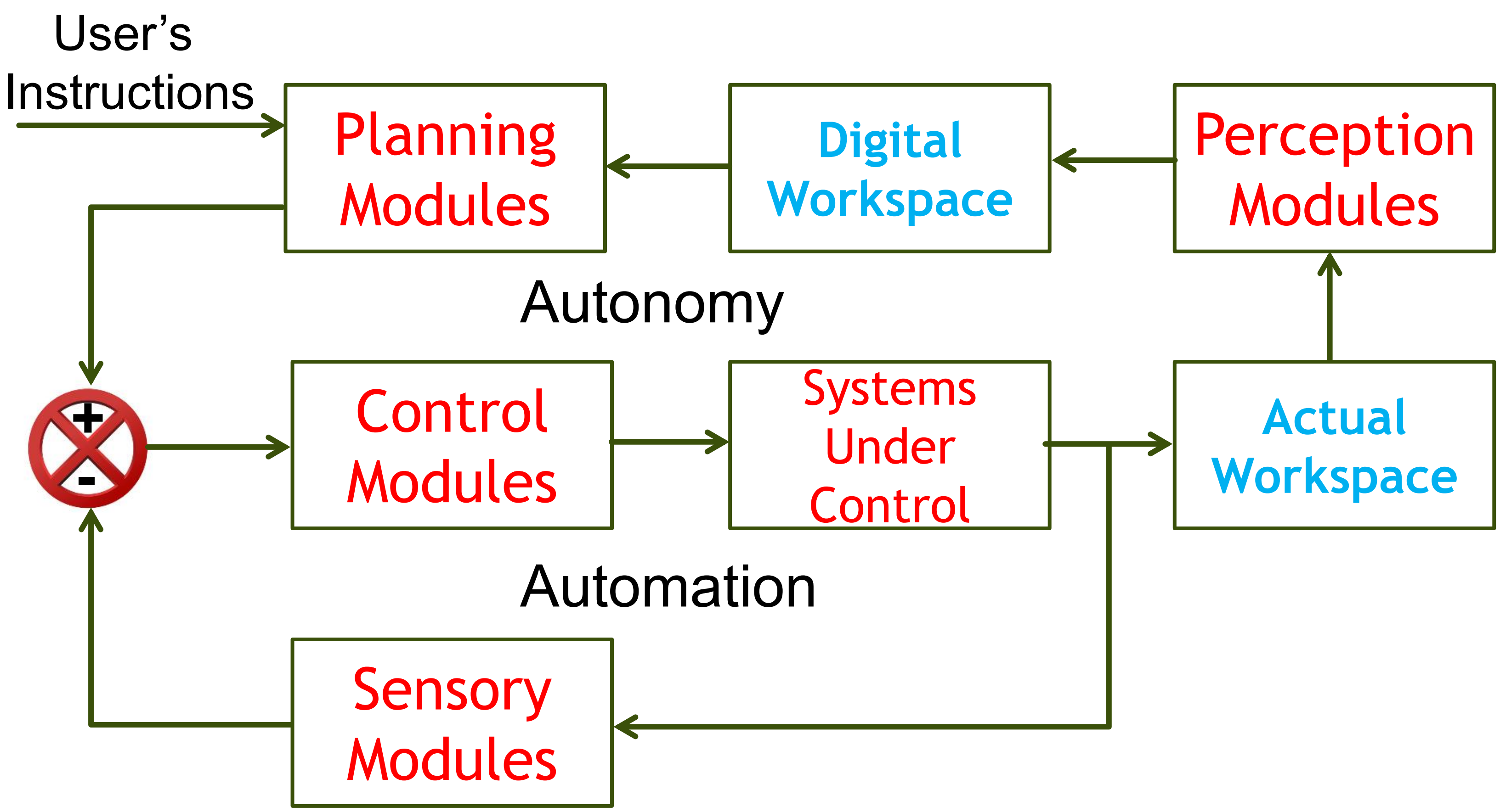
- Module 1: Foundation of AI Sensors
- Module 2: Sensors for Electrical Systems
- Module 3: Sensors for Mechanical Systems
- Module 4: Sensors for All Environments
- Module 5: Sensors for All Industries

Remember your mission as MAE undergraduates …

- You are here to grow your knowledge and skills so as to be able to design machines with controllable behaviors and hopefully in some intelligent ways.

How to fulfill your mission?

- To apply learnt knowledge and skills into the implementation of the following universal blueprint underlying all the intelligent machines or systems.



Why to study this course?

We are living inside an ocean of signals

How to study this course?

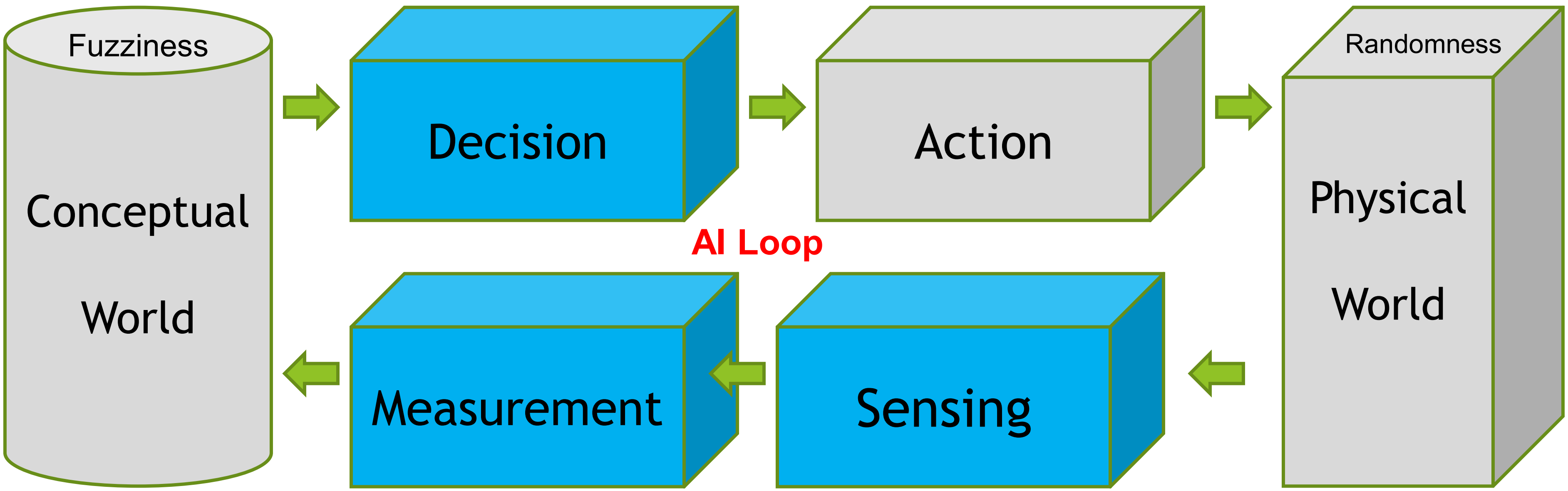
- To put yourselves into the mindset of designers of networked sensors as products:
  - Who are the users?
  - What are the needs of users?
  - What are your Internet of Sensors, which could meet the needs of your users or buyers?
  - What are the solutions behind the design of your Internet of Sensors?

Practice with MATLAB

Market Demands or Needs
↓
Product Specifications
↓
Design Specifications
↓
Conceptual Design
↓
Selection of Materials/Components/Devices
↓
Embodiment Design
↓
Prototyping
↓
Optimizing
↓
Production
↓
Marketing

What are you going to study in this course?

Module 1: Foundation of AI Sensors
- Basics of Physical World
- Randomness of Physical World
- Basics of Conceptual Worlds
- Fuzziness of Conceptual Worlds



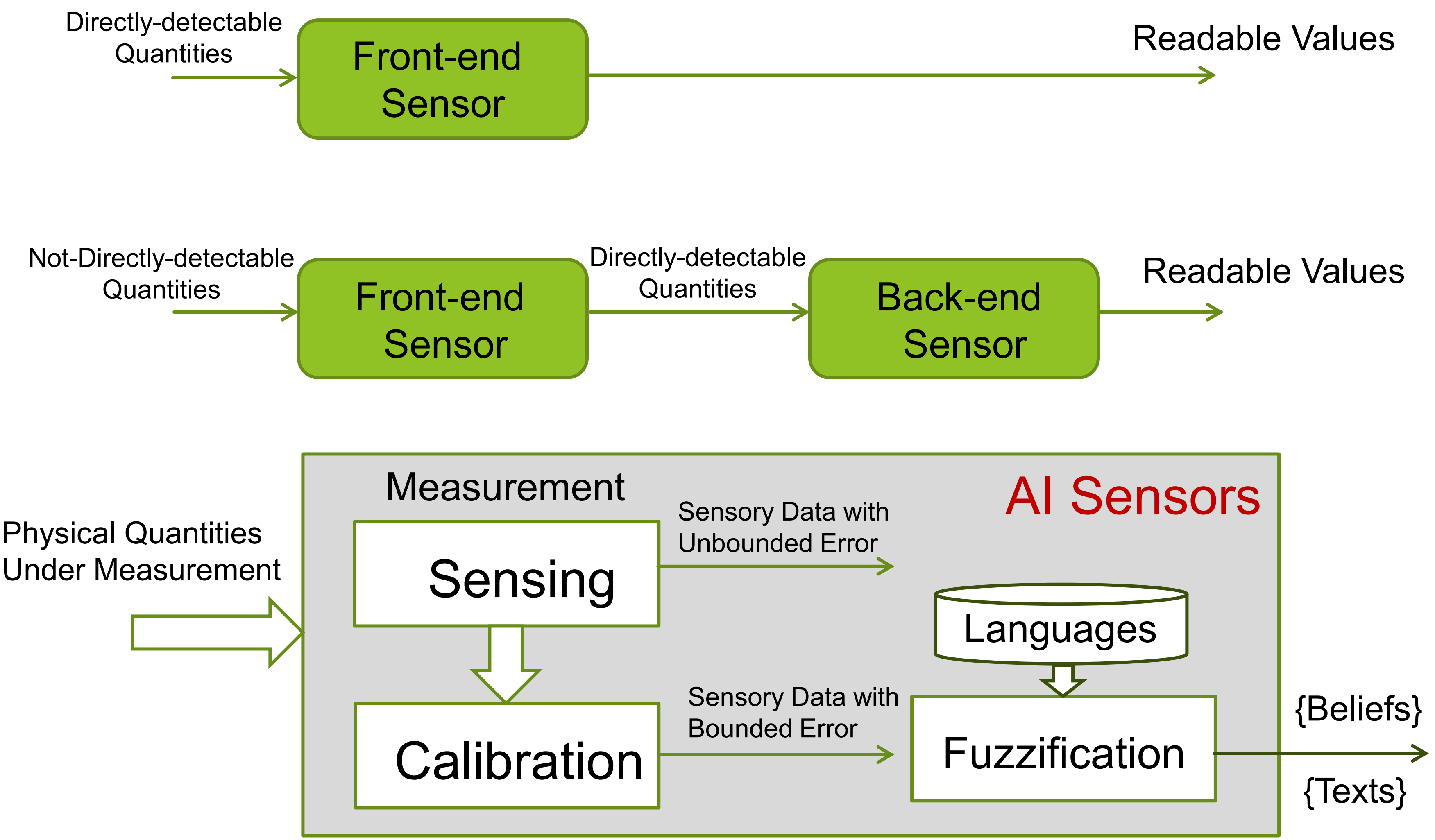
Module 2: For Electrical Systems
- Measurement of Voltage
- Measurement of Current
- Measurement of Resistance
- Measurement of Capacitance
- Measurement of Inductance

Module 3: For Mechanical Systems
- Measurement of Position
- Measurement of Velocity
- Measurement of Acceleration
- Measurement of Force
- Measurement of Torque

Module 4: For All Environments
- Measurement of Pressure
- Measurement of Temperature
- Measurement of Humidity
- Measurement of Vibration
- Measurement of Air Quality

Module 5: For All Industries
- Measurement of Fluid Level
- Measurement of Flow Rate
- Measurement of Sound/Voice
- Measurement of Photometry
- Measurement of Geometry

How to apply?



Directly-detectable Quantities
Front-end Sensor
Readable Values
Not-Directly-detectable Quantities
Front-end Sensor
Directly-detectable Quantities
Back-end Sensor
Readable Values
Physical Quantities Under Measurement
Measurement
AI Sensors
Sensing
Sensory Data with Unbounded Error
Languages
Calibration
Sensory Data with Bounded Error
Fuzzification
{Beliefs}
{Texts}

Today’s Lectures …

- Module 1: Foundation of AI Sensors
- Module 2: Sensors for Electrical Systems
- Module 3: Sensors for Mechanical Systems
- Module 4: Sensors for All Environments
- Module 5: Sensors for All Industries

Module 5

MA4822

Sensors for All Industries

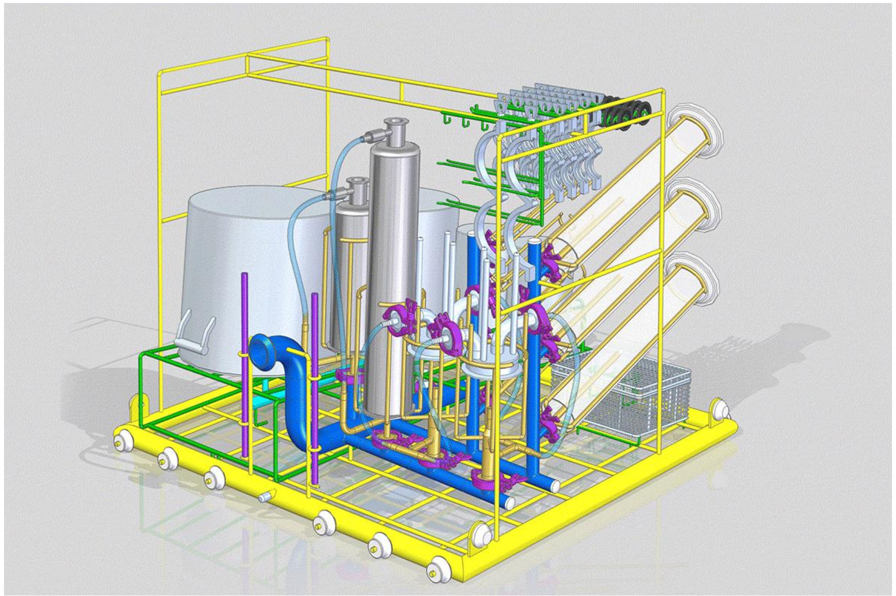
Xie Ming, PhD (France)

mmxie@ntu.edu.sg

http://personal.ntu.edu.sg/mmxie

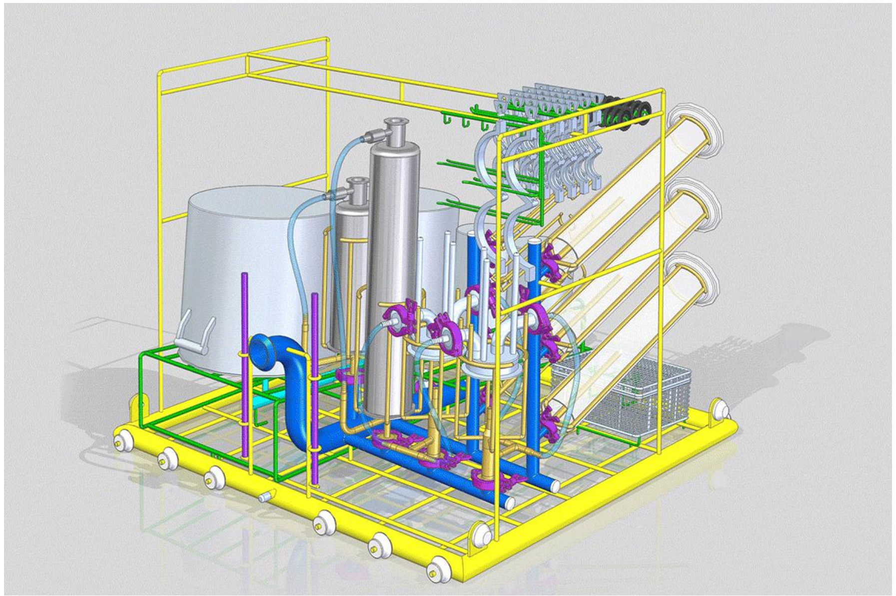
Outline of Module 5

- Lecture 1:
  - Measurement of Fluid Level
- Lecture 2:
  - Measurement of Flow Rate
- Lecture 3:
  - Measurement of Sound/Voice
- Lecture 4:
  - Measurement of Photometry
- Lecture 5:
  - Measurement of Geometry



Outline of Module 5

- Lecture 1:
  - Measurement of Fluid Level
- Lecture 2:
  - Measurement of Flow Rate
- Lecture 3:
  - Measurement of Sound/Voice
- Lecture 4:
  - Measurement of Photometry
- Lecture 5:
  - Measurement of Geometry



School of Mechanical & Aerospace Engineering

Design, Machine, Control, Intelligence

Module 5 Lecture 1

MA4822

Measurement of Fluid Level

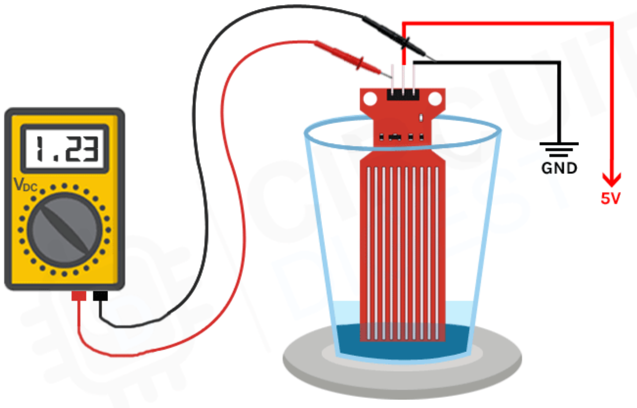
Xie Ming, PhD (France)

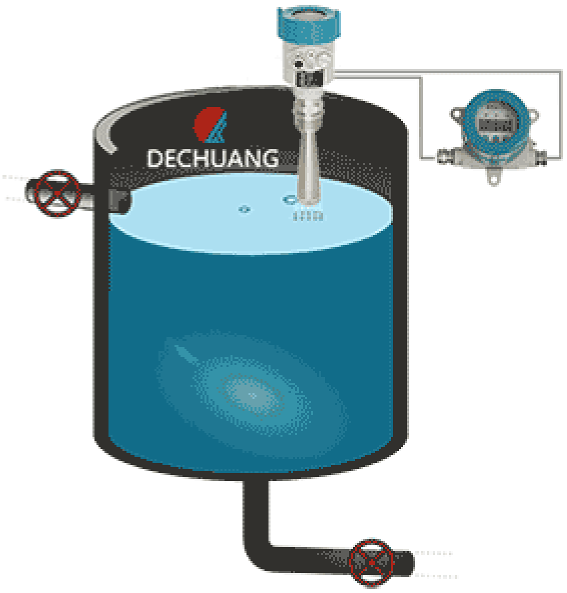
mmxie@ntu.edu.sg

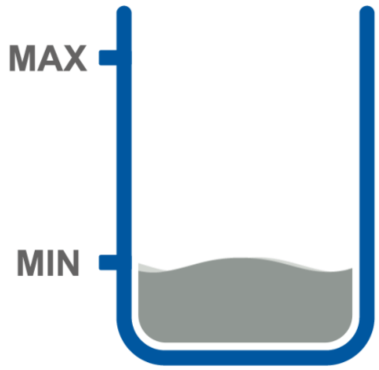
http://personal.ntu.edu.sg/mmxie

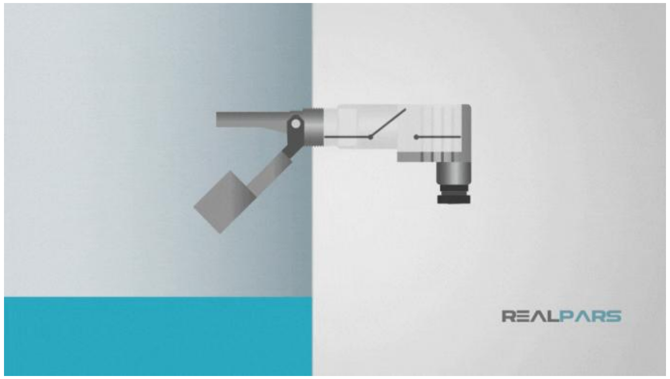
Outline

- Understanding of Fluid Level
- Computation of Fluid Level
- Measurement of Fluid Level



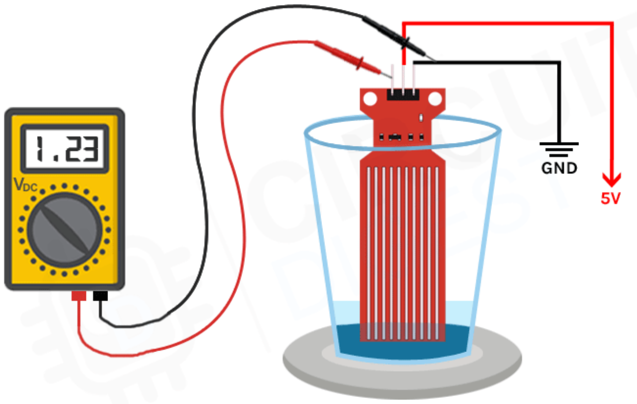


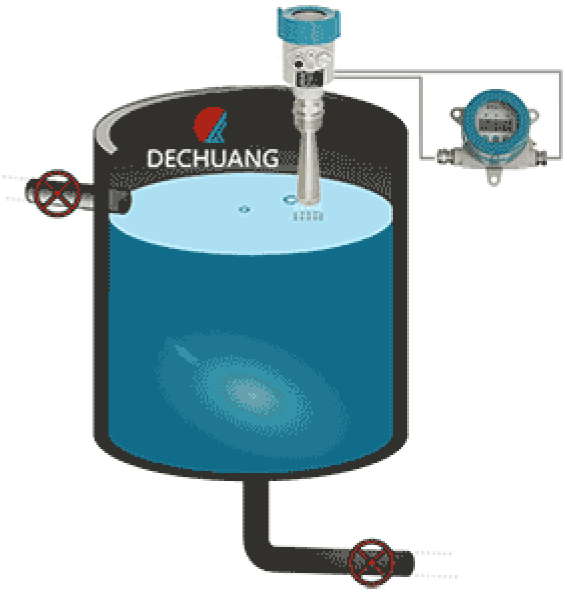


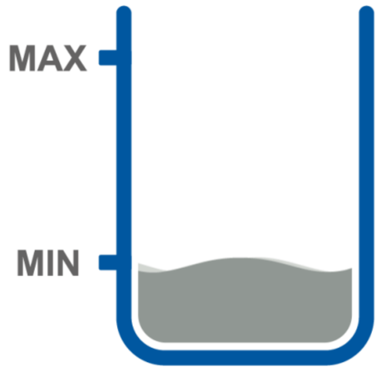


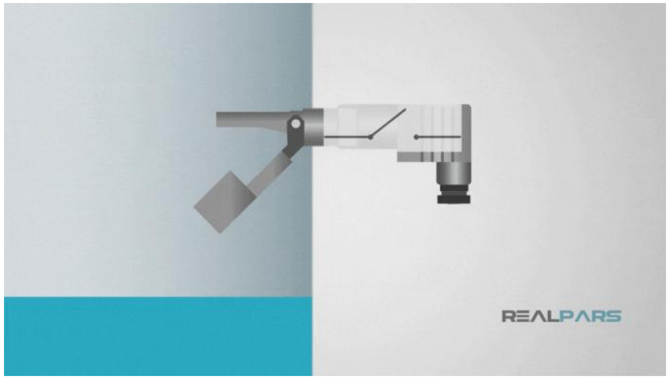
Outline

- Understanding of Fluid Level
- Computation of Fluid Level
- Measurement of Fluid Level



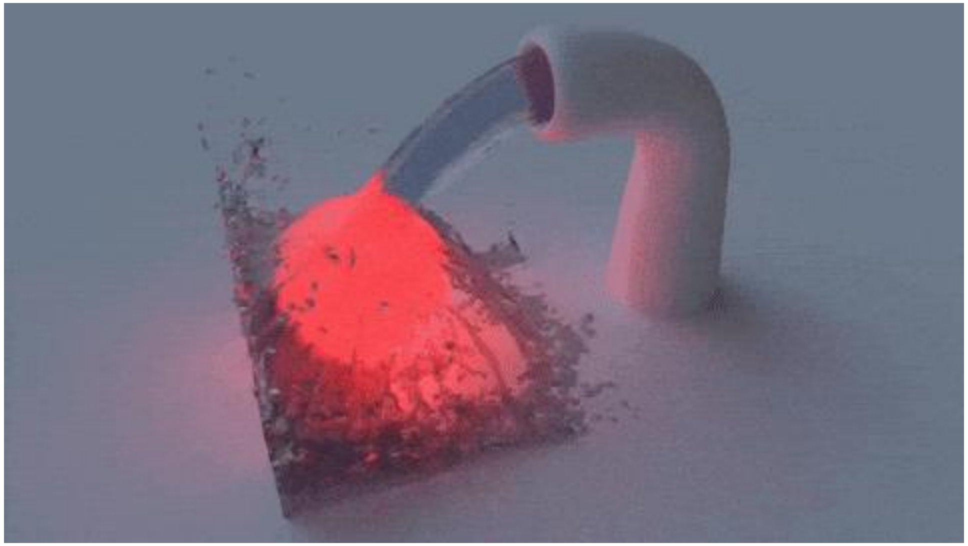


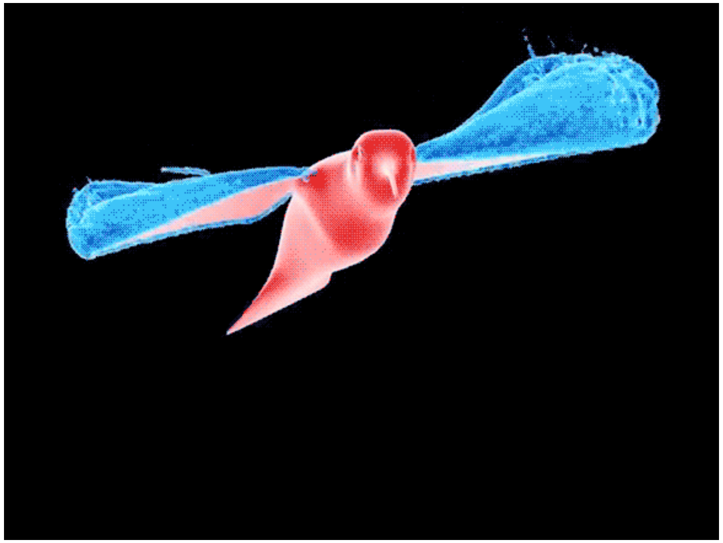




What is fluid?

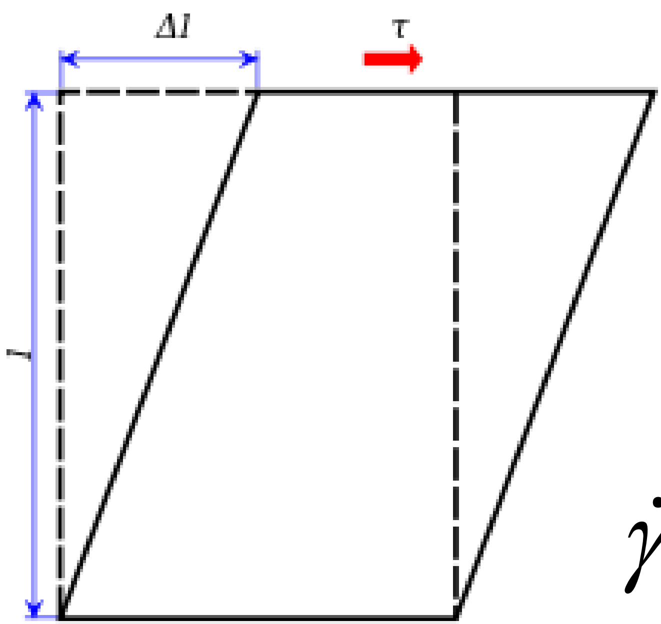
- Fluid refers to any substance which could undergo continuous movements in the form of flow.
- Fluid includes substances in liquid state and gas state.





About Shear Stress, Shear Strain and Shear Rate

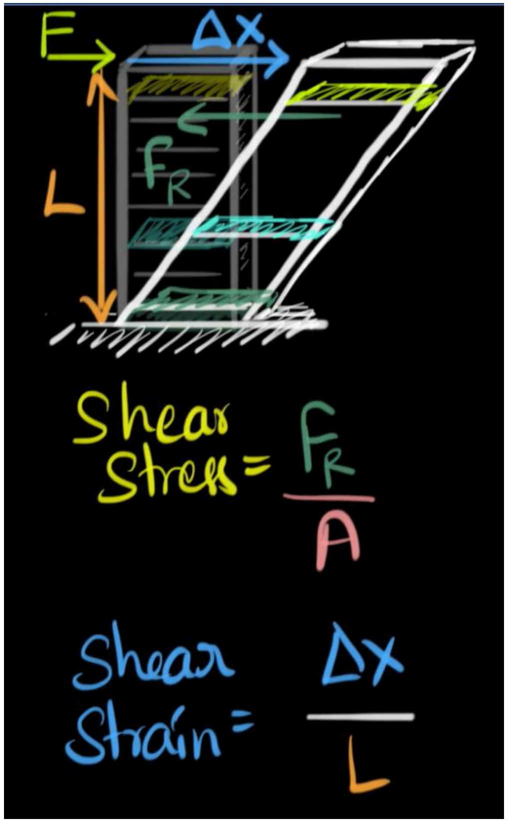
- Shear stress is the co-planar force per unit area.



$$\tau = \frac{F_{\parallel}}{A}$$

$$\dot{\gamma} = \frac{\Delta l}{\Delta t} \times \frac{1}{l}$$

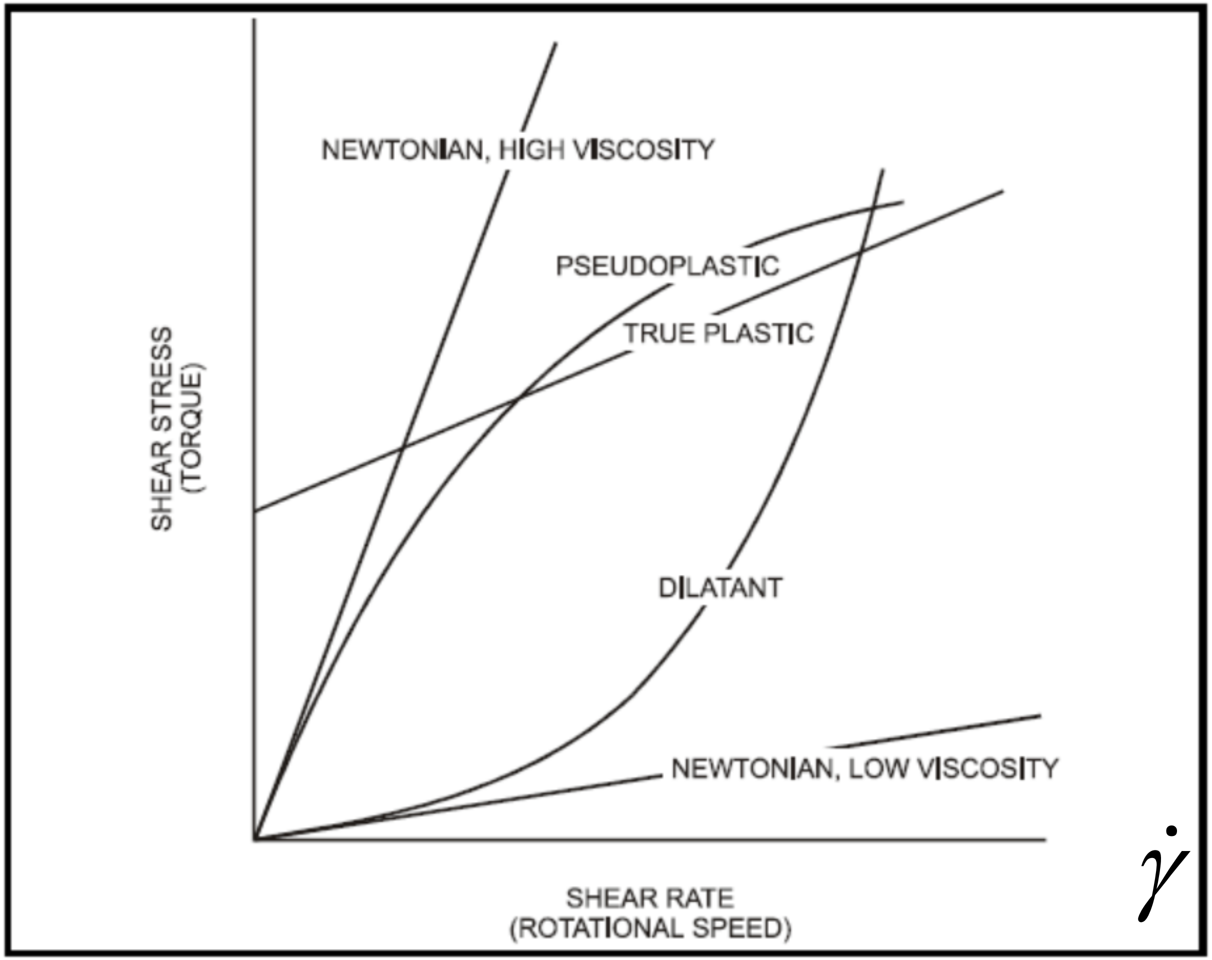
Side view: from cube to parallelogram



Shear Strain Rate or Rotational speed

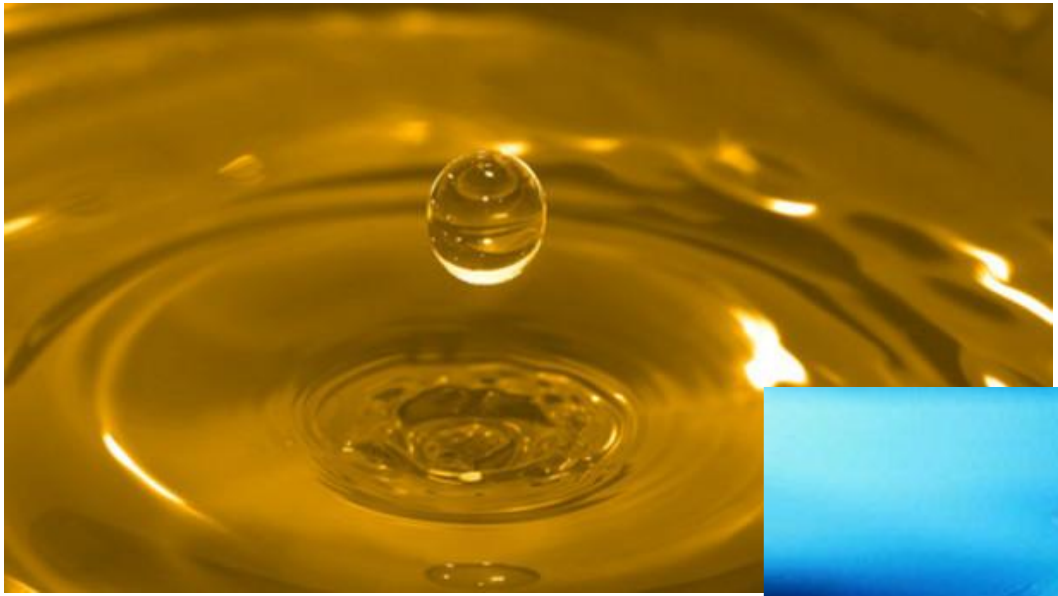
What is Newtonian fluid?

$$\tau = \frac{F_{\parallel}}{A}$$



$$\dot{\gamma} = \frac{\Delta l}{\Delta t} \times \frac{1}{l}$$

Example of Newtonian Fluids



Example of Non-Newtonian Fluids

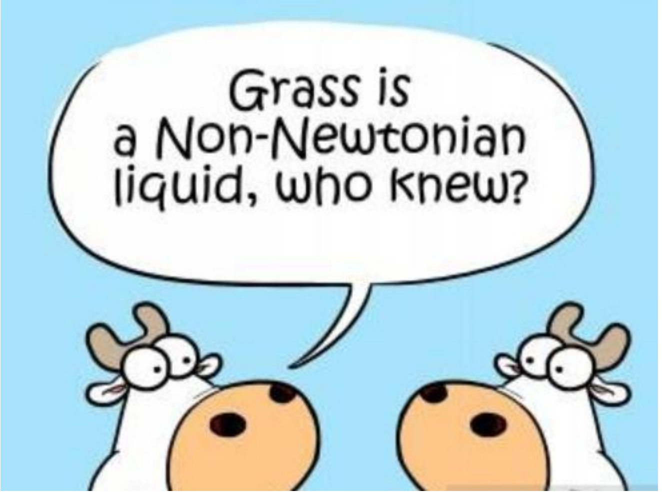
Cream of Milk

Ketchup

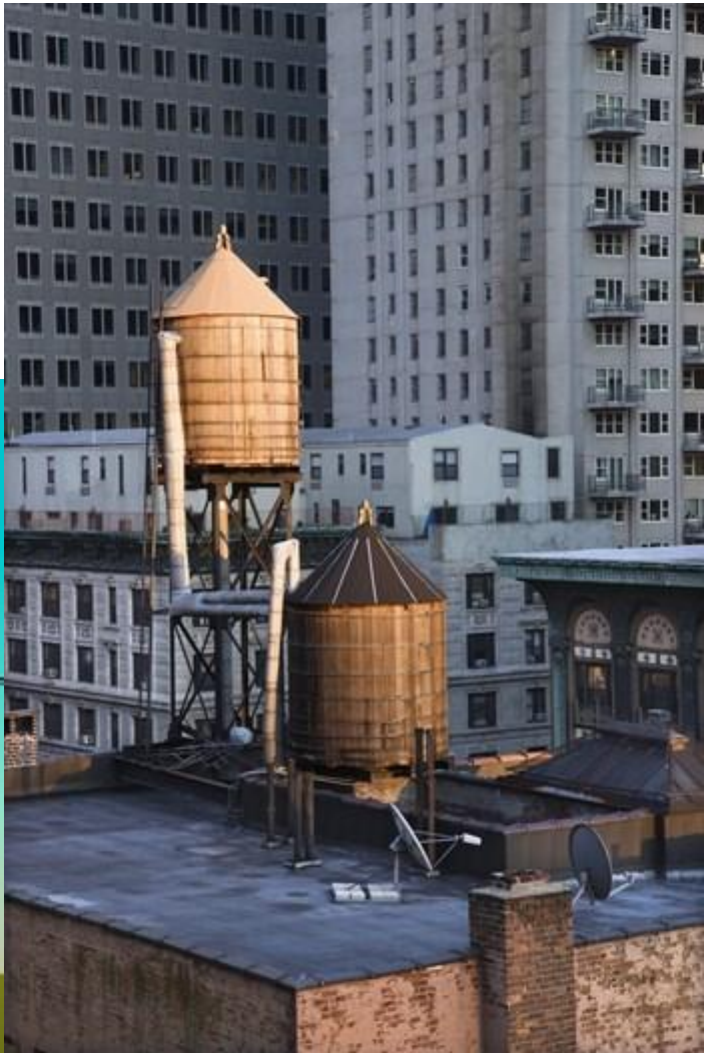
Example of Non-Newtonian Fluids

- Using just cornflour and water, you can make a non-Newtonian liquid.

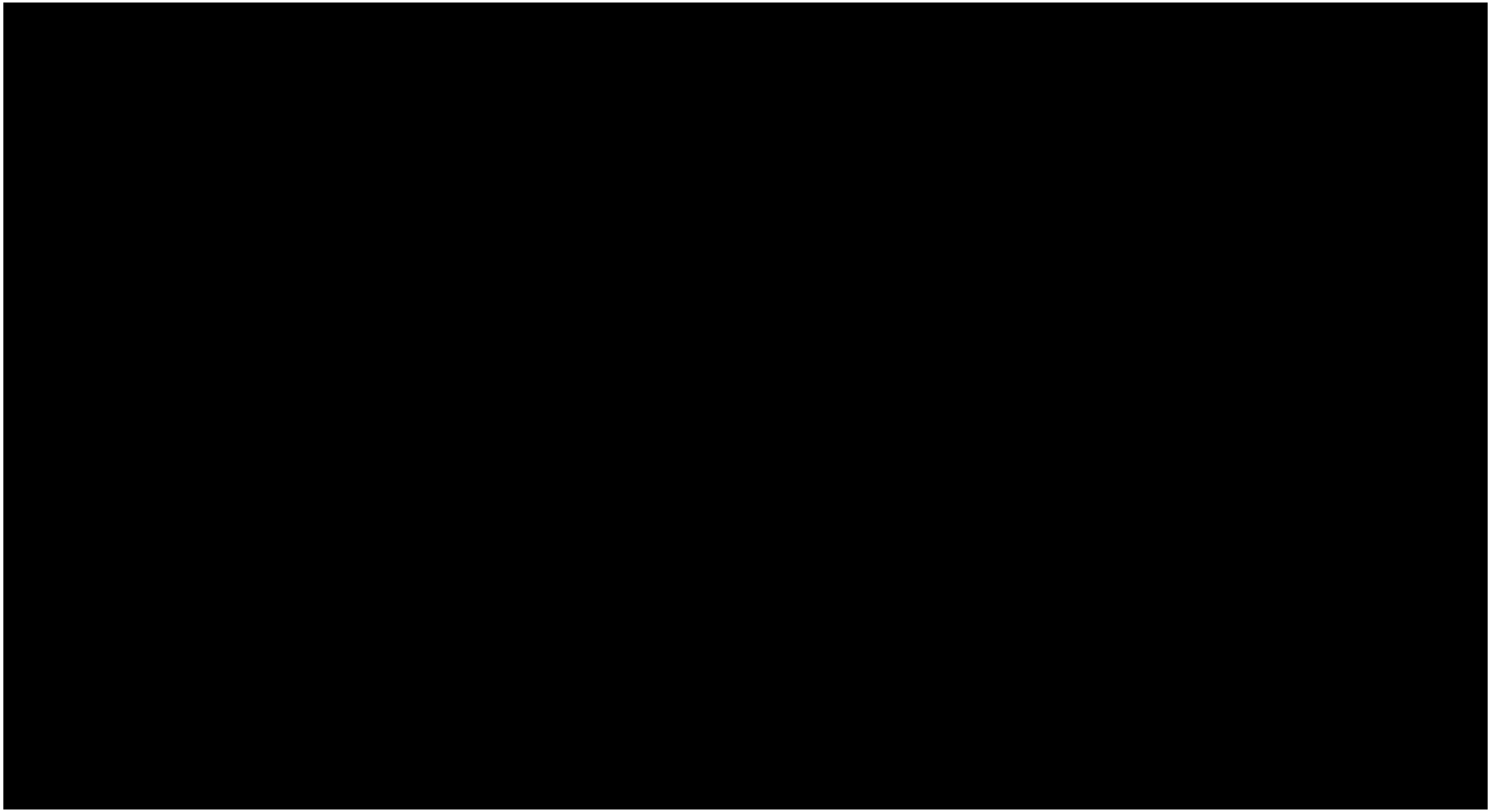
Example of Non-Newtonian Fluids



Water Storage in Our Daily Life

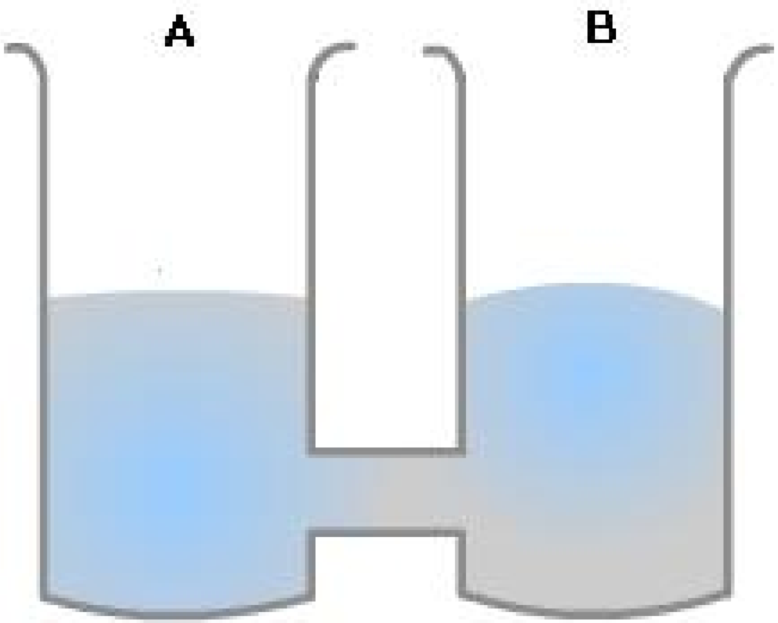


Fluid Storage in Industry



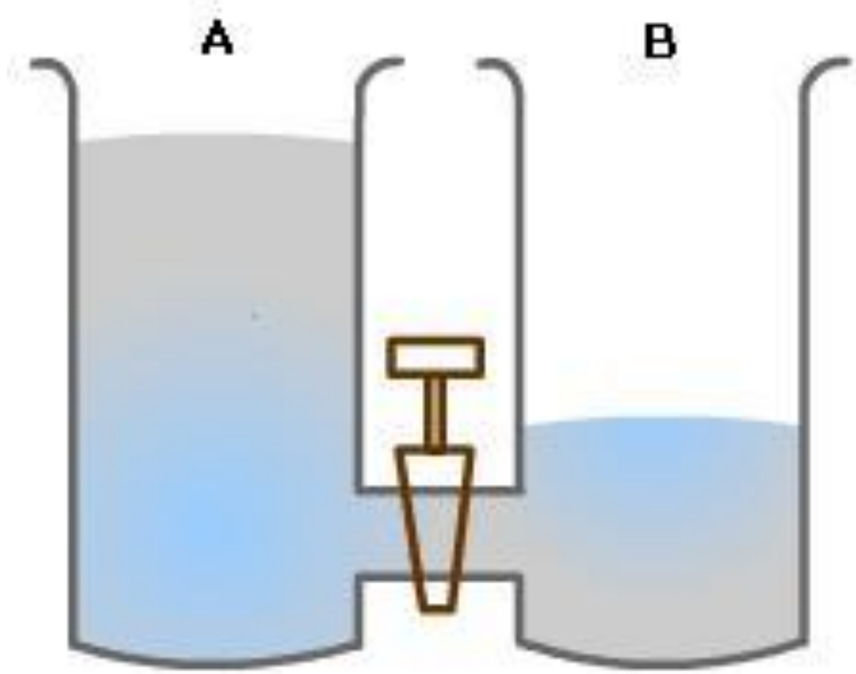
Understanding Fluid Levels (1)

- Within a same fluid system, the pressure at a same level remains the same.



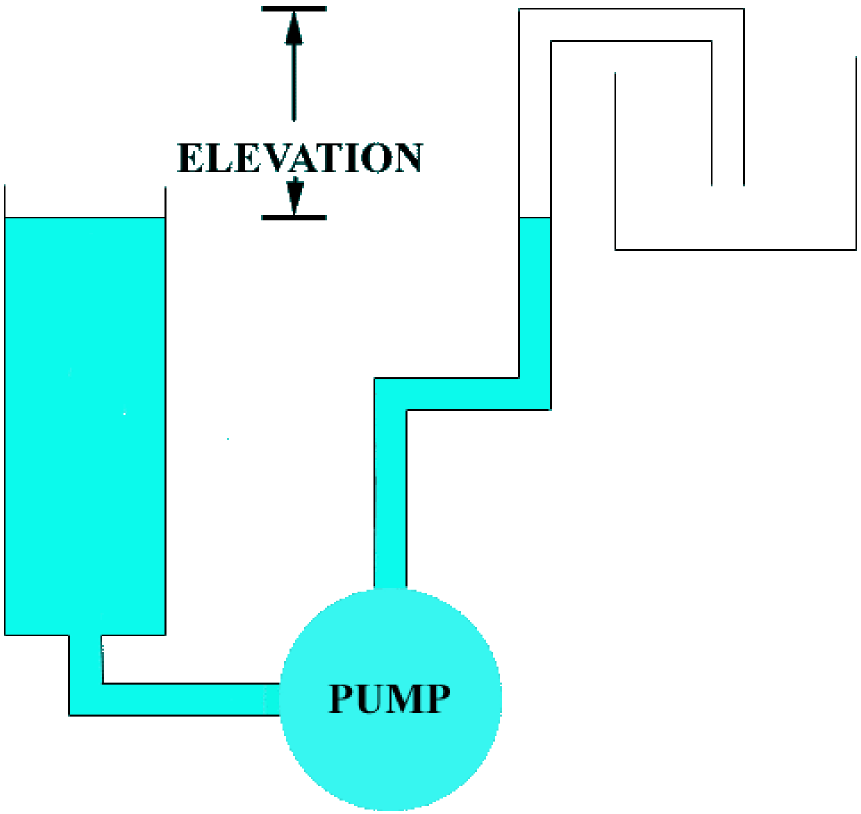
Understanding Fluid Levels (2)

- The flow levels of two different fluid systems can be different.



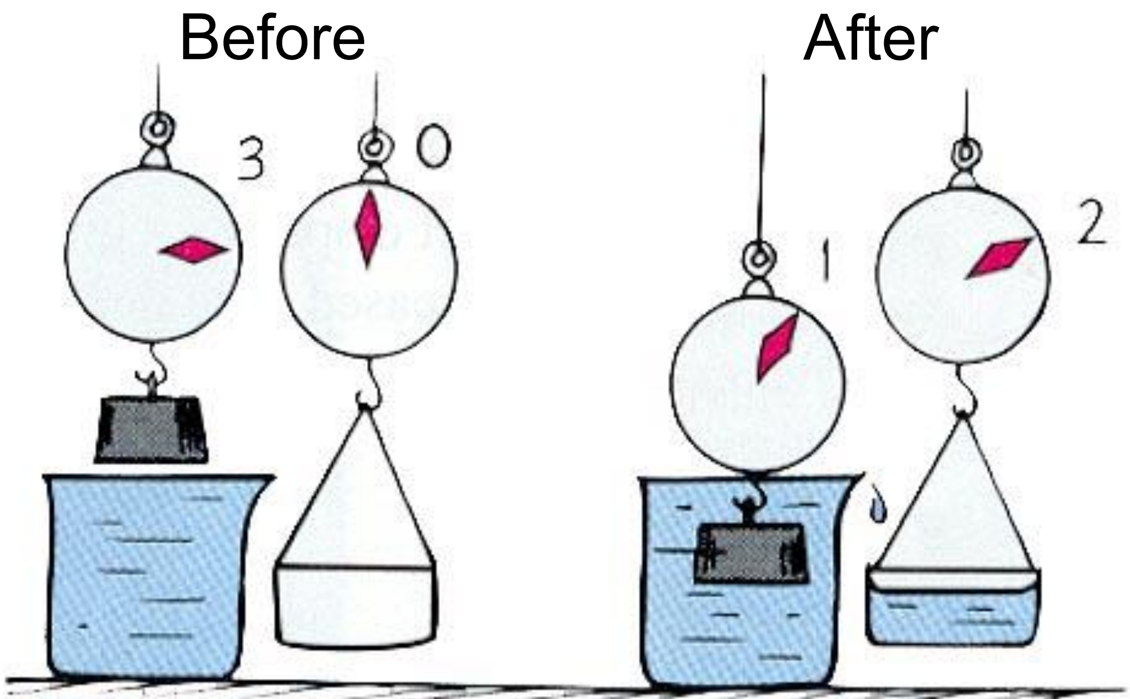
Understanding Fluid Levels (3)

- Fluids flow from places of higher pressure to places of lower pressure until the pressures or fluid levels are equals.



Understanding Fluid Levels (4)

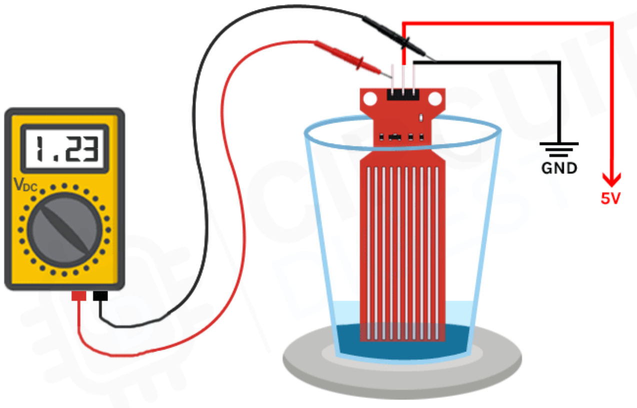
- It is important to know that fluid in a tank could produce Buoyant Force. Buoyant force is equal to the weight of displaced liquid.

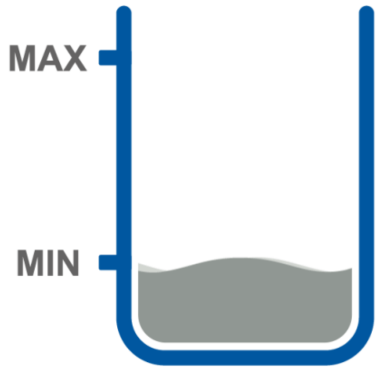


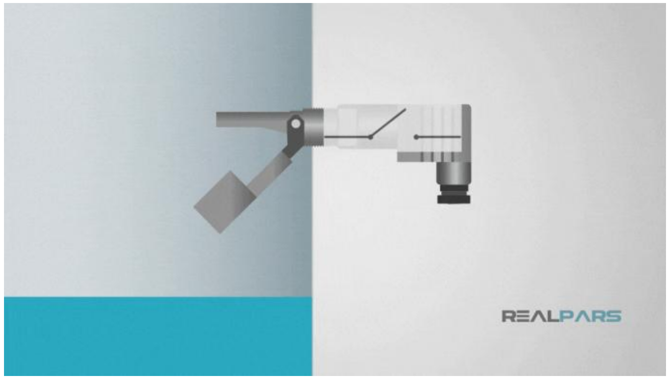
Weight Loss = Weight of Displaced Liquid

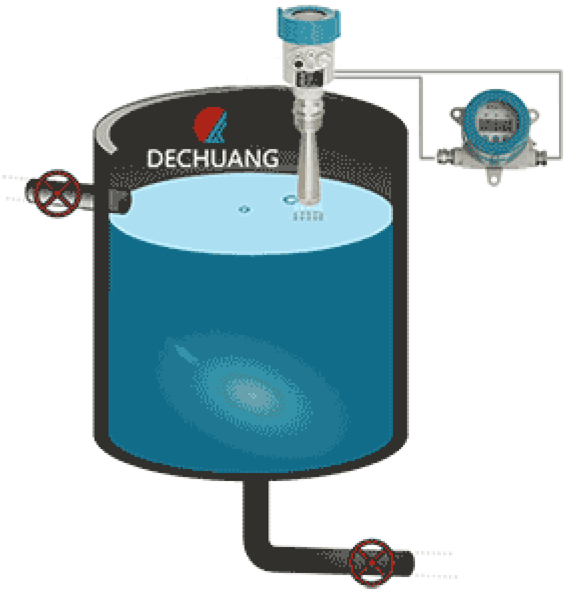
Outline

- Understanding of Fluid Level
- Computation of Fluid Level
- Measurement of Fluid Level







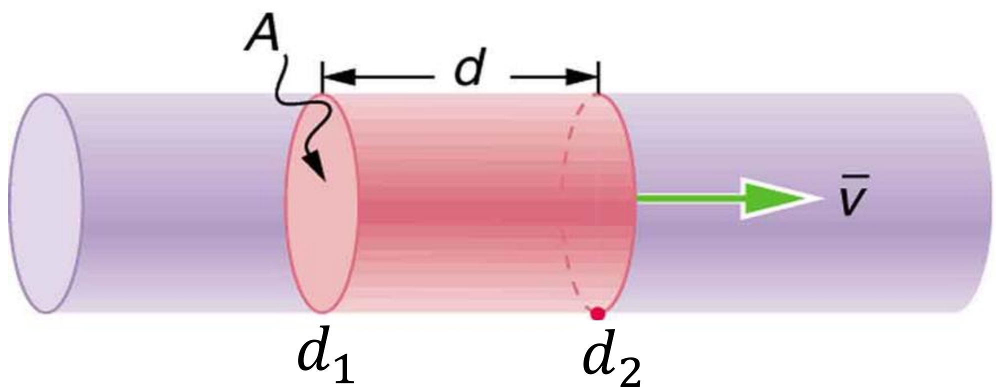


One important parameter of storage tank is liquid level …

Equations of Computation

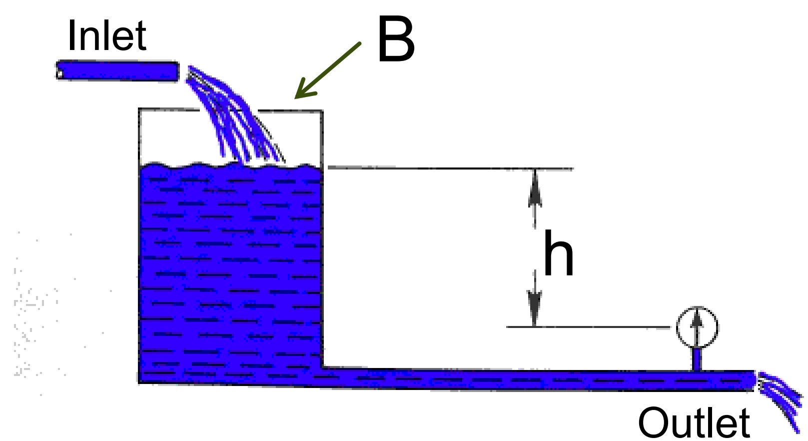
- Fluid level is a function of net change of fluid's volume in a tank.

$$Q = \frac{V}{t} = \frac{A \times d}{t} = A \times \bar{v}$$



$$\bar{v} = \frac{d}{t}$$

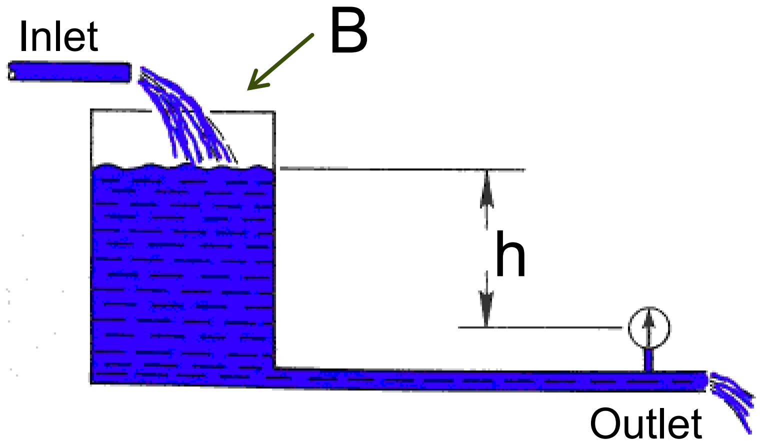
$$\Delta Q = Q_{in} - Q_{out}$$



$$\Delta h = \frac{\Delta Q}{B}$$

Example

- As shown in the figure, the section area of the tank is 100.0 m^2. The flow at the inlet is 20.0 m^3/h while the flow at the outlet is 18.0 m^3/h. What is the change of the level h within 10.0 minutes?



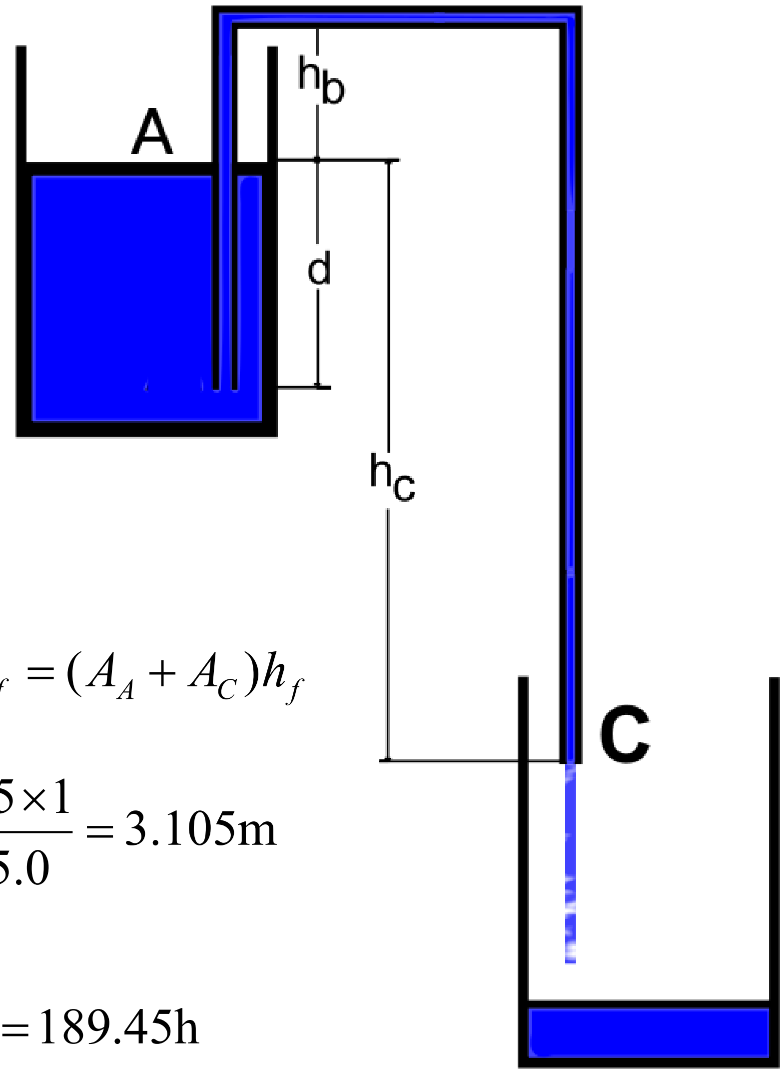
- Answer:

$$\Delta Q = Q_{in} - Q_{out} = \frac{20.0 - 18.0}{60.0} = \frac{1}{30} \mathrm{m}^3 / \mathrm{minute}$$

$$\Delta h = \frac{\Delta Q \Delta t}{B} = \frac{1}{30} \times 10 \times \frac{1}{100} = 3.33\mathrm{mm}$$

Example

- As shown in the figure, the section area of tank A is 50.0 m^2 while the section area of tank C is 45.0 m^2. The initial level of tank A is 5.0 m while the initial level of tank C is 1.0 m. If the flowrate is 0.5 m^3/h, how long will it take for the levels of tanks A and C to be equal?



- Answer: $A_A h_{A,i} + A_C h_{C,i} = A_A h_{A,f} + A_C h_{C,f} = (A_A + A_C) h_f$

$$h_f = \frac{A_A h_{A,i} + A_C h_{C,i}}{A_A + A_C} = \frac{50 \times 5 + 45 \times 1}{50.0 + 45.0} = 3.105\text{m}$$

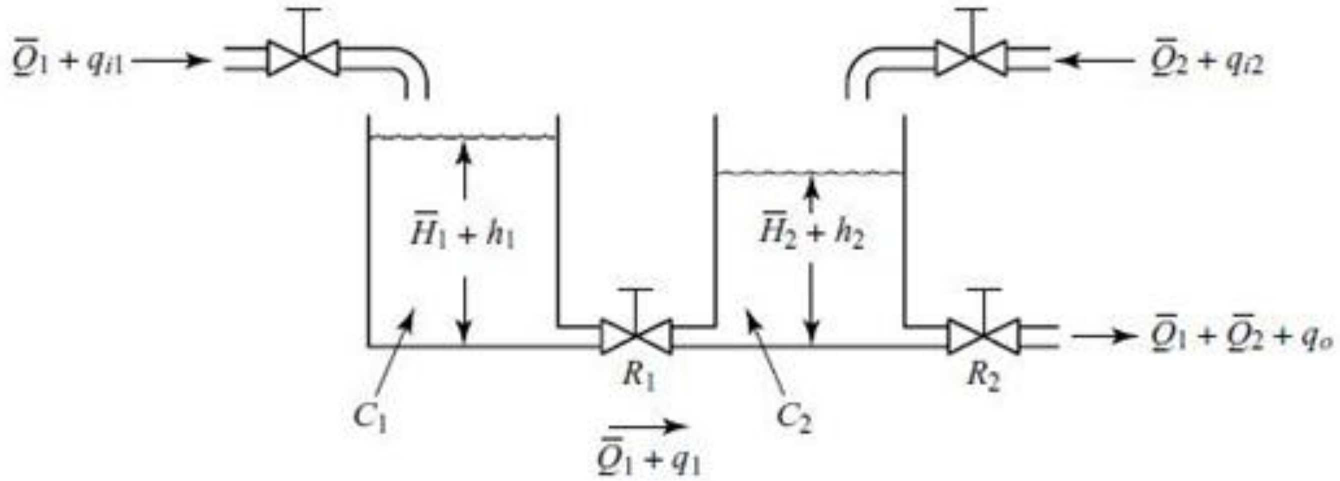
$$\Delta t = \frac{A \Delta h}{\Delta Q} = \frac{45.0 \times (3.105 - 1.0)}{0.5} = 189.45\text{h}$$

Example

- As shown in the figure, what is the flow change in tank C2 if the fluid levels remain constant?

- Answer:

$$q_0 = q_1 + q_{i2}$$



Example

- The areas of tanks 1, 2 and 3 are the same and are equal to 25.0 m^2. If Q12=0.2 m^3/h and Q23 = 0.15 m^3/h, what are the level changes of tanks 1, 2 and 3 within 30.0 minutes?
- Answer:

$$\Delta h_1 = \frac{0 - Q_{12}}{A} = \frac{-0.2}{25} = -8mm/h$$

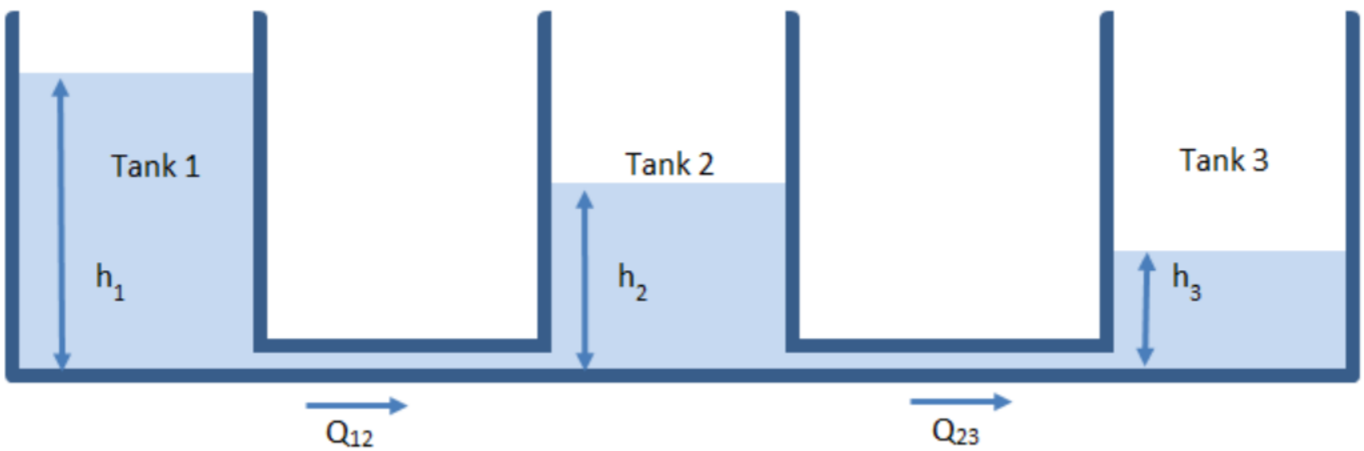
⇨ Level change in tank 1 is -4 mm

$$\Delta h_2 = \frac{Q_{12} - Q_{23}}{A} = \frac{0.2 - 0.15}{25} = 2mm/h$$

⇨ Level change in tank 2 is 1 mm

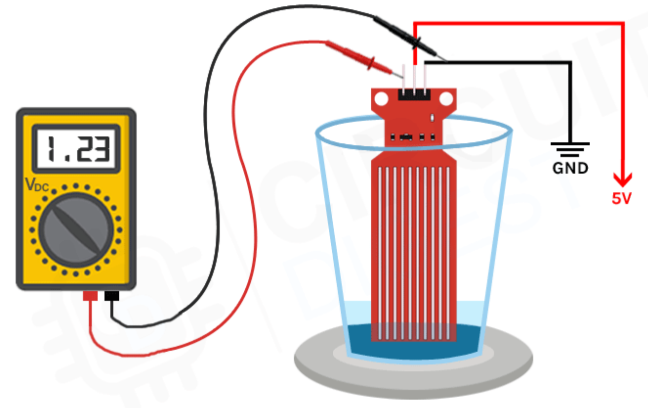
$$\Delta h_3 = \frac{Q_{23} - 0}{A} = \frac{0.15 - 0}{25} = 6mm/h$$

⇨ Level change in tank 3 is 3 mm

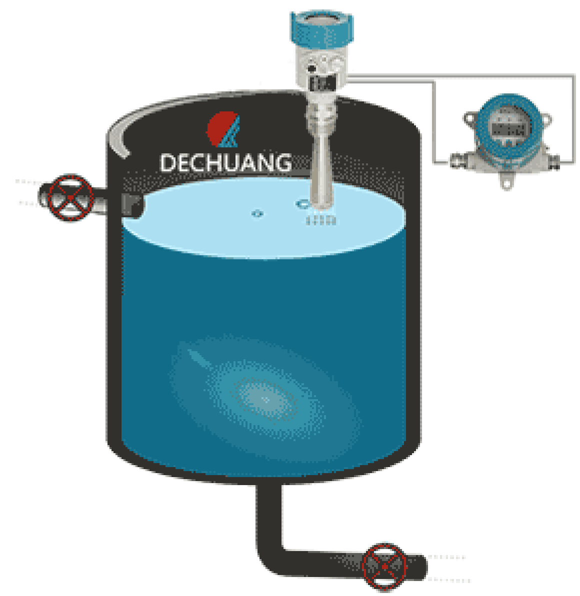


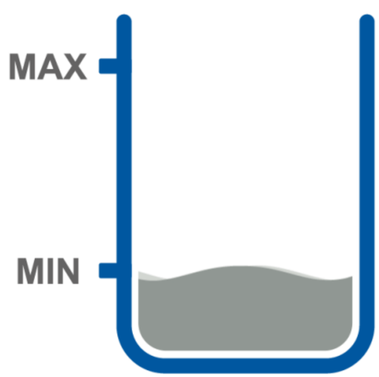
Outline

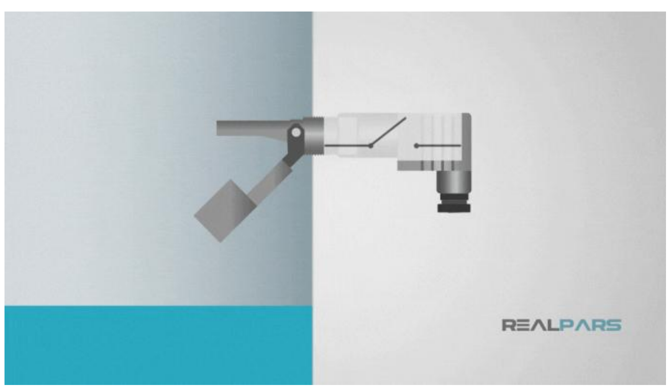
- Understanding of Fluid Level



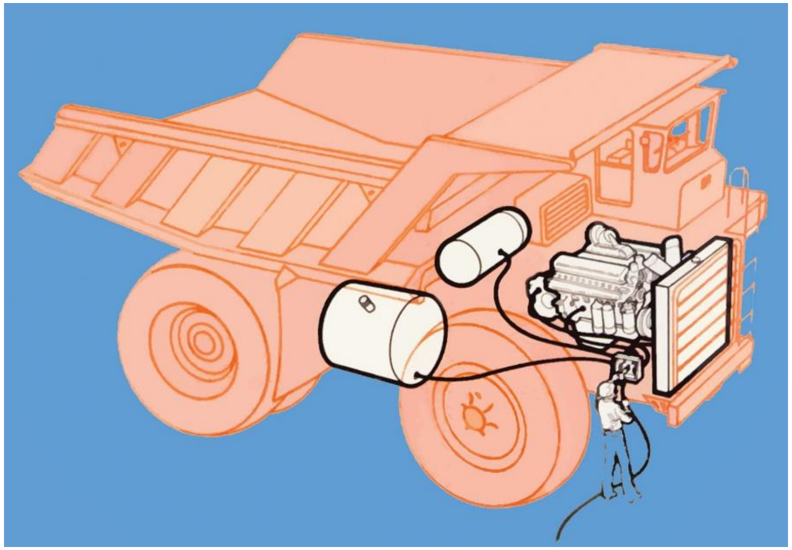
- Computation of Fluid Level
- Measurement of Fluid Level

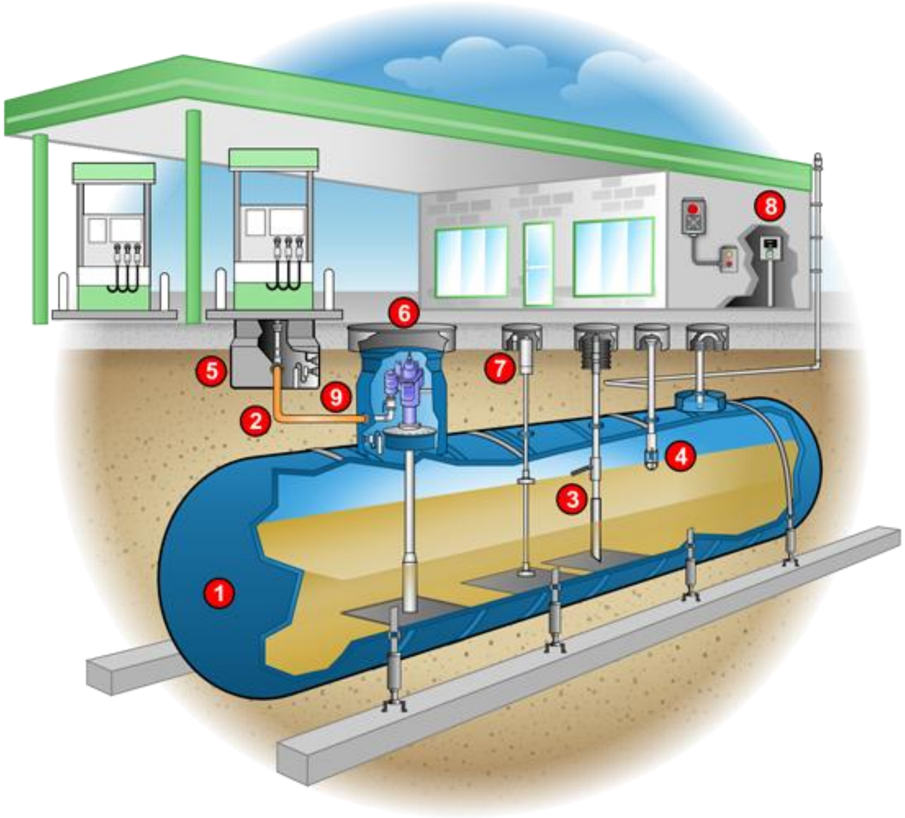




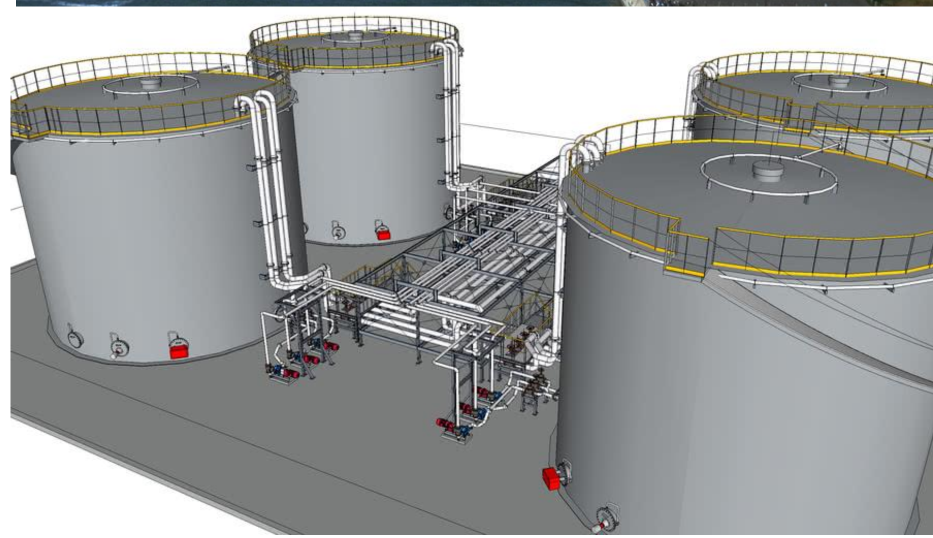


Measuring fluid levels …



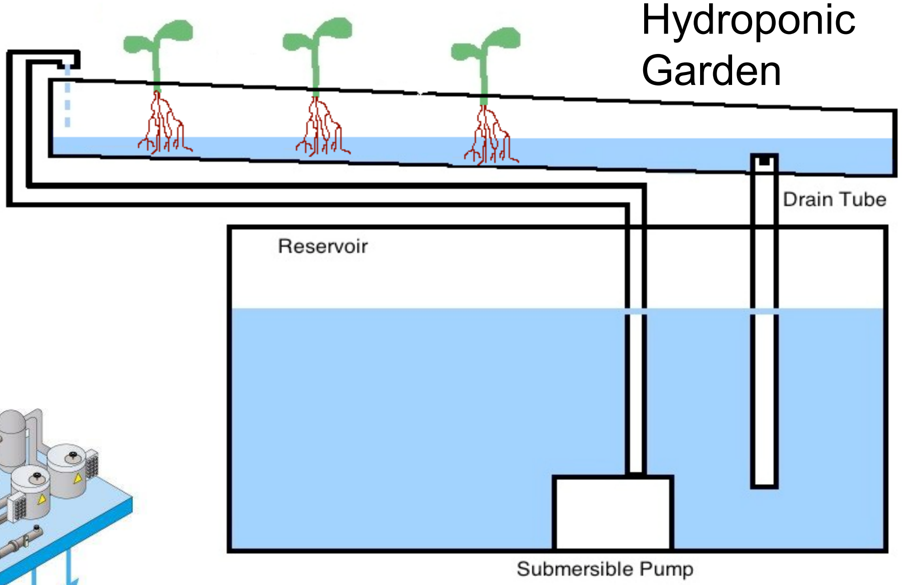


Controlling fluid levels …

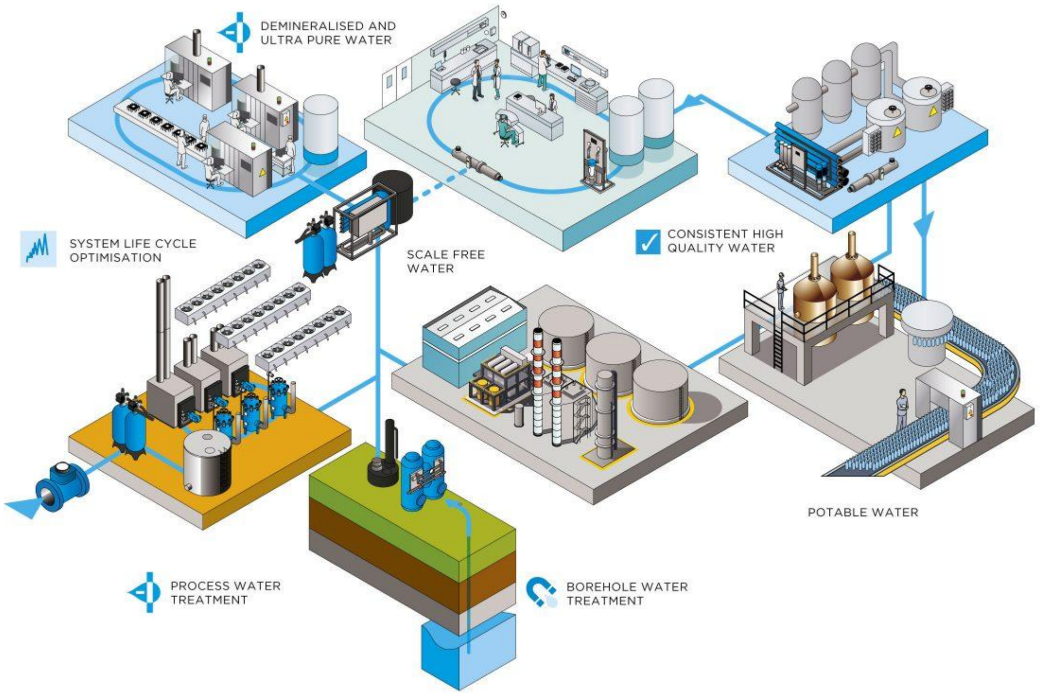


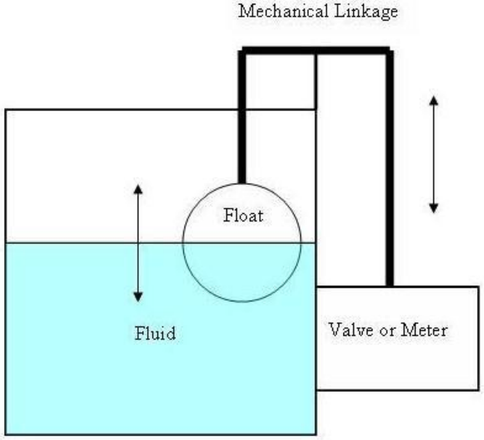
Controlling fluid levels …

Hydroponic Garden



Water Treatment Plant





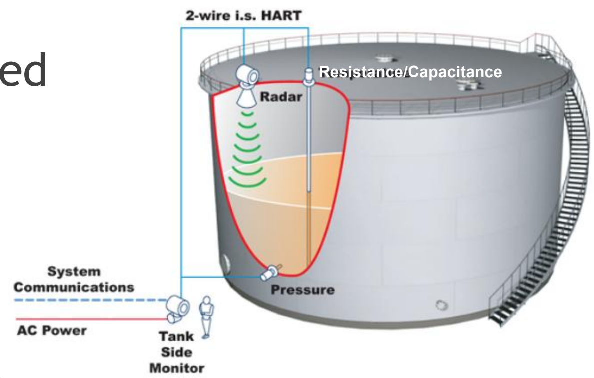
Principles of Measurement

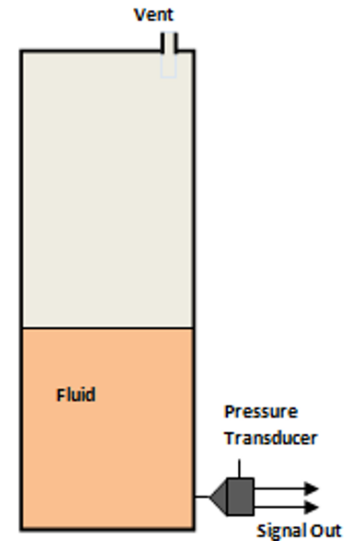
- Principle 1: Liquid level is converted into pressure, which could be converted into DC voltage. DC voltage could be automatically measured.

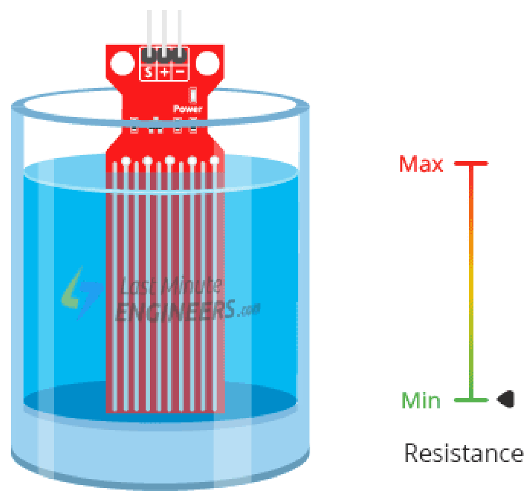
- Principle 2: Liquid level is converted into capacitance, which could be converted into DC voltage. DC voltage could be automatically measured.

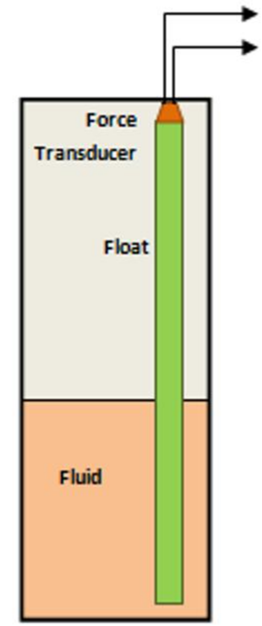
- Principle 3: Liquid level is converted into resistance, which could be converted into DC voltage. DC voltage could be automatically measured.

- Principle 4: Liquid level is converted into buoyant force, which could be converted into DC voltage. DC voltage could be automatically measured.



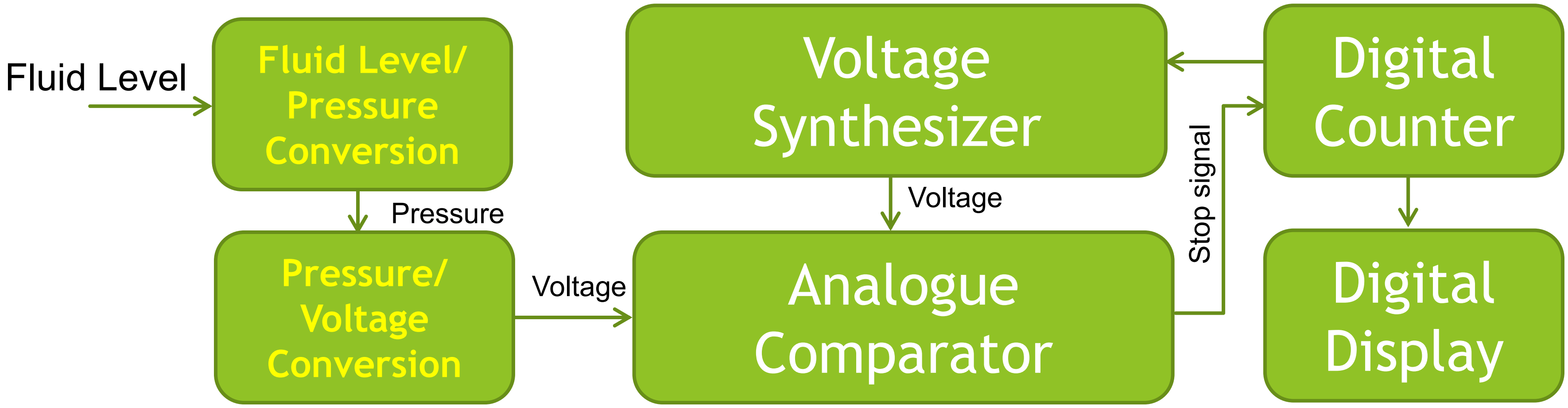






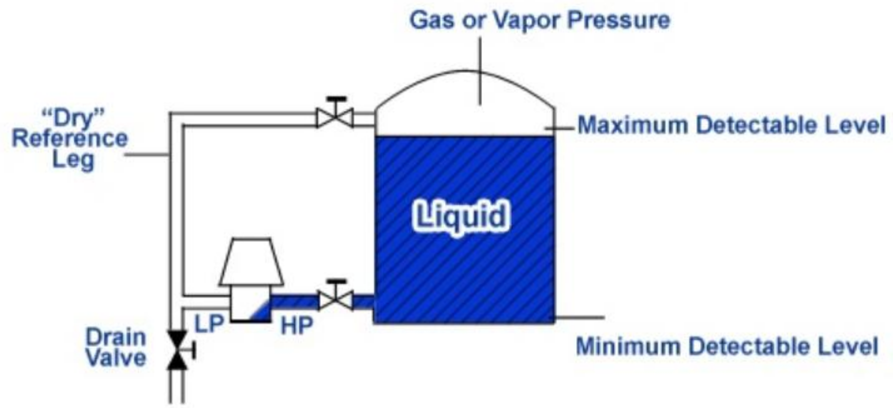
How to apply principle 1 to design digital measurement and sensing systems for fluid level?

- Fluid level is converted to pressure which is then converted to voltage. Finally, the voltage is measured by digital voltmeter (e.g. microcontrollers).

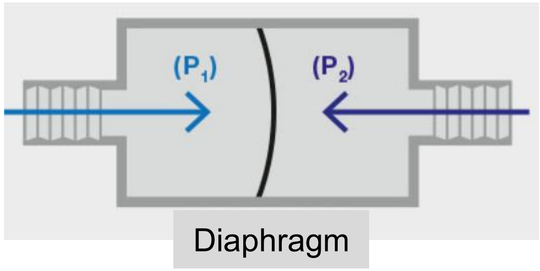


All microcontrollers are programmable digital sensors of voltage!

How to convert fluid level to differential pressure



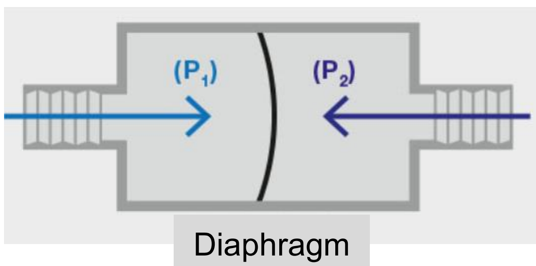
- We use a diaphragm.
- One side of the diaphragm is exposed to low pressure above the fluid inside a tank.
- The other side of the diaphragm is exposed to high pressure at the bottom of a tank.



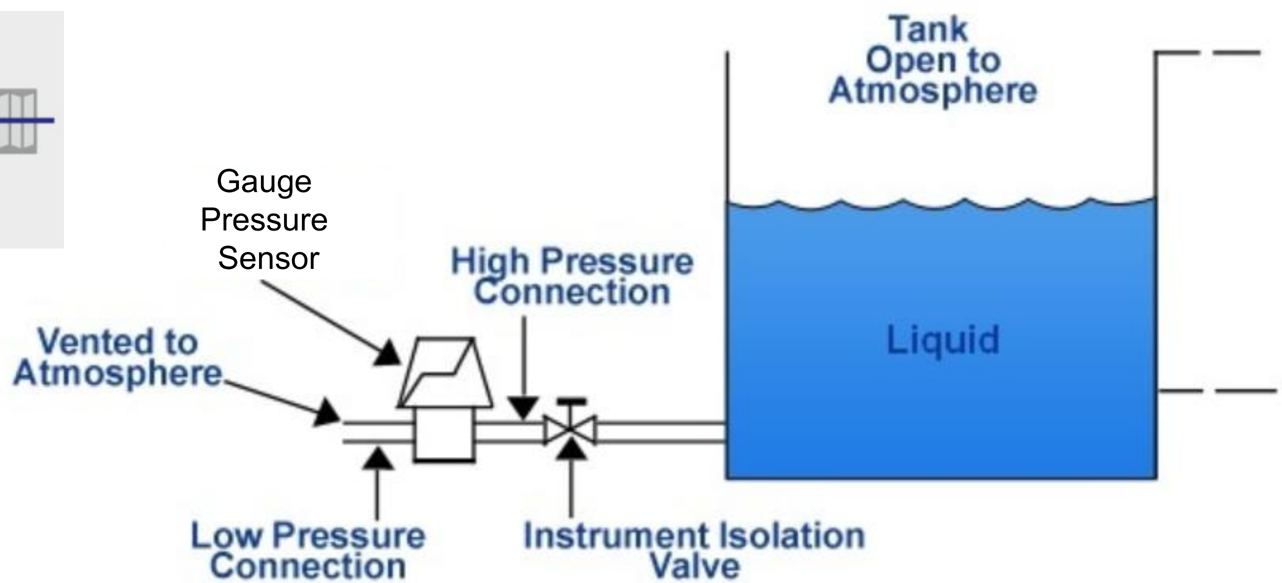
$$\Delta P = P_2 - P_1 = \rho g h \quad \Rightarrow \quad h = \frac{\Delta P}{\rho g}$$

How to convert fluid level to gauge pressure?

- A tank is open to atmosphere. We use a diaphragm. One side of the diaphragm is open to atmosphere. The other side of the diaphragm is exposed to high pressure at the bottom of the tank.

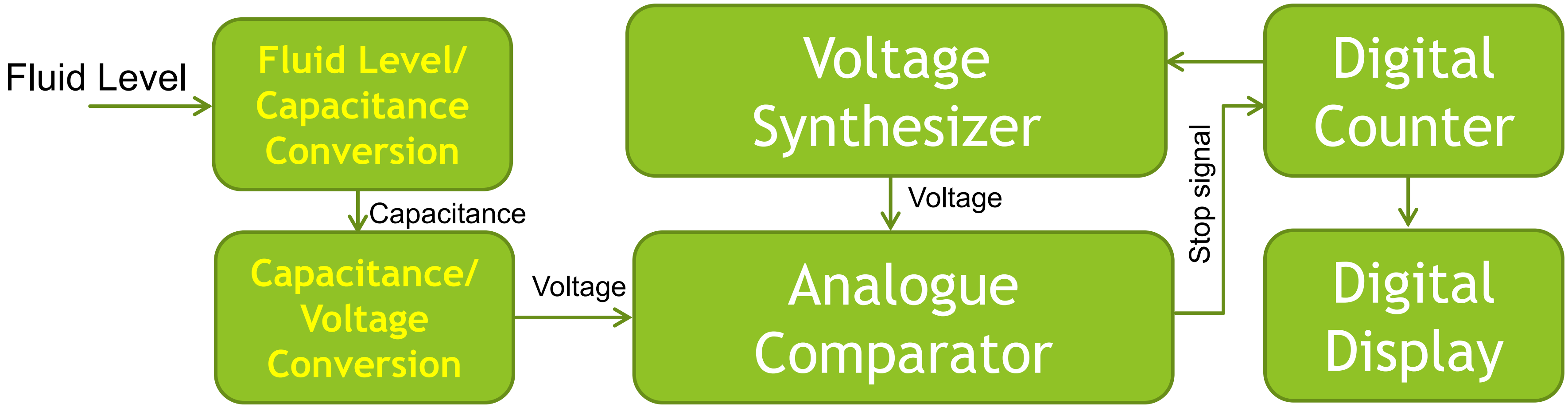


$$P_2 = P_0$$



How to apply principle 2 to design digital measurement and sensing systems for fluid level?

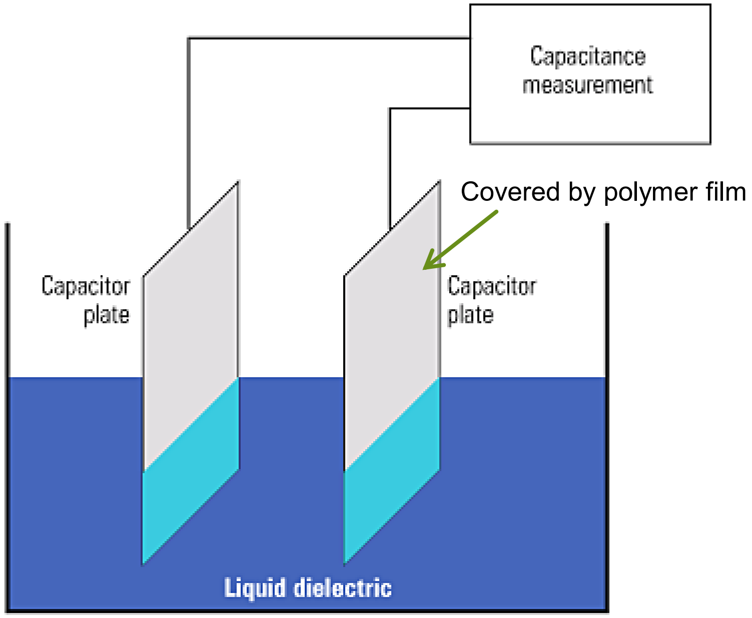
- Fluid level is converted to capacitance which is then converted to voltage. Finally, the voltage is measured by digital voltmeter (e.g. microcontrollers).



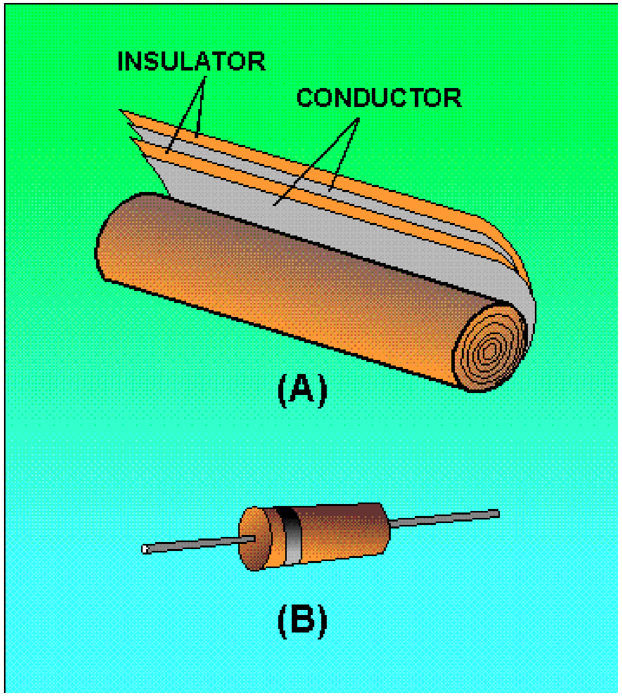
All microcontrollers are programmable digital sensors of voltage!

How to convert fluid level to capacitance?

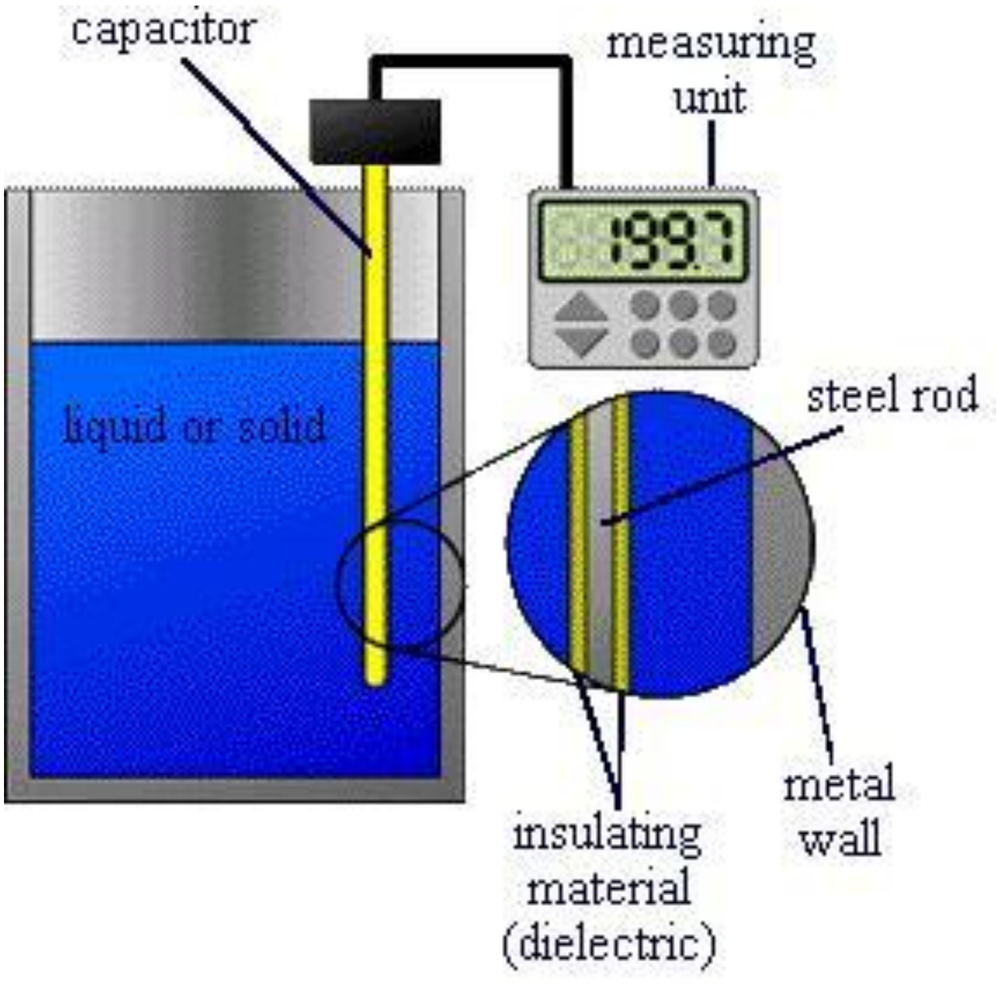
- Two parallel plates are placed inside the fluid of a tank.
- Each plate is covered by a layer of thin-film of polymer (i.e. insulting materials).
- The level changes of the fluid will cause the changes of the capacitance.



Example of Implementation

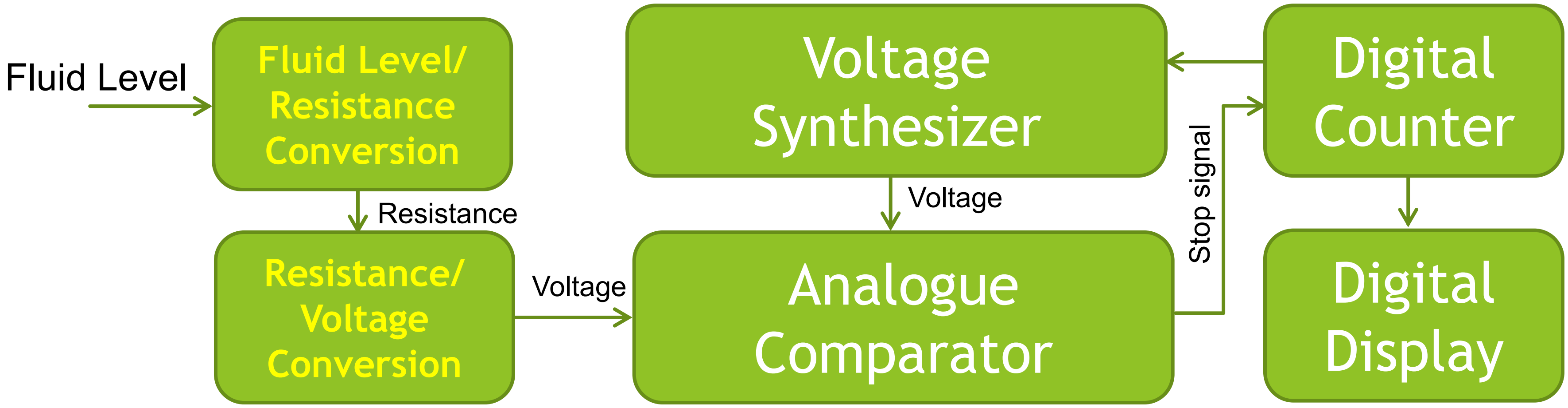


Capacitor in Cylindrical Shape



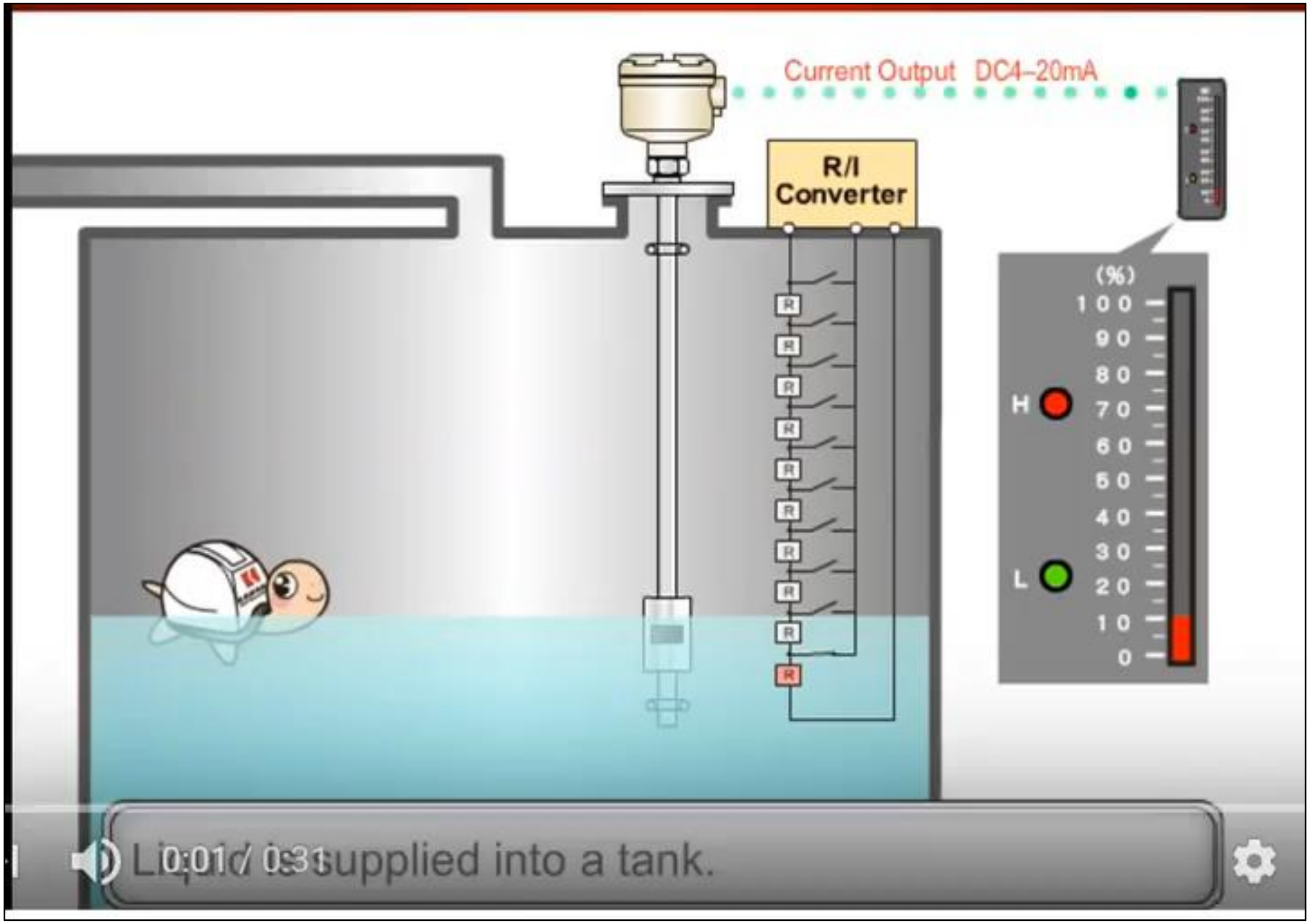
How to apply principle 3 to design digital measurement and sensing systems for fluid level?

- Fluid level is converted to resistance which is then converted to voltage. Finally, the voltage is measured by digital voltmeter (e.g. microcontrollers).



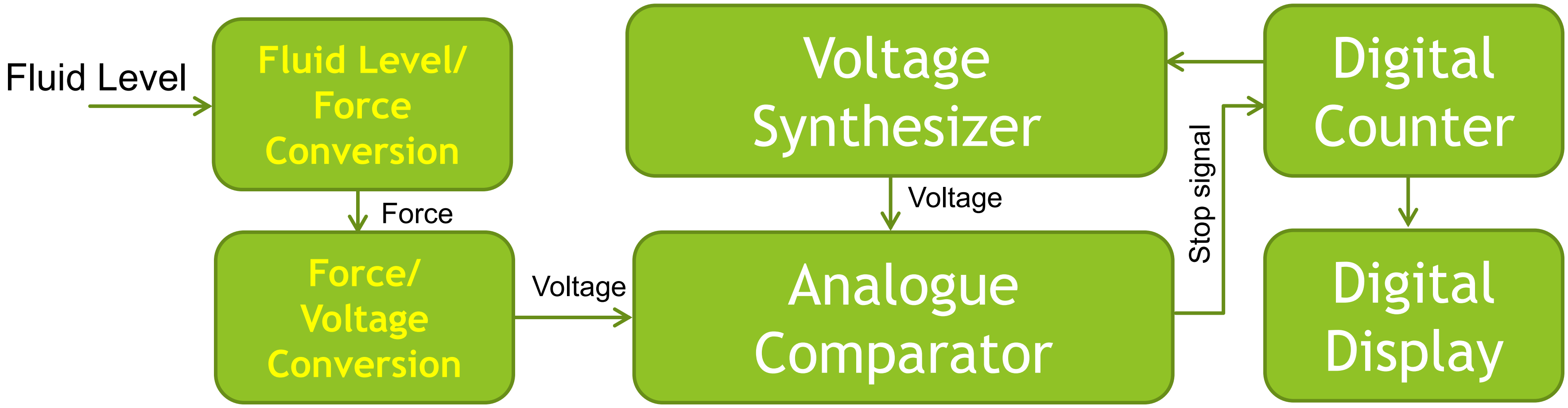
All microcontrollers are programmable digital sensors of voltage!

How to convert fluid level to resistance?



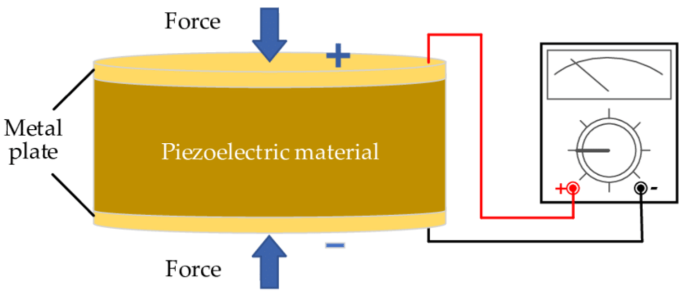
How to apply principle 4 to design digital measurement and sensing systems for fluid level?

- Fluid level is converted to force which is then converted to voltage. Finally, the voltage is measured by digital voltmeter (e.g. microcontrollers).

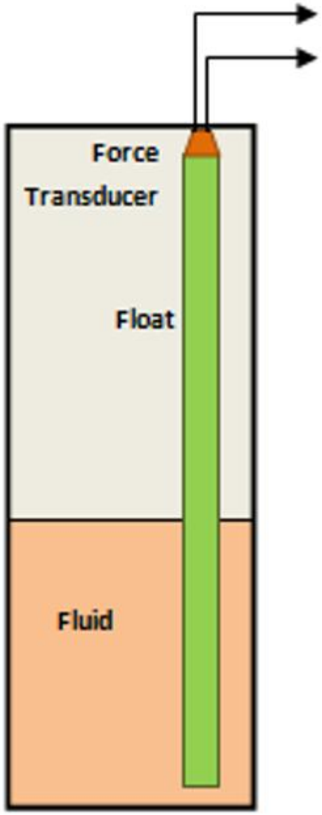


All microcontrollers are programmable digital sensors of voltage!

How to convert fluid level to buoyant force?

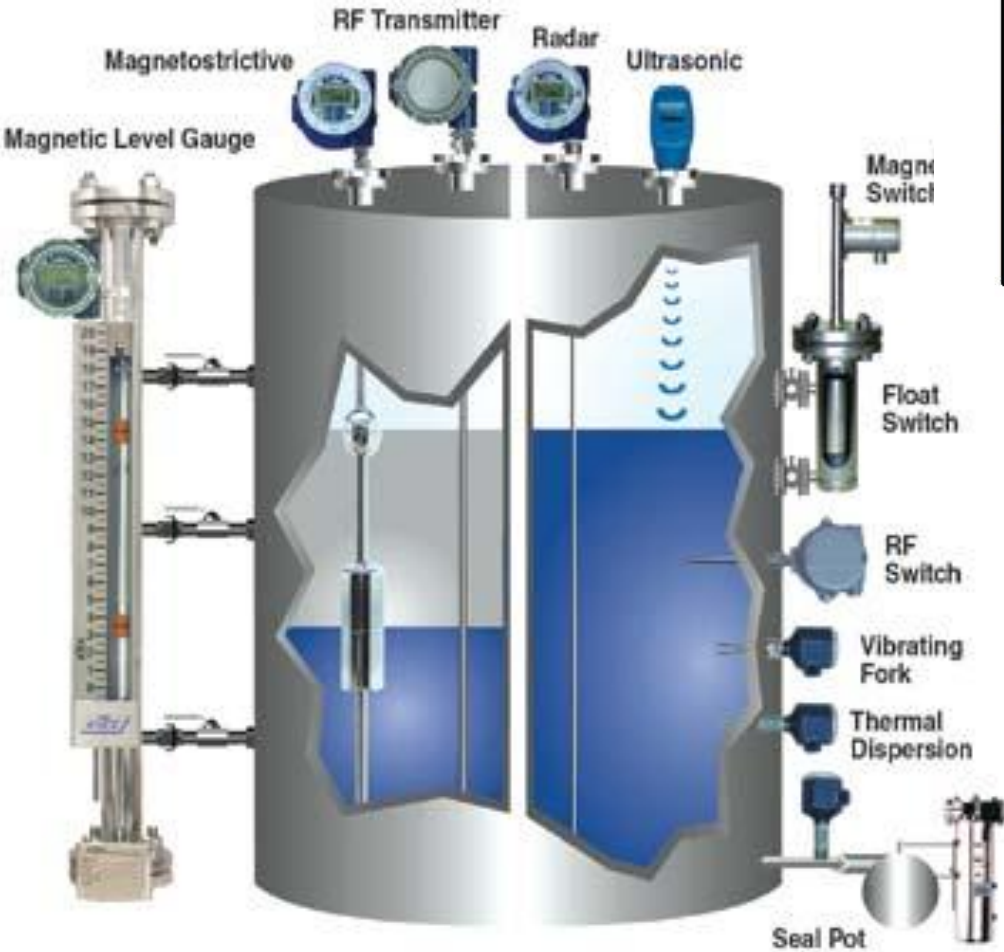


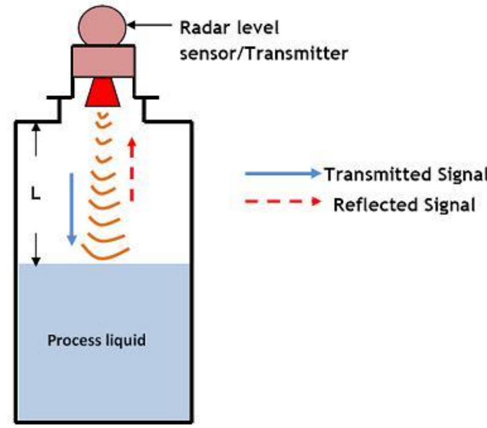
- A floating object is placed inside a tank with fluid.
- The floating object is acting on a piezoelectric material.
- When the fluid's level changes, the floating object's buoyant force changes.
- Such changes are converted into voltage changes by the piezoelectric material.

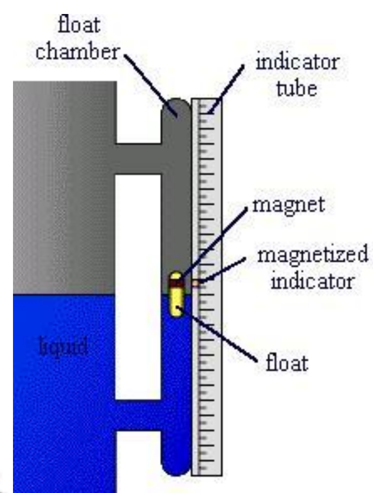


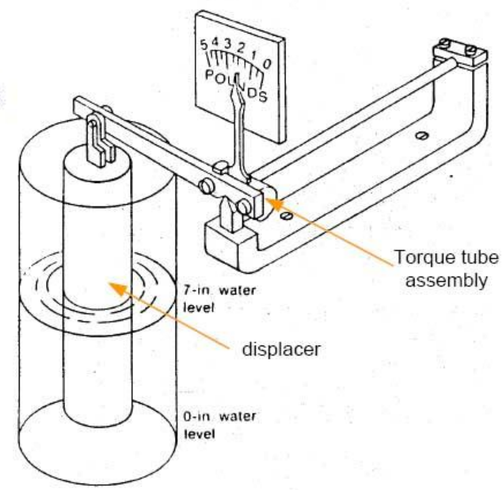
There are many other principles …

- Measurement of discrete levels
- Measurement of continuous levels









Example of Using Vibrating Fork …

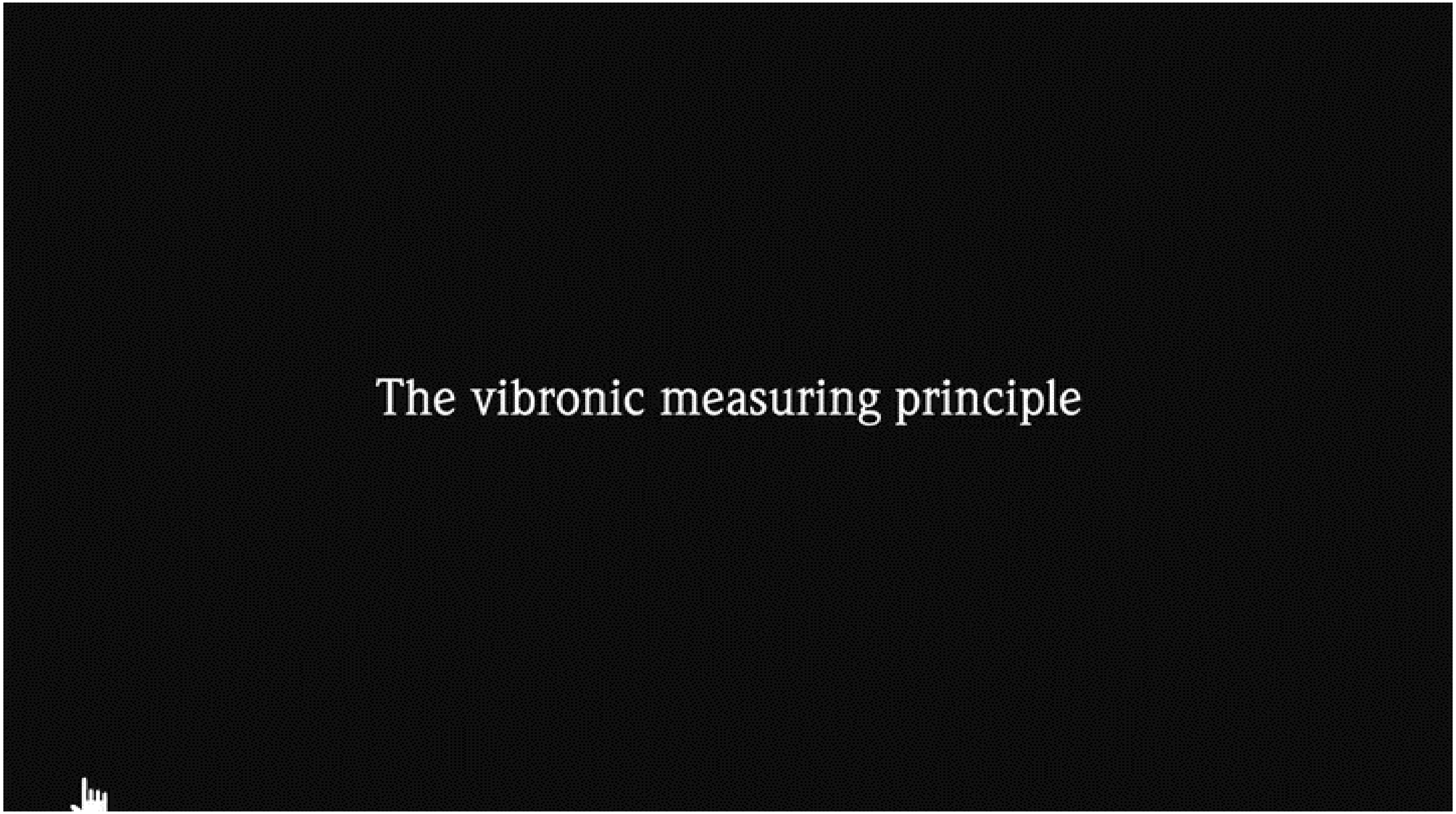
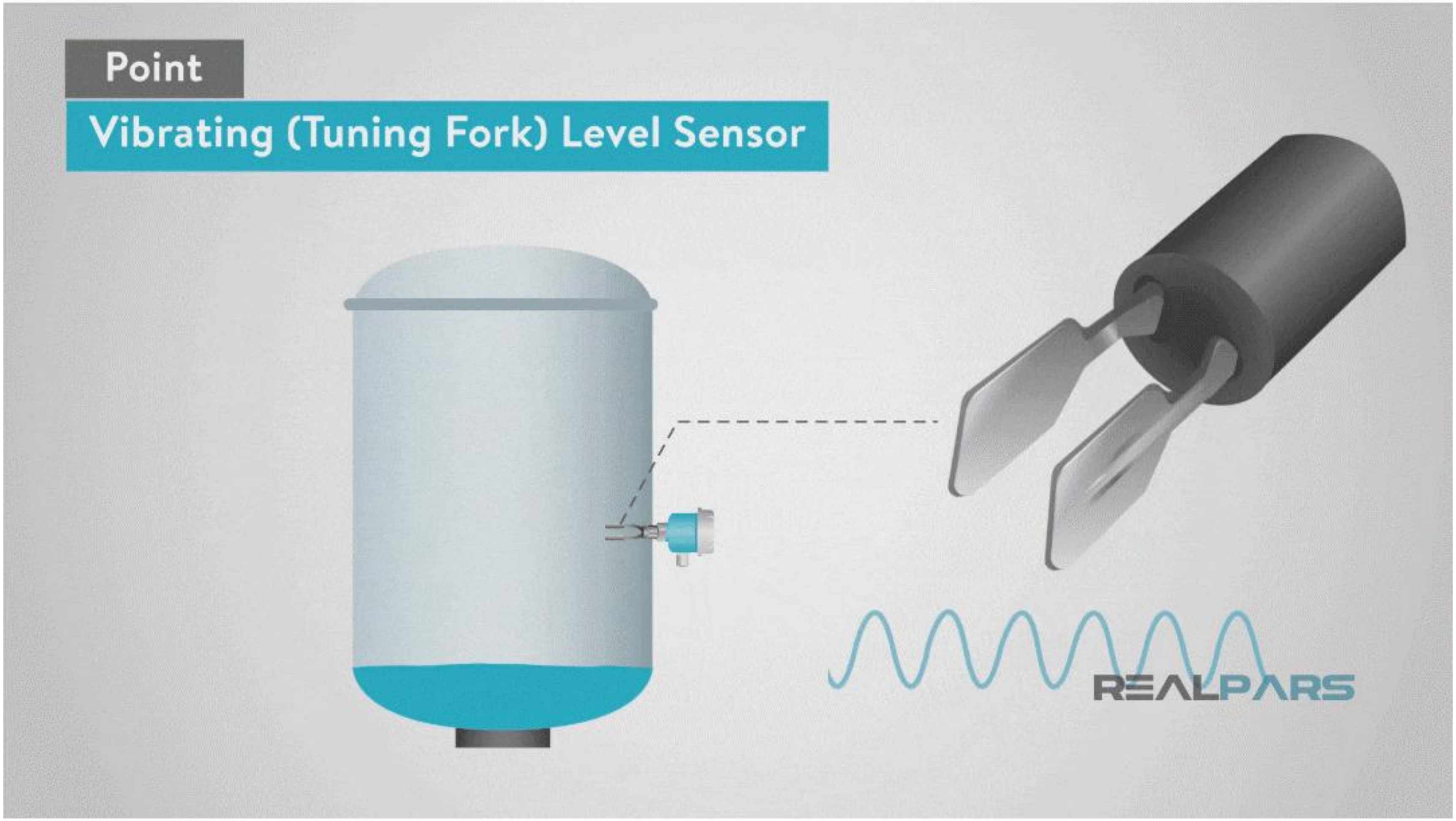
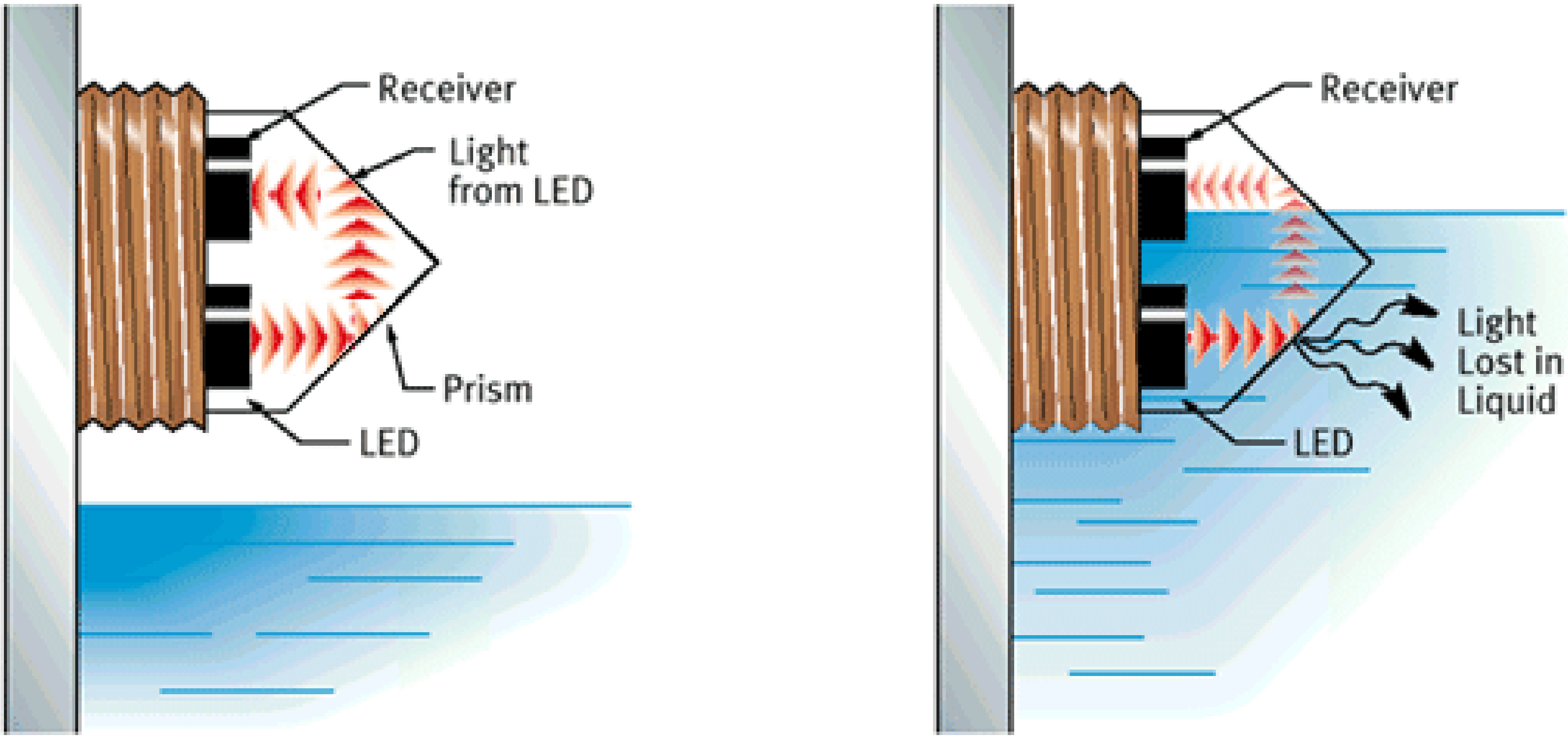


Illustration …

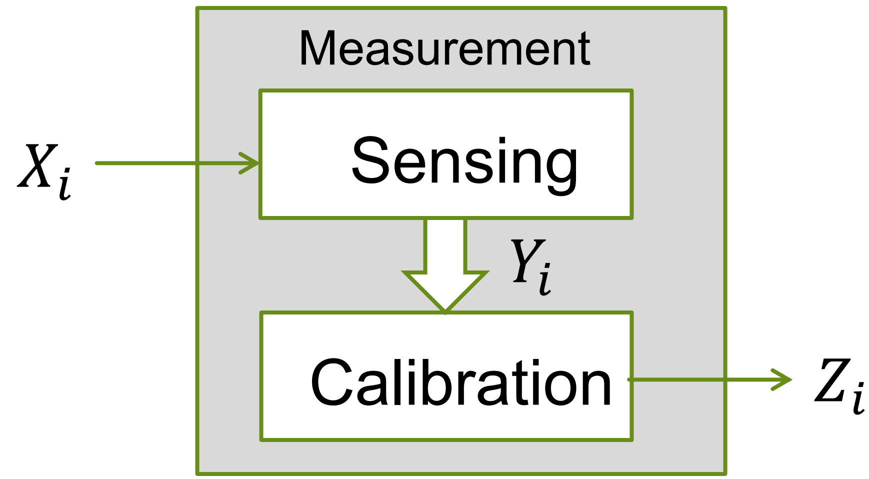


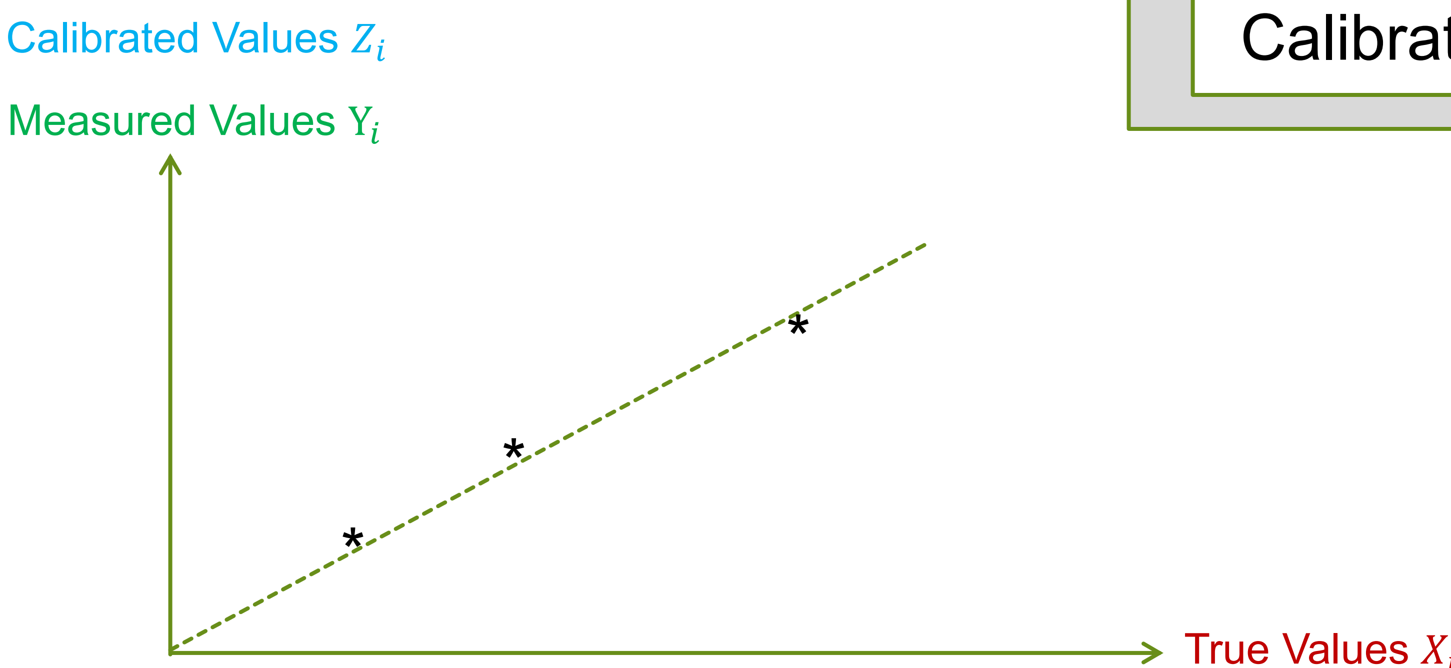
One more example …



Remember to Do Calibration

- Curve fitting for calibration:
  - Yi is produced by Xi
  - Zi is computed from Yi
  - Zi must be equal to Xi

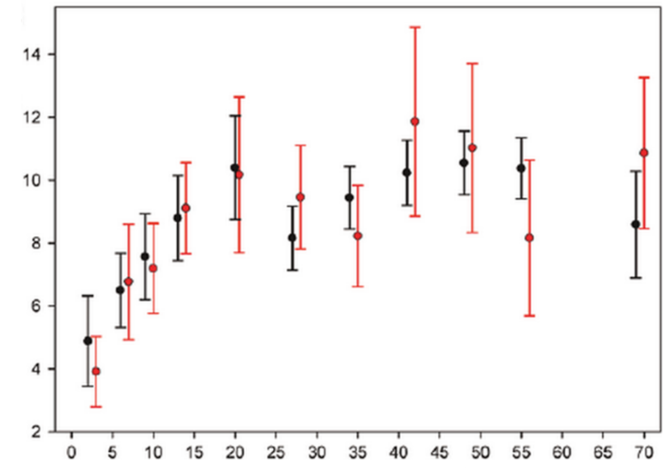


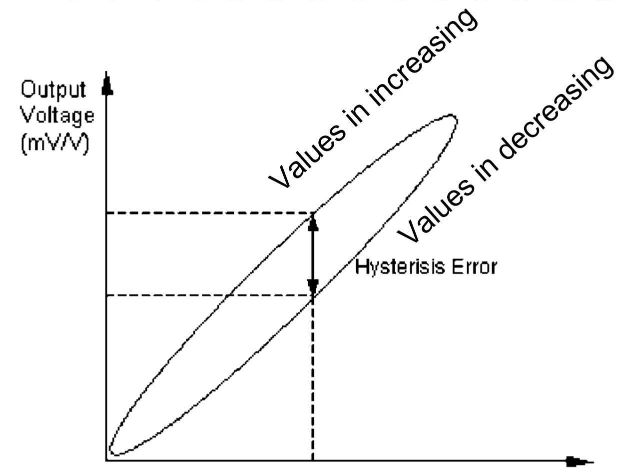


Remember to Do Error Analysis

- Systematic error = mean value – true value
- Repeatability error = value with maximum error – mean value
- Accuracy = value with minimum error – mean value
- Hysteresis error = |measured value in increasing – measured value in decreasing|

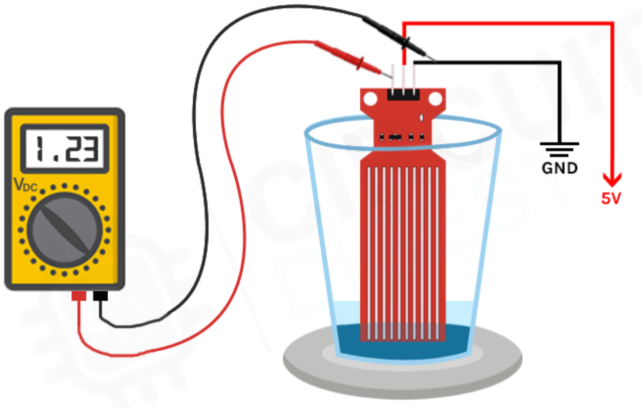
For each true value, we can do error analysis

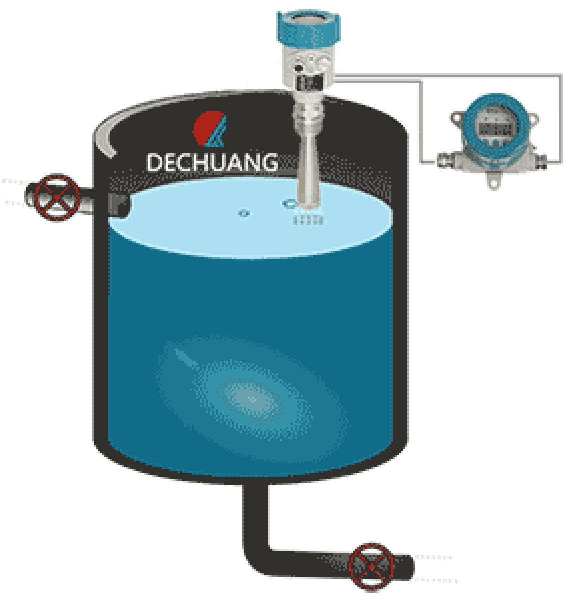


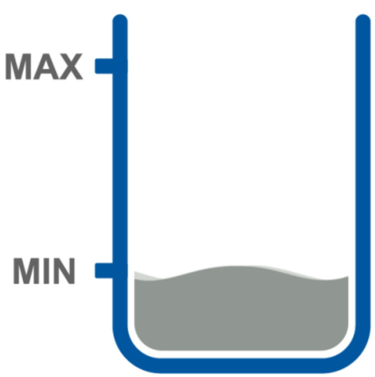


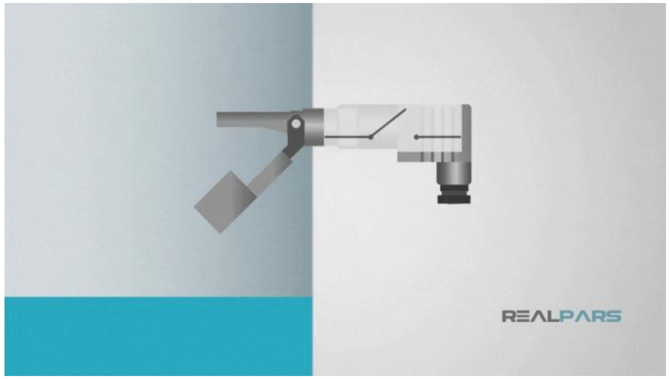
Summary

- Understanding of Fluid Level
- Computation of Fluid Level
- Measurement of Fluid Level



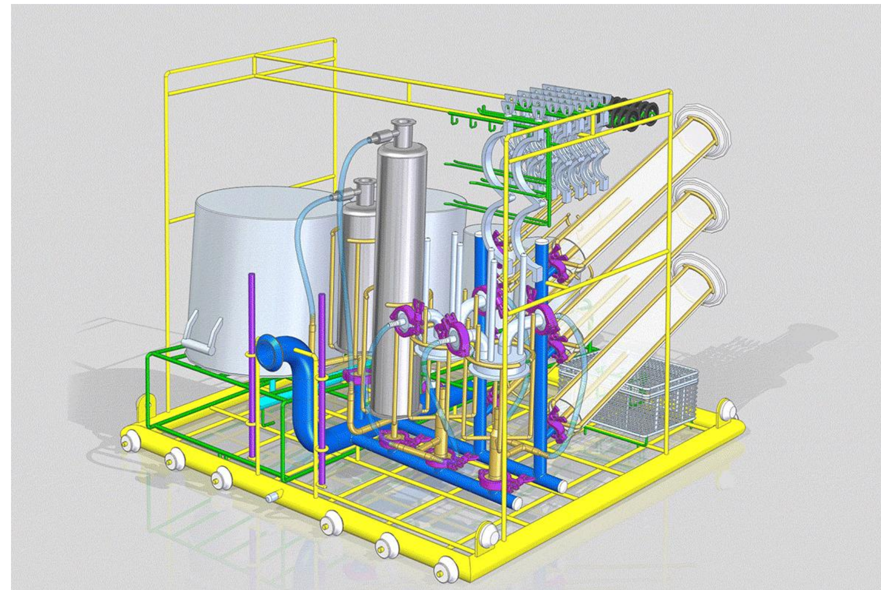






Outline of Module 5

- Lecture 1:
  - Measurement of Fluid Level
- Lecture 2:
  - Measurement of Flow Rate
- Lecture 3:
  - Measurement of Sound/Voice
- Lecture 4:
  - Measurement of Photometry
- Lecture 5:
  - Measurement of Geometry



Module 5 Lecture 2

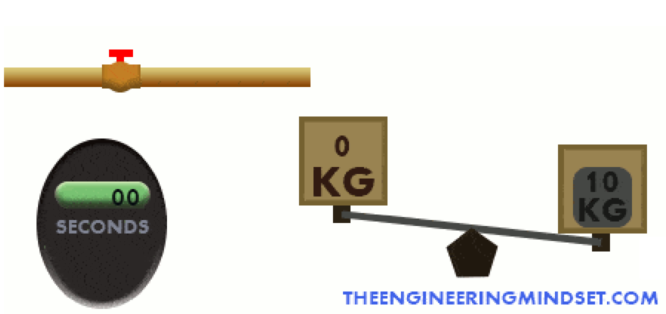
MA4822

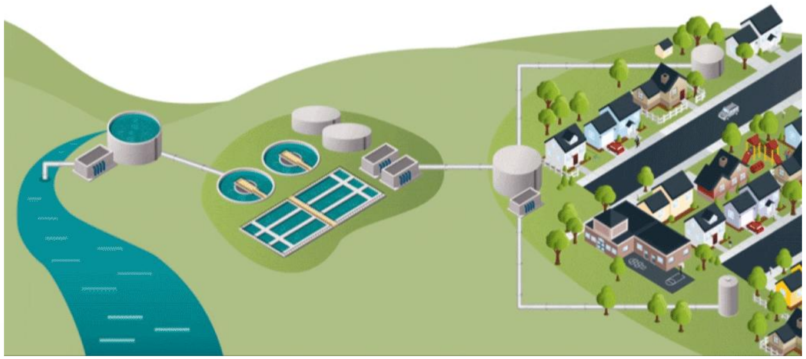
Measurement of Flow Rate

Xie Ming, PhD (France)
mmxie@ntu.edu.sg
http://personal.ntu.edu.sg/mmxie

Outline

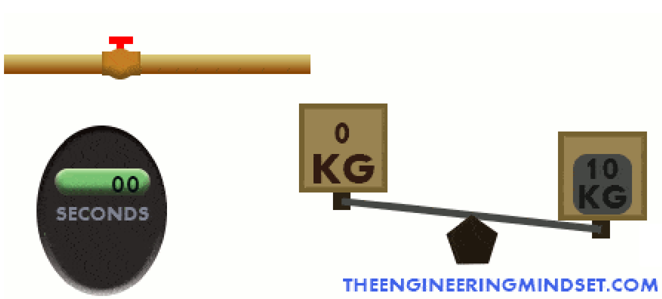
- Understanding of Flow Rate
- Computation of Flow Rate
- Measurement of Flow Rate

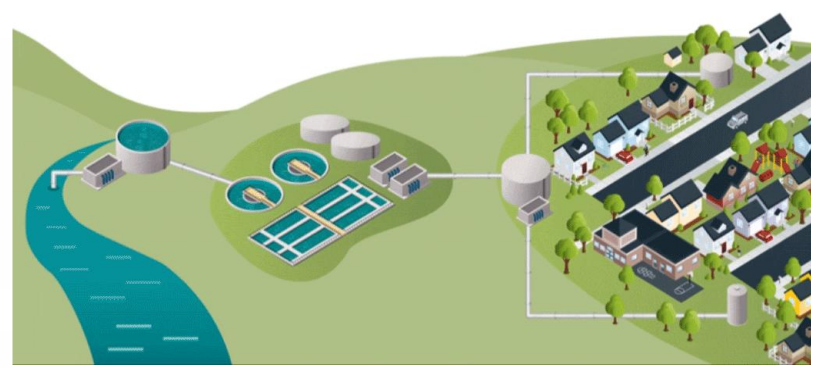




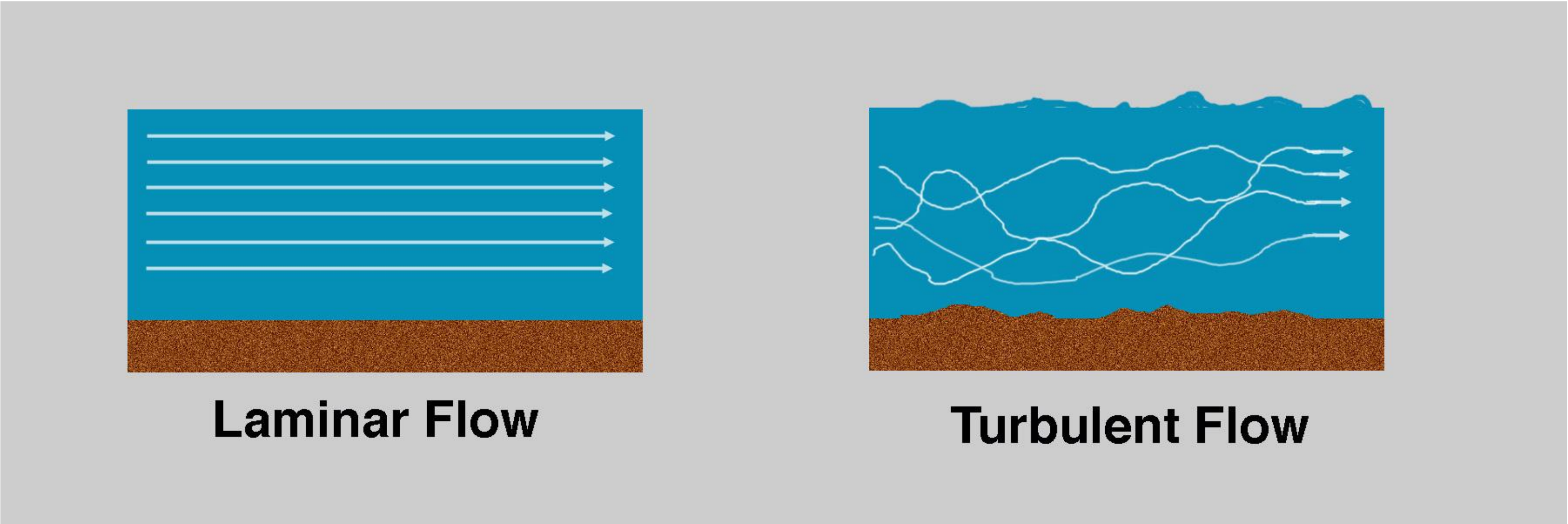
Outline

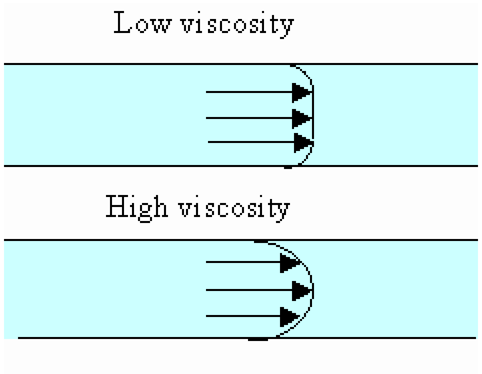
- Understanding of Flow Rate
- Computation of Flow Rate
- Measurement of Flow Rate

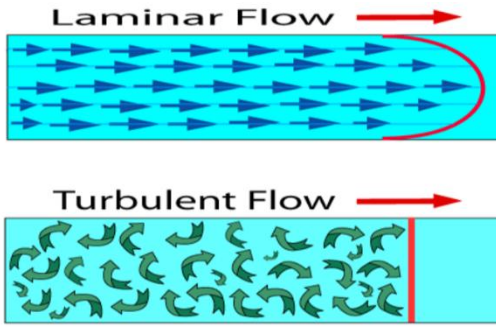




Phenomenon of Fluid's Flow

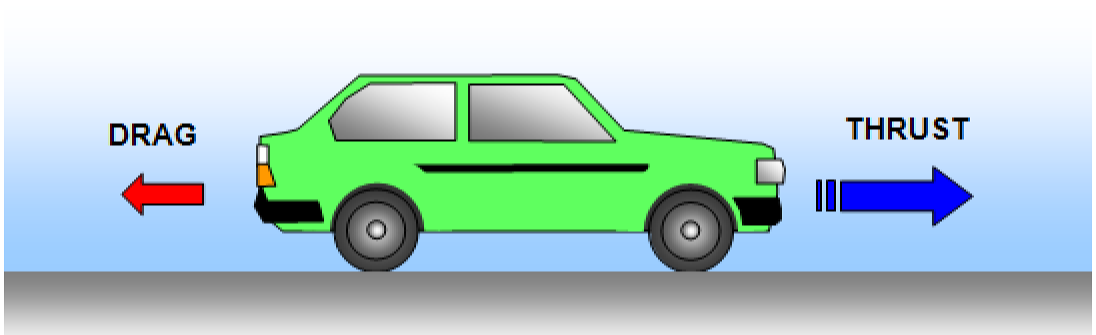




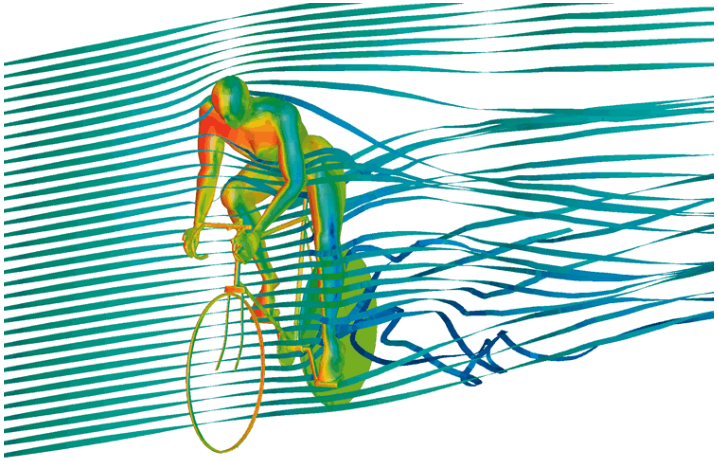


Phenomenon of Drag Force in Flow

$$F_D = \frac{1}{2} C_D \rho A v^2$$

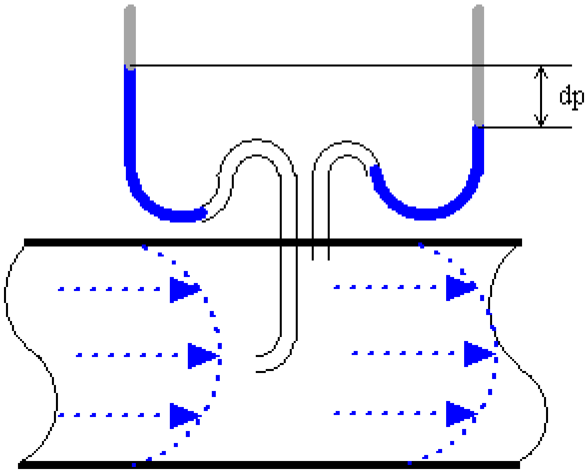


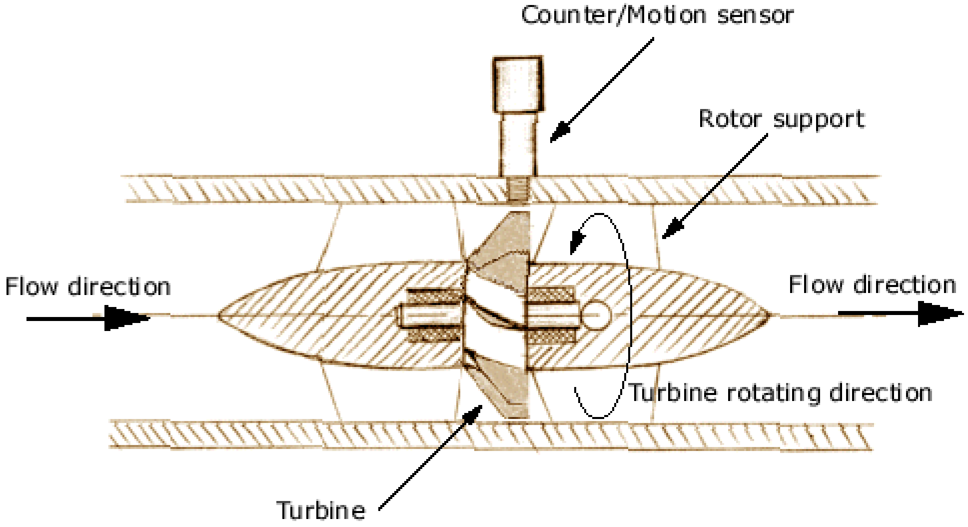
Flow of Substance in Gas State



Phenomenon of Drag Pressure in Flow

$$P_D = \frac{F_D}{A} = \frac{1}{2} C_D \rho v^2$$



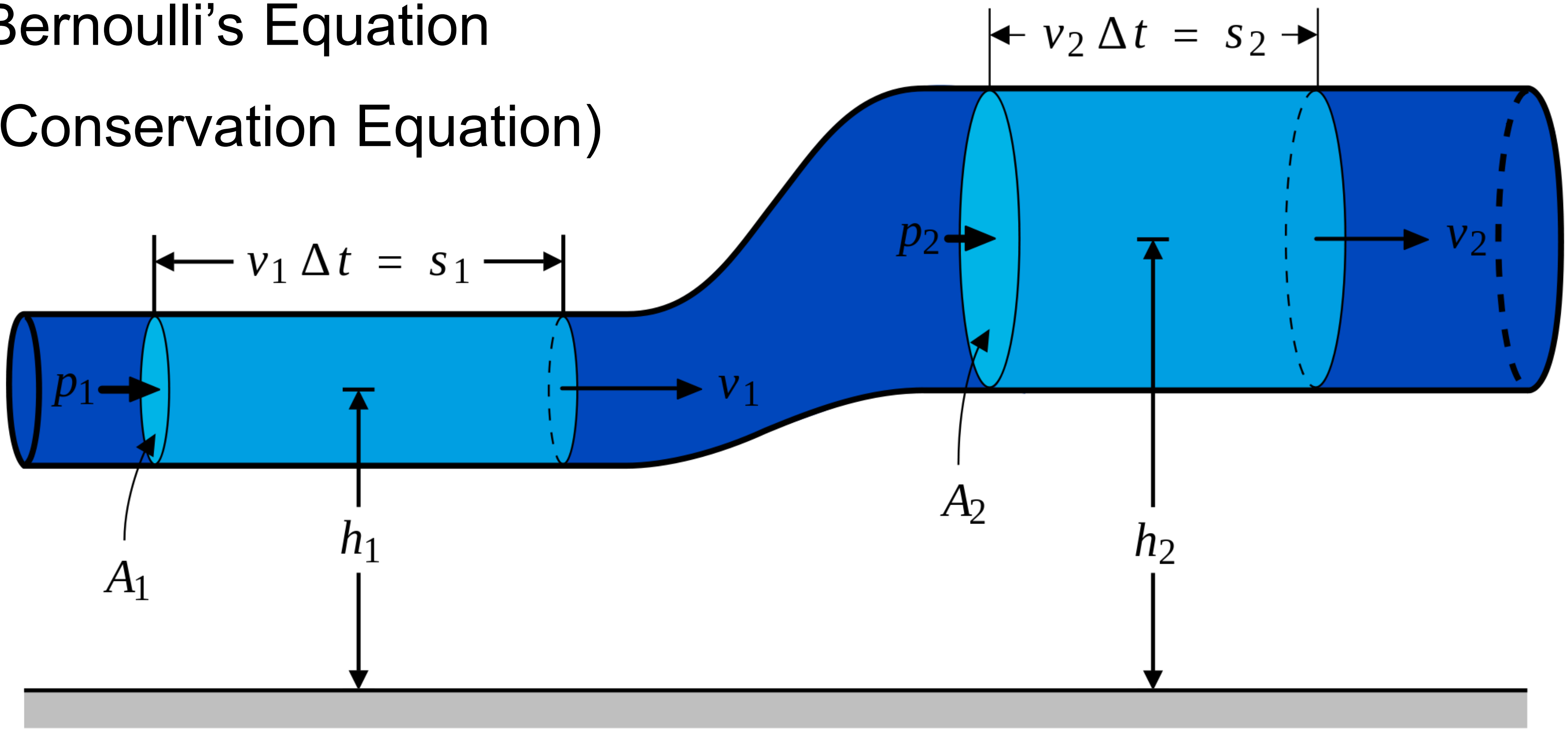


Flow of Substance in Liquid State

Phenomenon of Continuity in Flow

Bernoulli's Equation

(Conservation Equation)

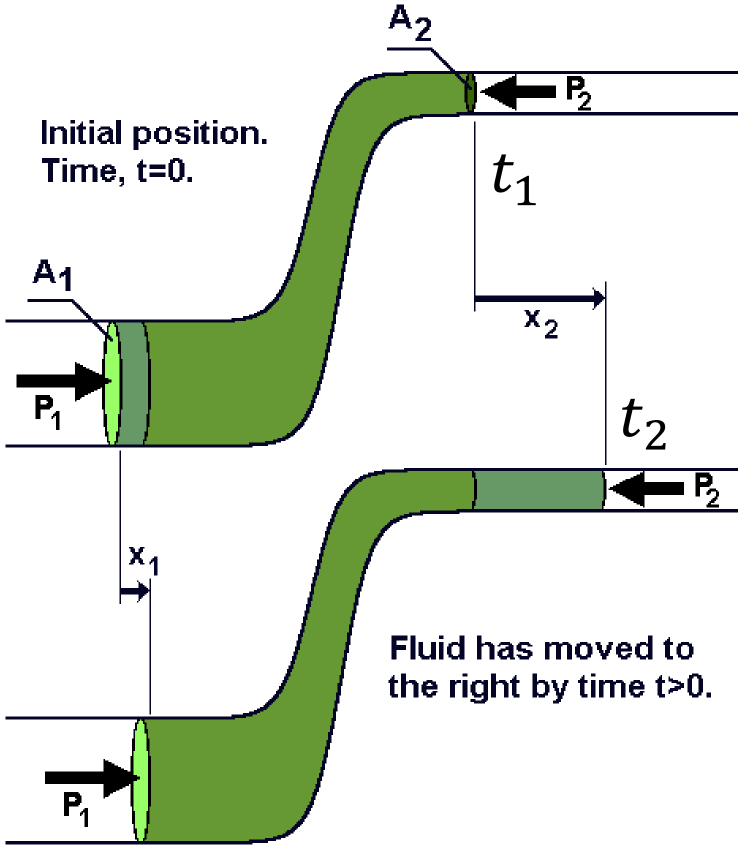


$$P + \rho hg + \frac{1}{2}\rho v^2 = \text{Constant}$$

Definition of Volumetric Flowrate

- It refers to the displacement of fluid's volume per unit of time.

$$Q = \frac{A \times D}{t} = Av$$



$$v = \frac{D}{t}$$

Fluid Velocity

Definition of Mass Flowrate

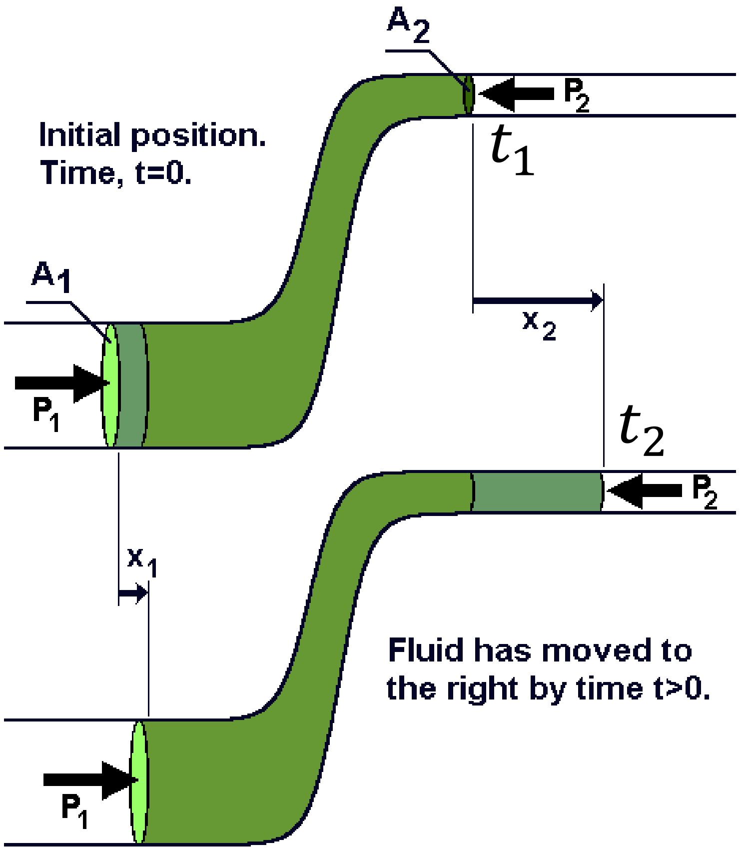
- It refers to the displacement of fluid's mass per unit of time.

$$\dot{m} = \frac{dm}{dt} = \frac{\rho A \times D}{t} = \rho A v$$

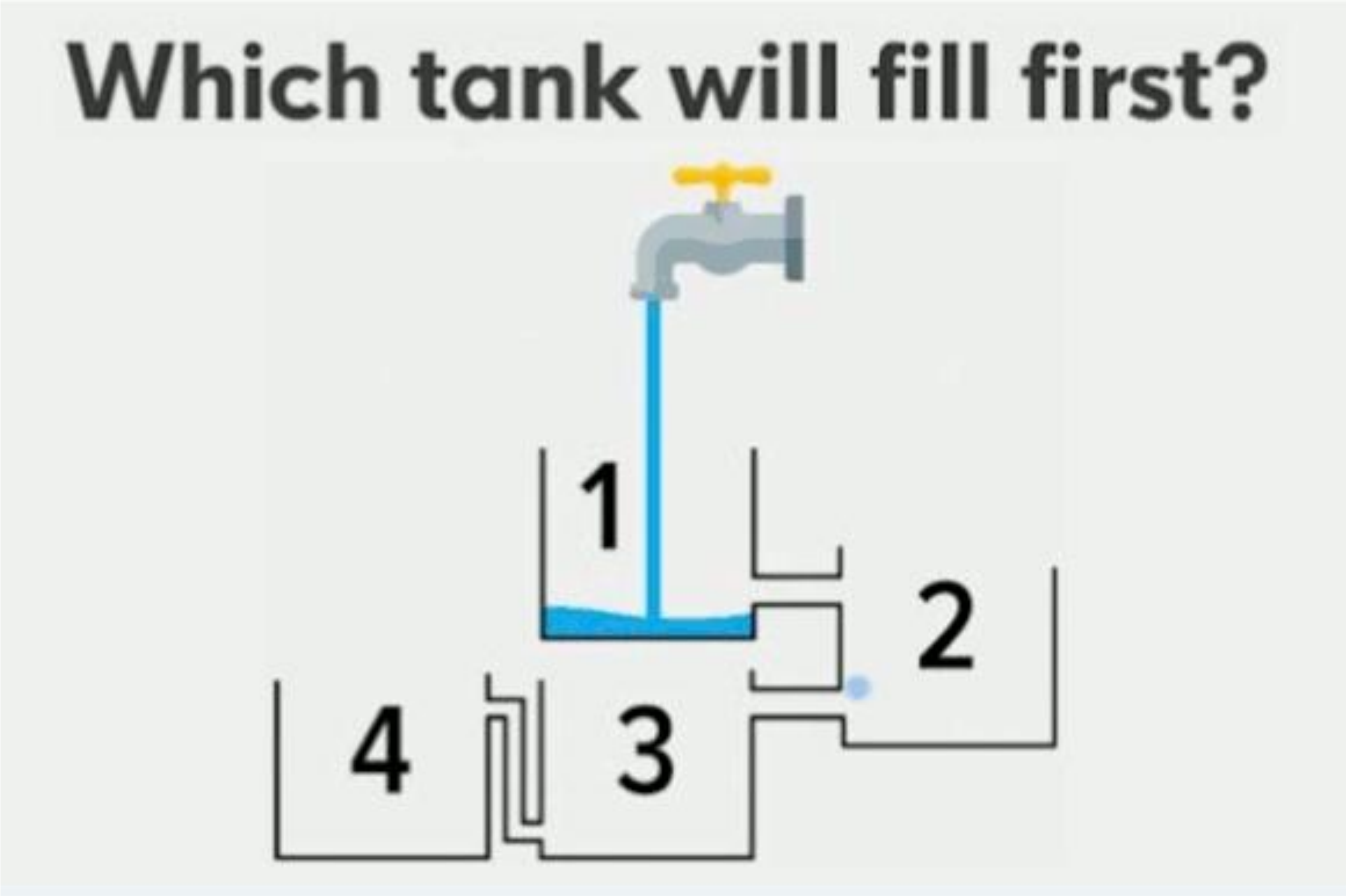
mass = density x volume

$$v = \frac{D}{t}$$

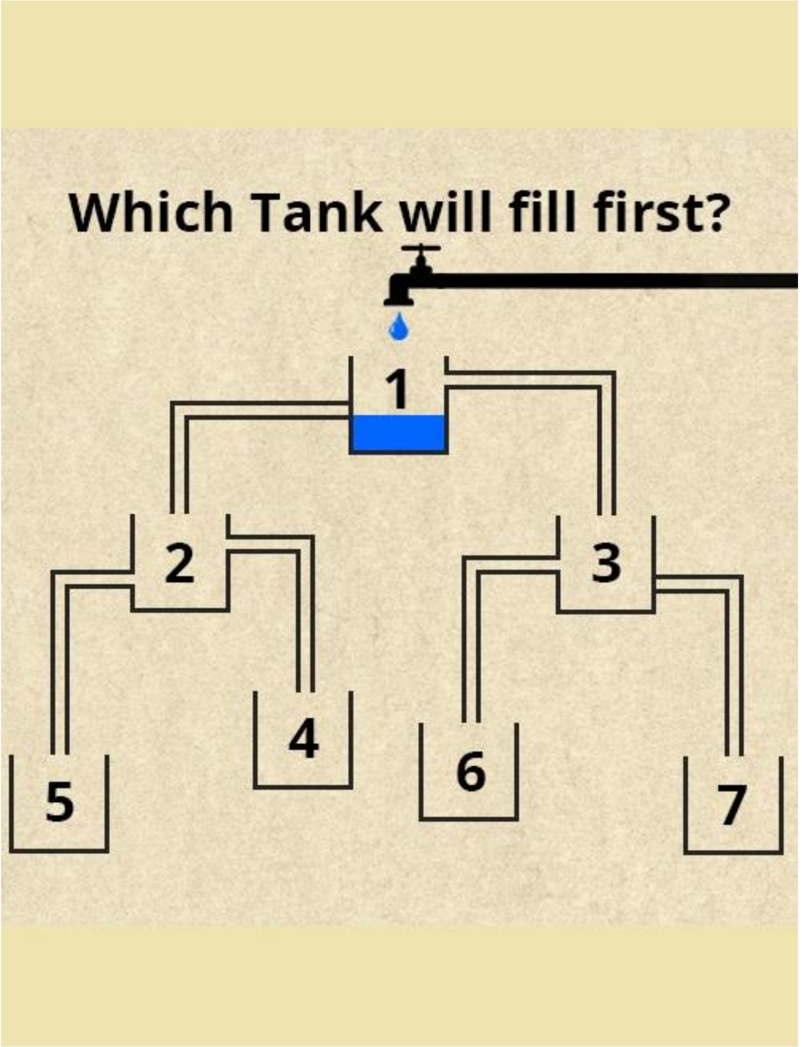
Fluid Velocity

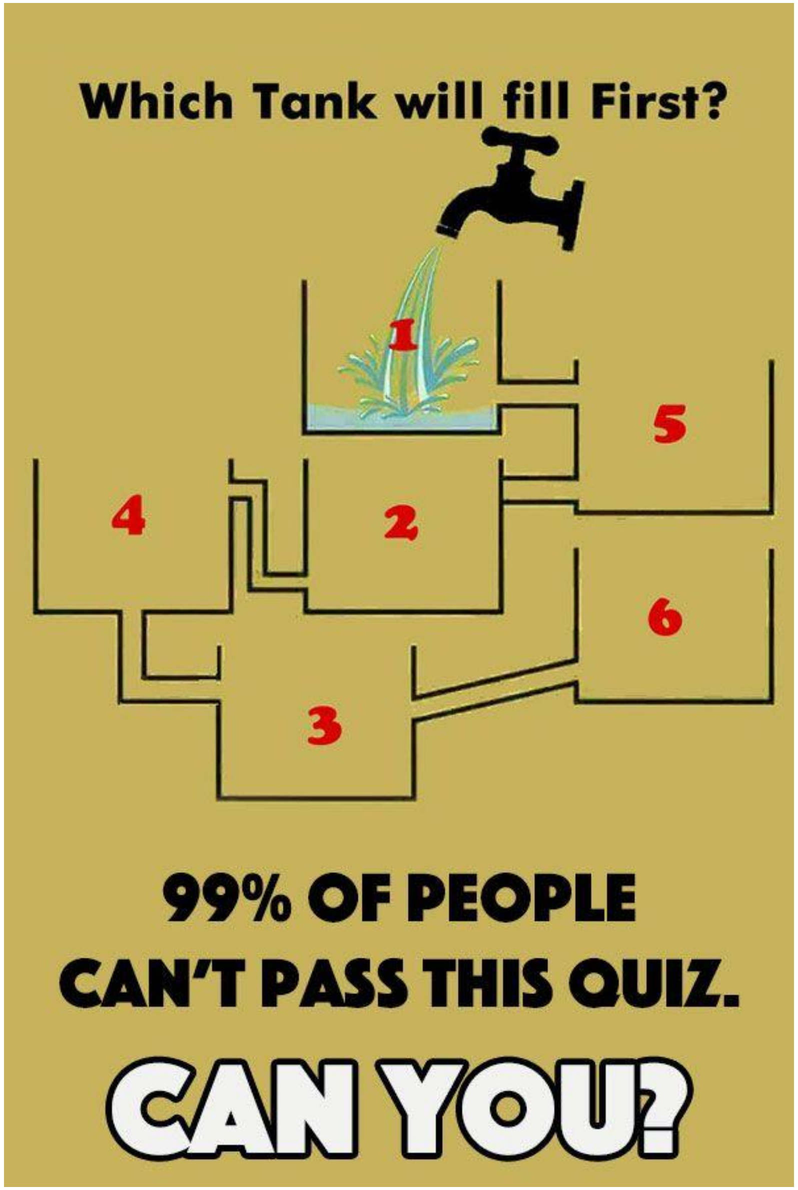


Exercise



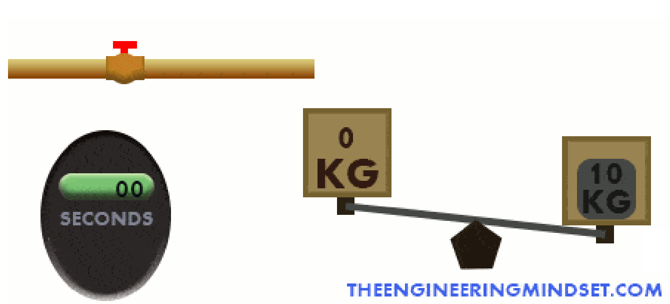
Exercise

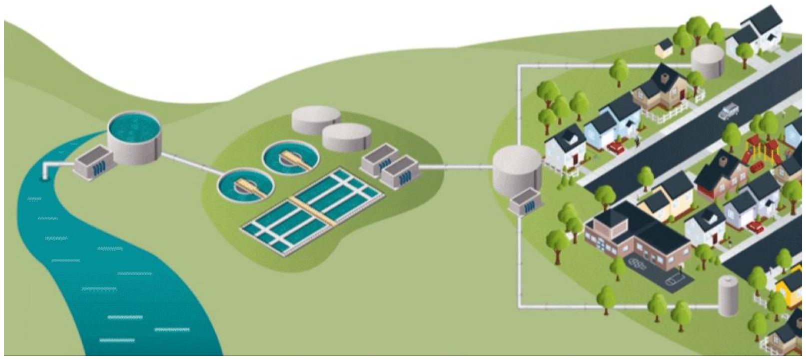

Which Tank will fill first?
1
2
3
4
5
6
7


Which Tank will fill First?
1
2
3
4
5
6
99% OF PEOPLE
CAN'T PASS THIS QUIZ.
CAN YOU?

Outline

- Understanding of Flow Rate
- Computation of Flow Rate
- Measurement of Flow Rate



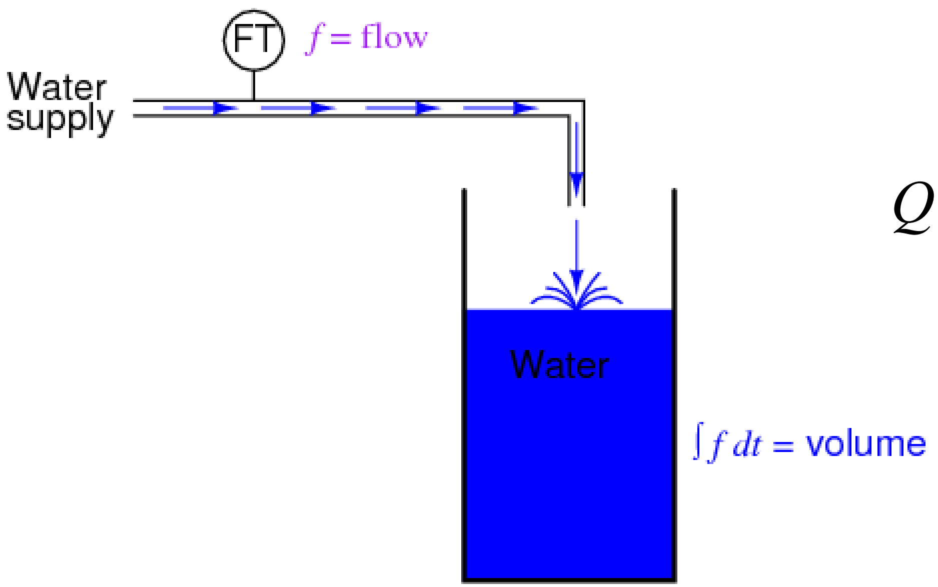


Example

- As shown in the figure, the tank's section area is 15.0 m^2. If the water level increases 10.0 cm per minute, what is the volumetric flowrate of the inlet pipe?
- Answer:

Change of volume

$$Q = \frac{\Delta V}{\Delta t}$$



$$Q = \frac{A\Delta h}{\Delta t} = \frac{15.0 \times 0.1}{60.0} = 0.025\,\mathrm{m}^3/s$$

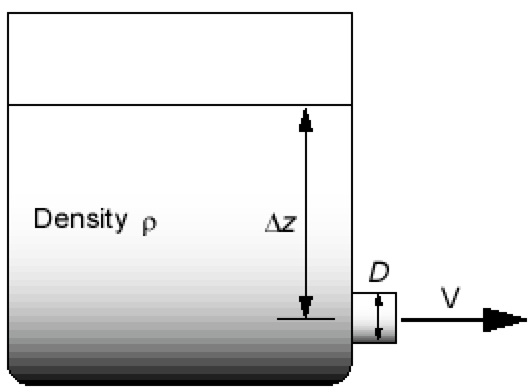
Example

- As shown in the figure, the density of water is 1000 kg/m^3. Δz decreases 5mm/s. If the tank's section area is 25.0 m^2, what is the mass flowrate at the exit of the outlet pipe?

Change of mass

- Answer:

$$\dot{m} = \frac{dm}{dt}$$

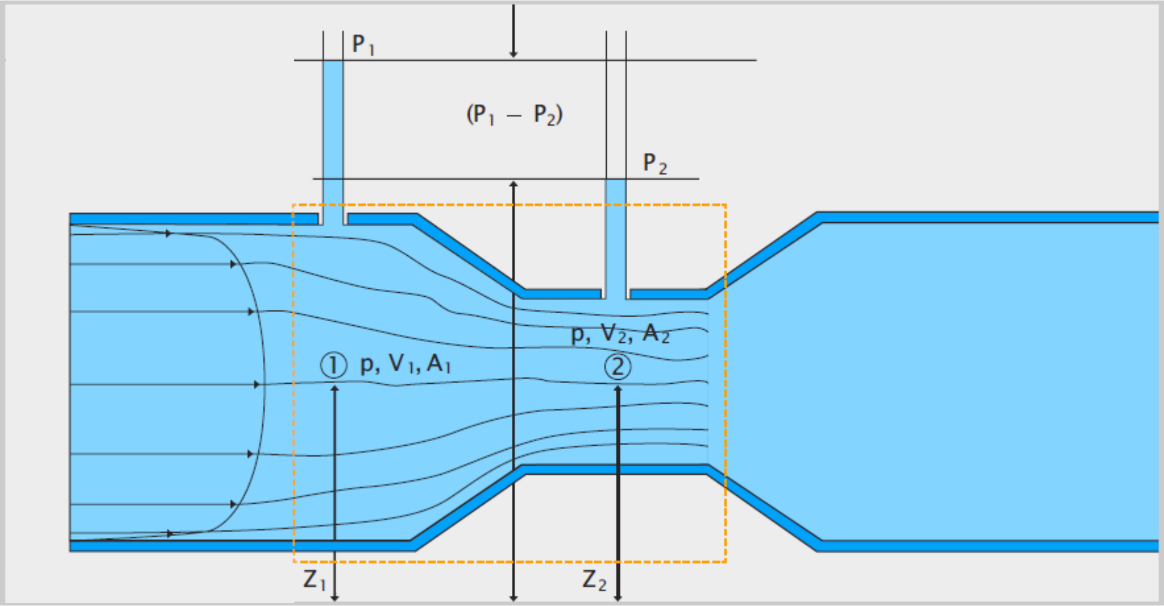


$$\dot{m} = \frac{dm}{dt} = \rho A \frac{dh}{dt}$$

$$\dot{m} = 1000 \times 25 \times 0.005 = 125 \text{ kg/s}$$

Example

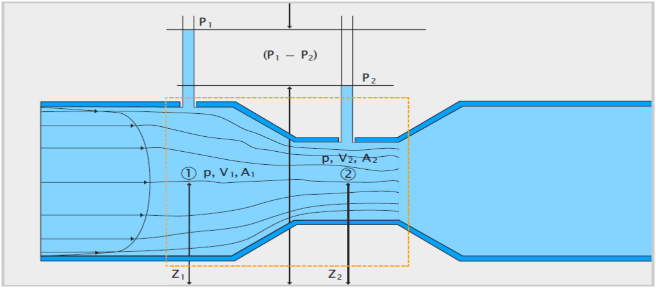
- As shown in the figure, the pressures at points 1 and 2 are P1 and P2, respectively. The section areas at points 1 and 2 are A1 and A2, respectively. What is the volumetric flowrate inside the pipe?



- Answer: (next slide)

Answer

Volumetric Flowrate = Constant



- 1. Application of continuity equation:

$$A_1 v_1 = A_2 v_2 \quad \Rightarrow \quad v_2 = (A_1 / A_2) v_1$$

Fluid Velocity

- 2. Application of Bernoulli Equation:

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2 \quad \rightarrow \quad v_2^2 - v_1^2 = \frac{2(p_1 - p_2)}{\rho}$$

$$v_1 = \sqrt{\frac{2(p_1 - p_2)}{\rho((A_1 / A_2)^2 - 1)}} \quad \rightarrow \quad Q = A_1 v_1 = A_1 A_2 \sqrt{\frac{2(p_1 - p_2)}{\rho(A_1^2 - A_2^2)}}$$

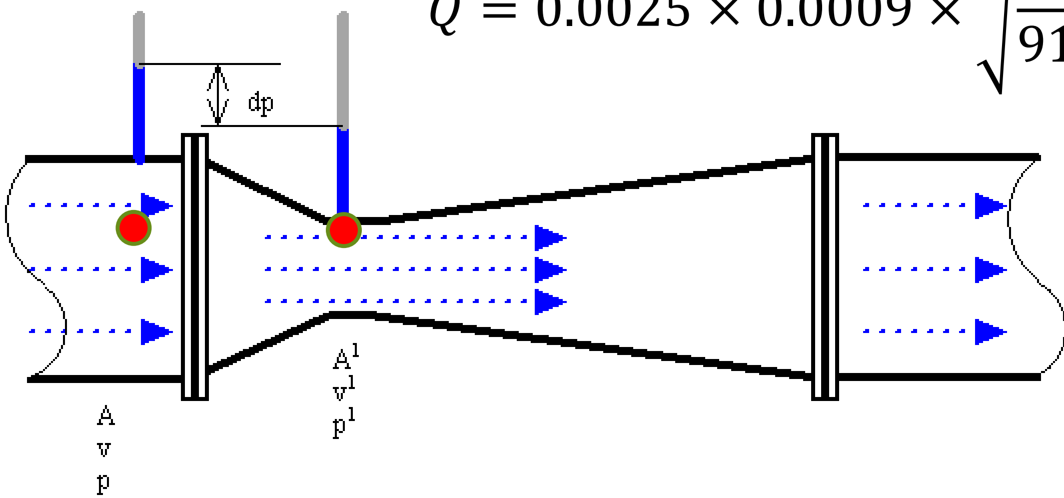
Example

- As shown in the figure, vegetable oil flows inside the pipe. The density of the oil is 910 kg/m³. Assume that the section area A is 25 cm² while the section area A1 is 9 cm². If the pressure difference is 0.1 atm, what is the volumetric flowrate inside the pipe?

- Answer:

$$Q = A_1 v_1 = A_1 A_2 \sqrt{\frac{2(p_1 - p_2)}{\rho(A_1^2 - A_2^2)}}$$

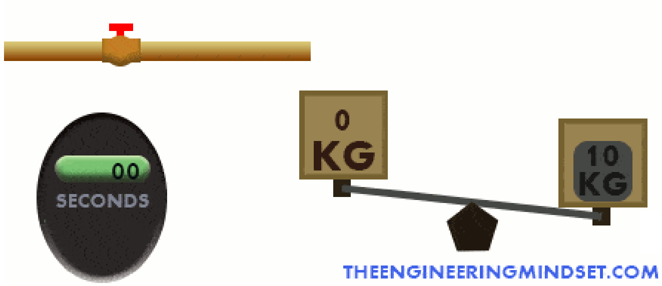
$$Q = 0.0025 \times 0.0009 \times \sqrt{\frac{2 \times 0.1 \times 101325 kg/m.s^2}{910 \times (0.0025^2 - 0.0009^2)}}$$



$$Q = 0.00455 \text{ m}^3/\text{s}$$

Outline

- Understanding of Flow Rate
- Computation of Flow Rate
- Measurement of Flow Rate

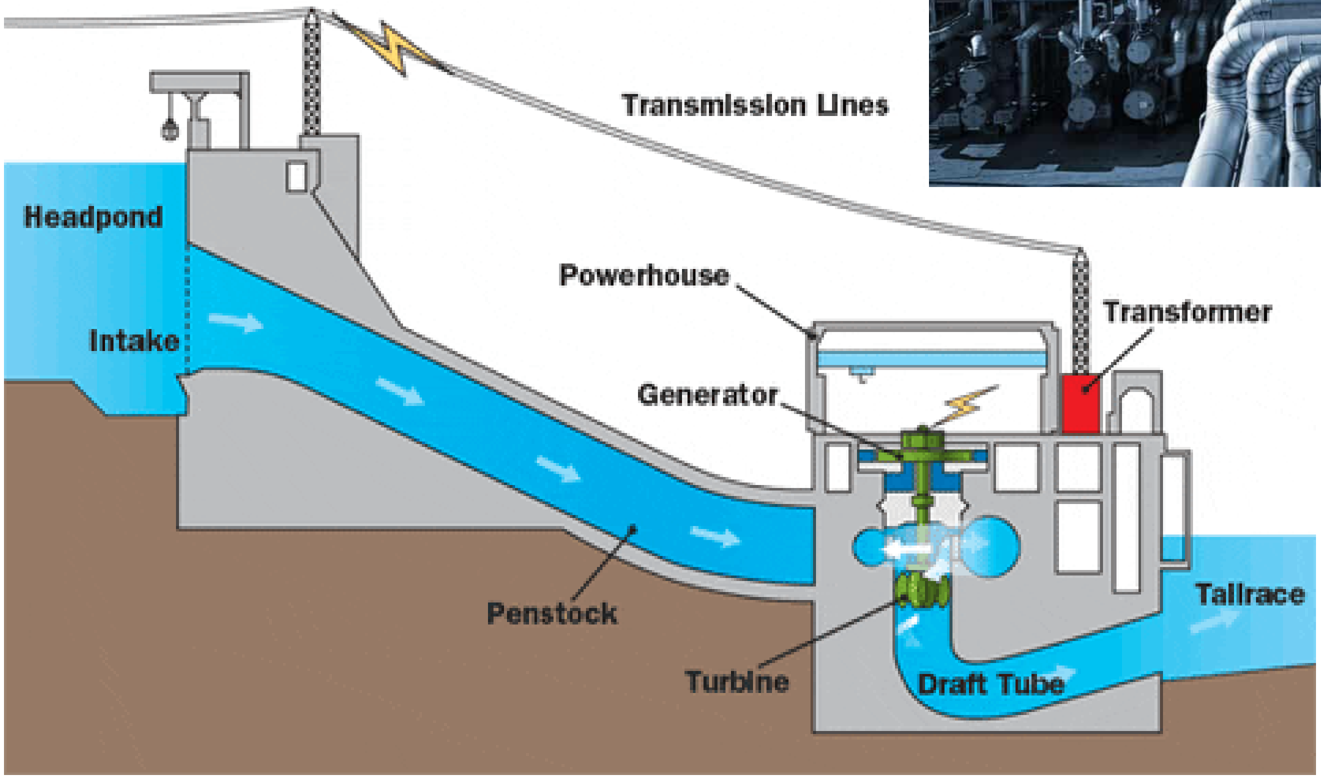


Is fluid's flow rate important?

- Without flow rate, there will be no supply systems of fluids.

Applications of Fluid Supply Systems in Industry

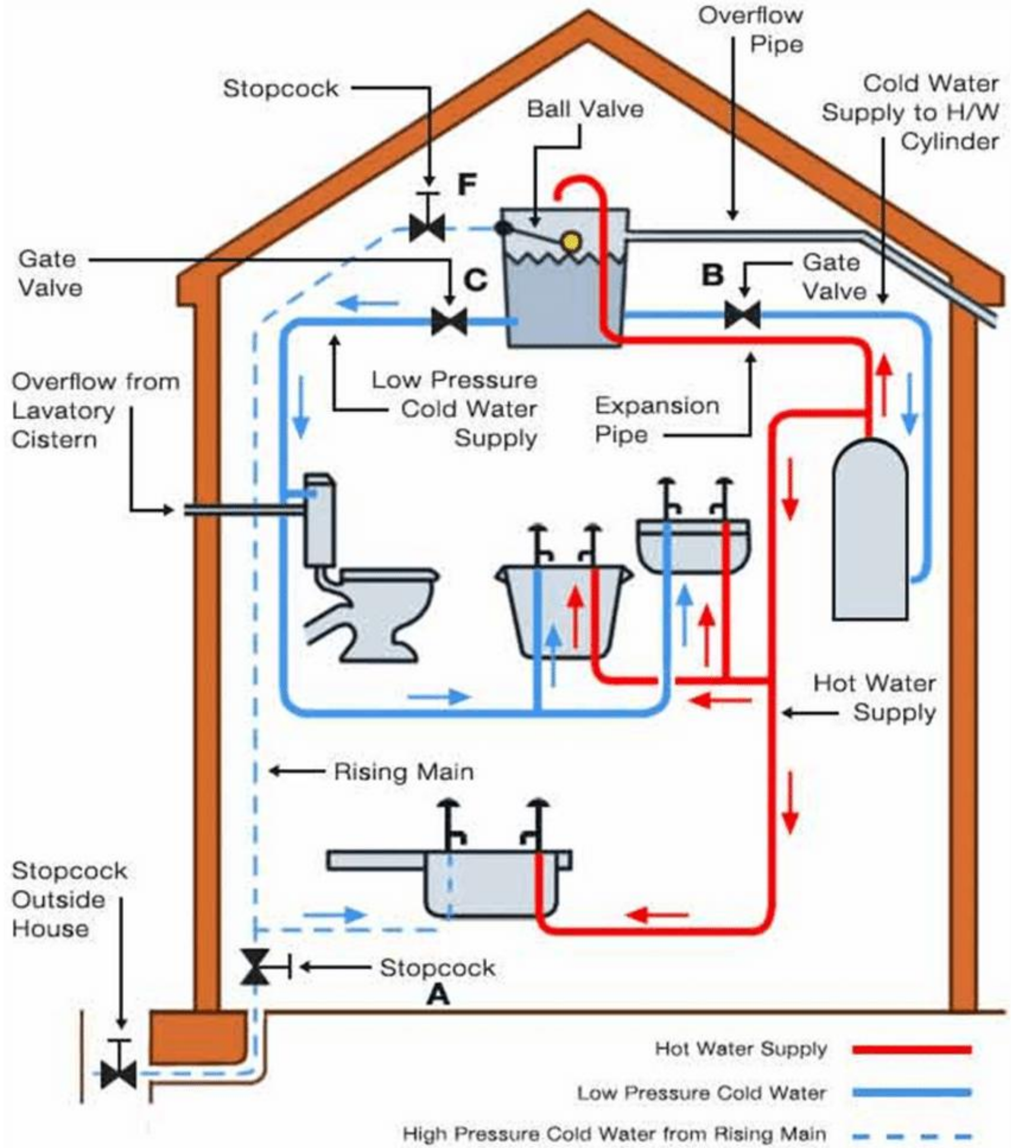
Chemical Plant



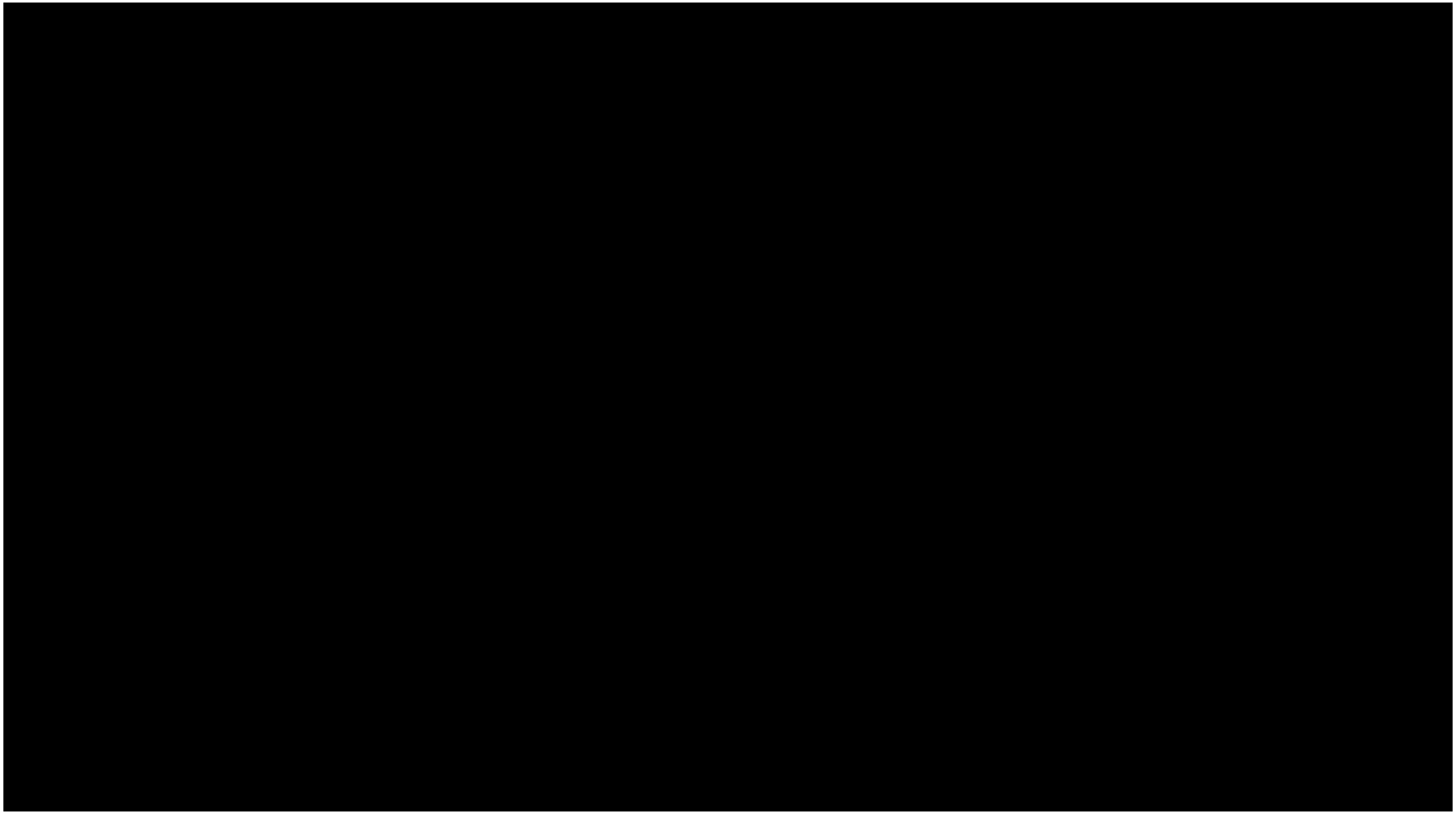
Hydro Power Plant

Applications of Water Supply Systems in Home

- Water Storage
- Water Distribution



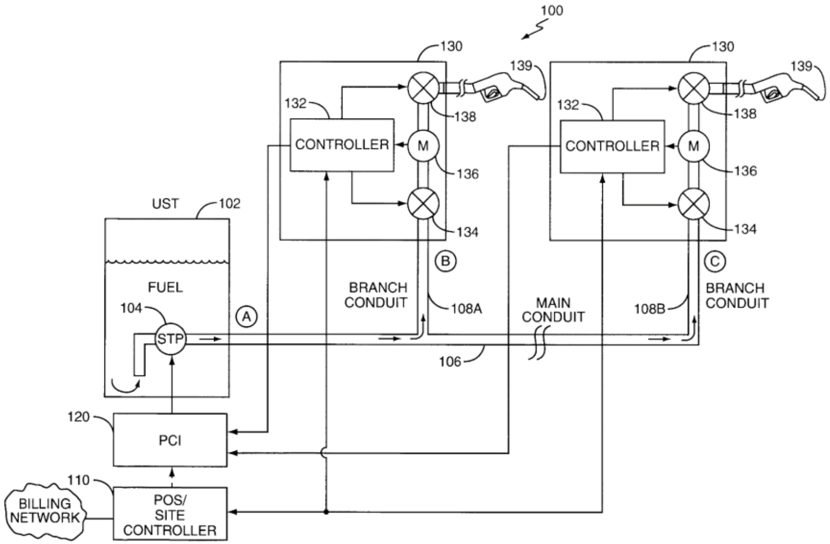
Example of Water Supply Systems to Homes …

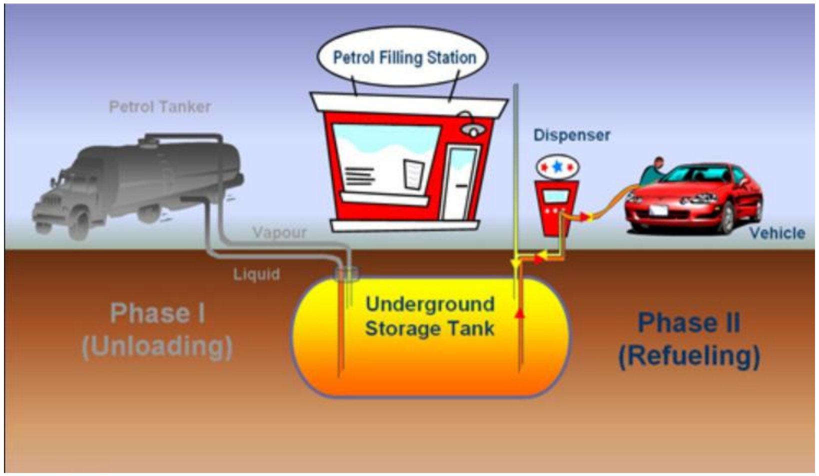


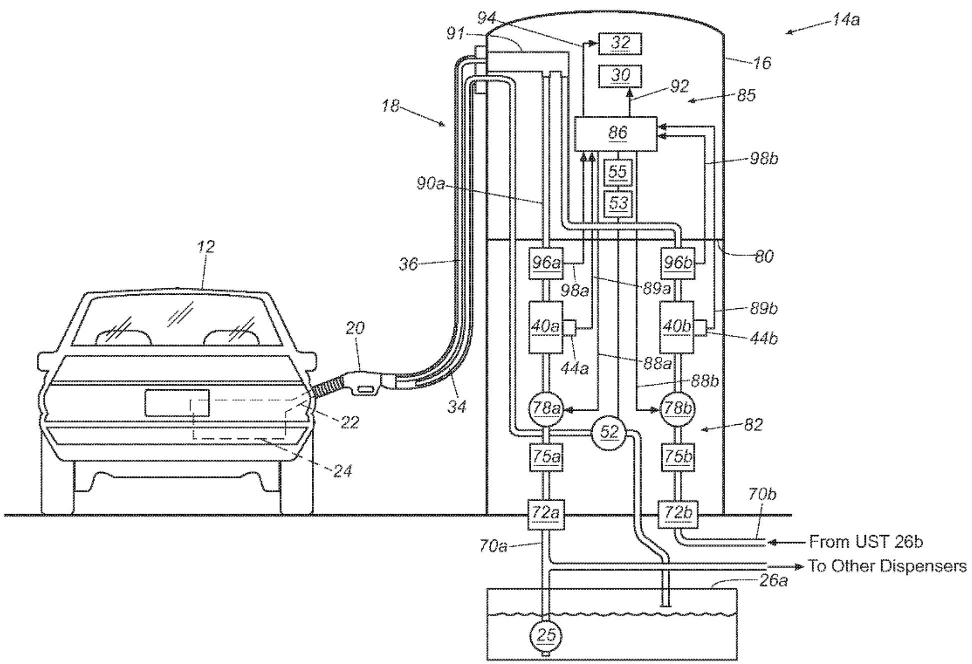
When there is a supply of fluid, we need to monitor or charge the consumption?

- The consumption of fluids could be charged by the amounts of volumes.
- The consumption of fluid could also be charged by the amounts of masses.

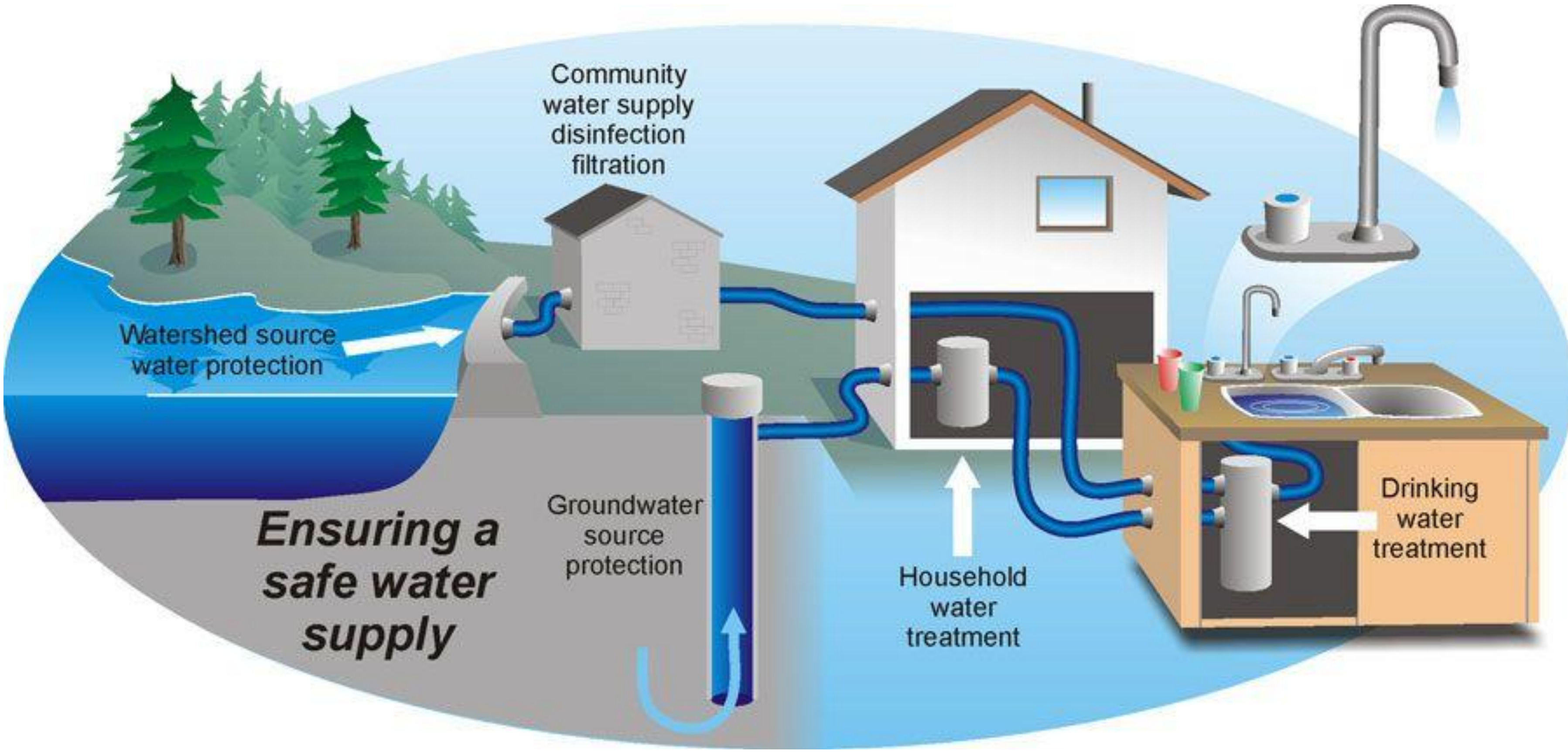
Example of Measuring Flowrates in Petrol Stations …





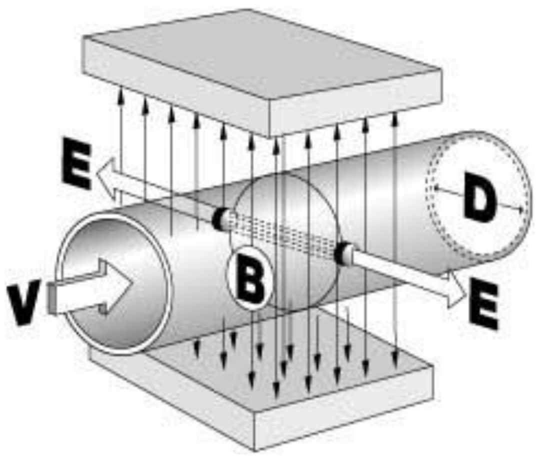


Example of Measuring Water Consumption at Home …

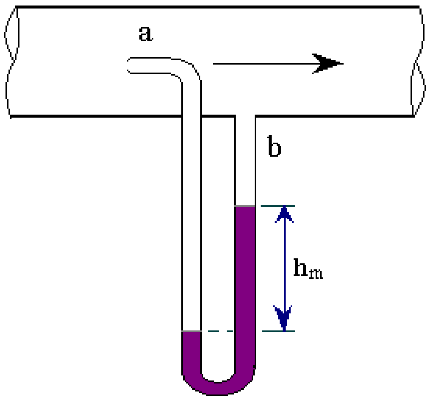


Example of Measuring Flowrates in Rivers …

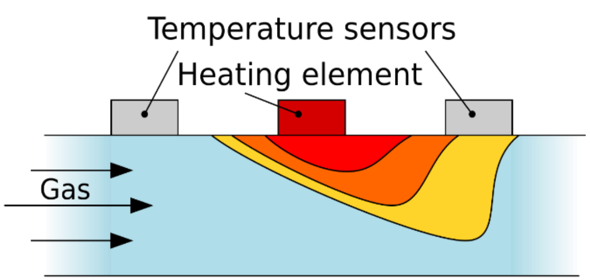
Principles of Measurement



- Principle 1: Fluids are normally electrically conductive. When such fluids flow under magnetic field, electrons could escape and travel toward the direction which is perpendicular to the fluid's flow. The escaped electrons will build up voltage which can be measured.



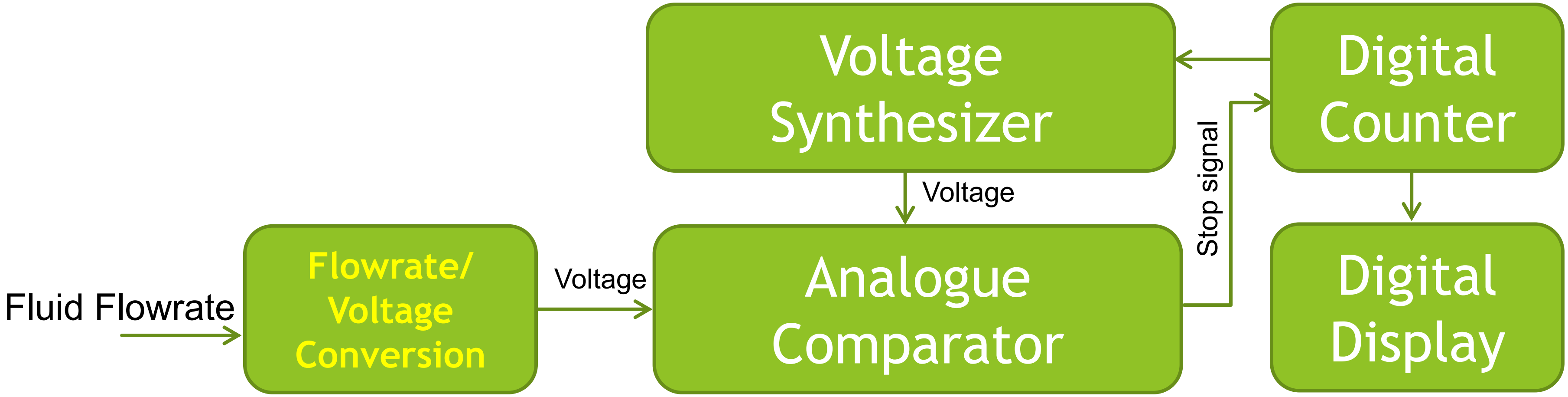
- Principle 2: The difference of fluid velocities inside a pipe will cause the pressure difference, which can be measured.



- Principle 3: Heat could be injected into a pipe. The profile of temperature distribution inside the pipe is a function of flowrate. The values of temperature help to determine the flowrate inside the pipe.

How to apply principle 1 to design digital measurement and sensing systems for fluid flowrate?

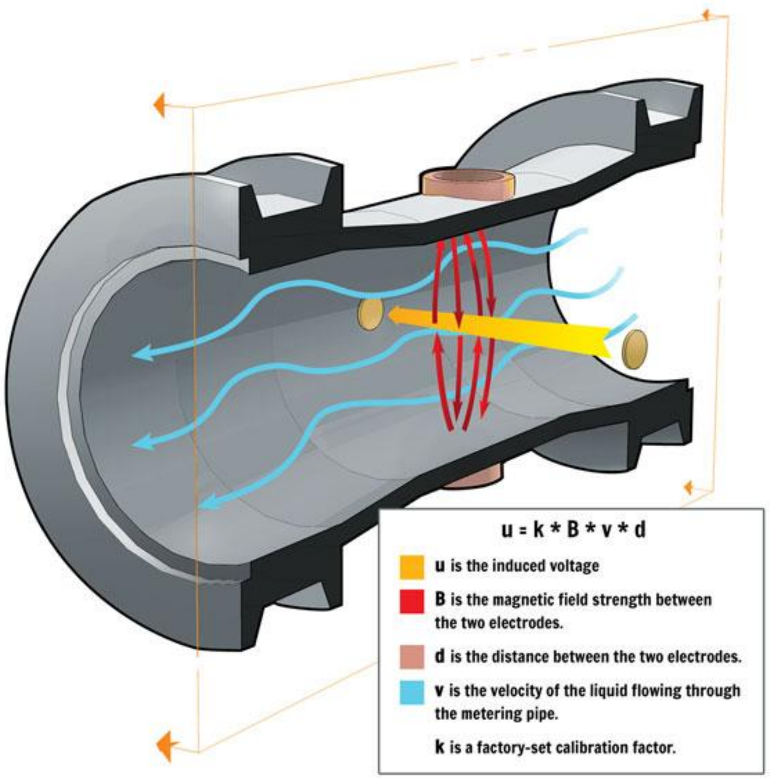
- Fluid flowrate is converted to voltage which is measured by digital voltmeter (e.g. microcontrollers).



All microcontrollers are programmable digital sensors of voltage!

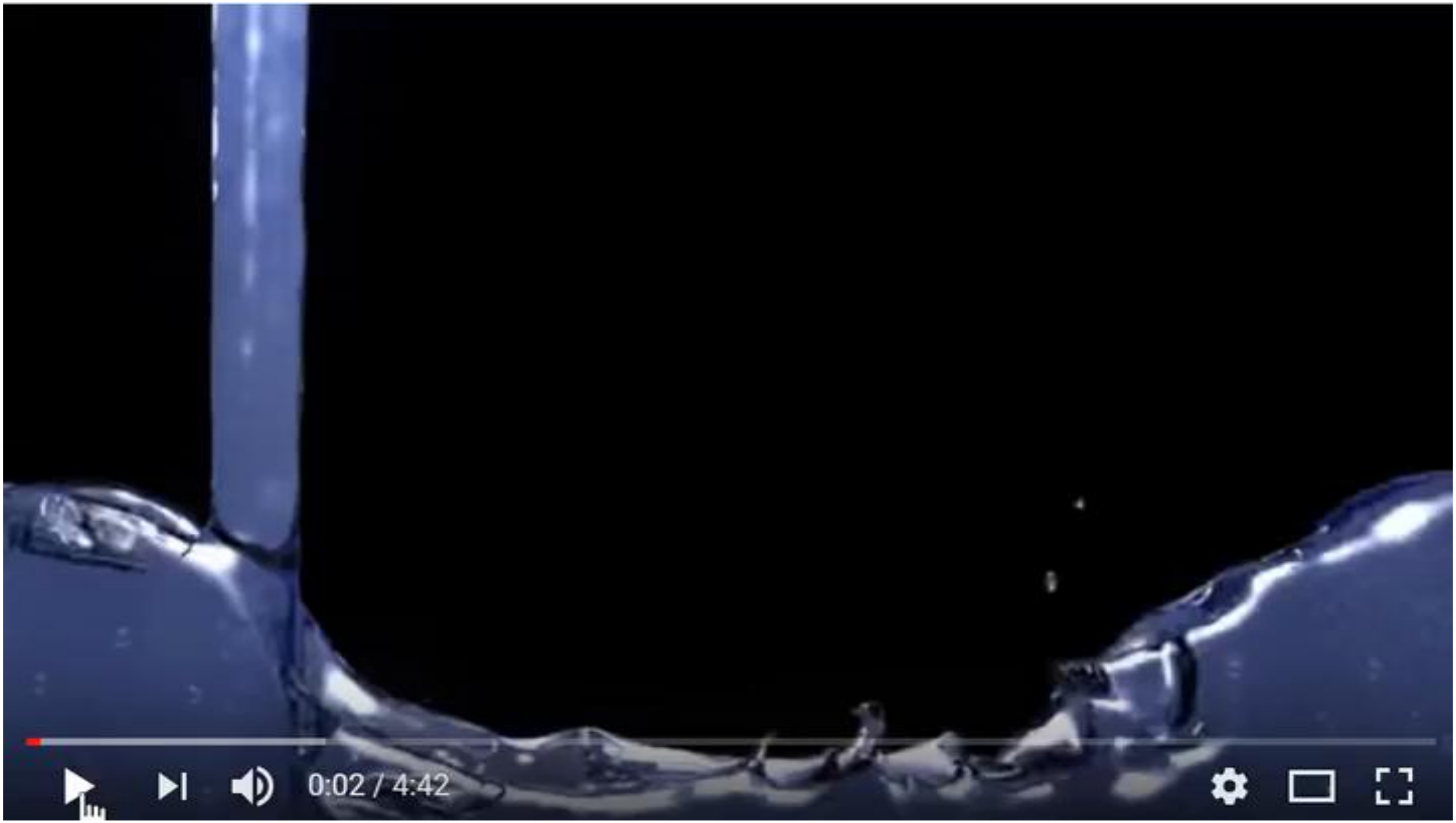
How to convert flowrate into voltage?

- A magnetic field is perpendicularly applied to a pipe.
- When an electrically-conductive fluid flows, magnetic force will be act on the electrons of the electrically-conductive fluid.
- Magnetic force will push electrons to move toward another direction which is perpendicular to both the magnetic field and the flow.
- The voltage built-up by these electrons can be measured.



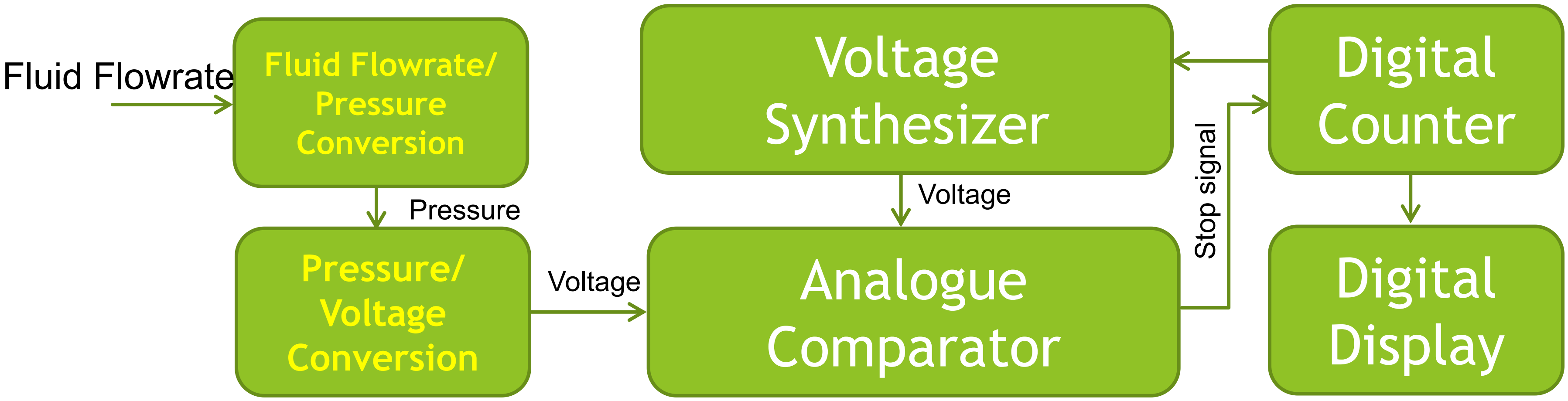
$$u = kdBv$$

How to convert flowrate into voltage?



How to apply principle 2 to design digital measurement and sensing systems for fluid flowrate?

- Fluid is passing through a section of special tube which creates variable pressures along the flow. In this way, fluid flowrate is converted to differential pressure which is then converted to voltage. Finally, the voltage is measured by digital voltmeter (e.g. microcontrollers).

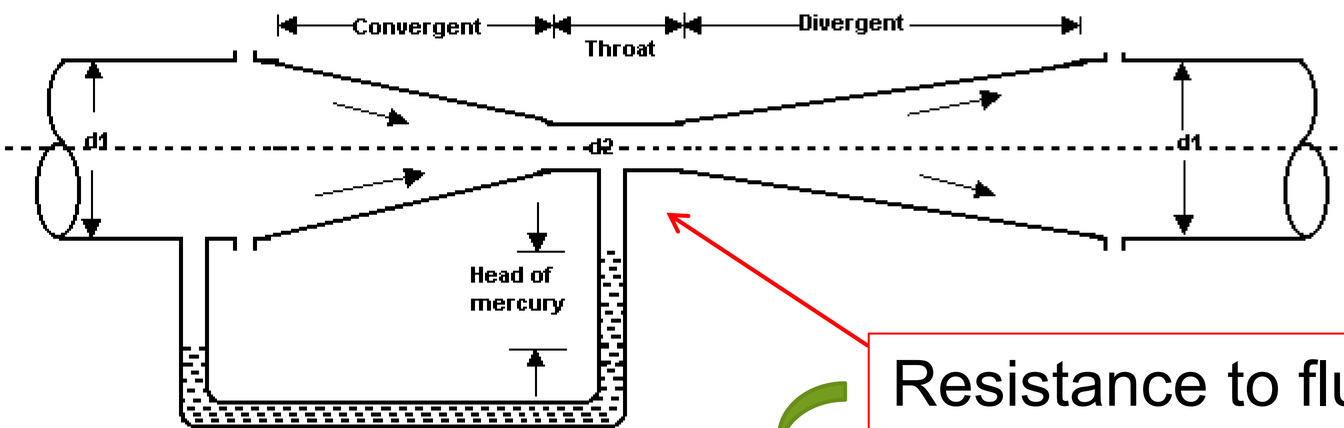


All microcontrollers are programmable digital sensors of voltage!

How to convert flowrate into differential pressure (or pressure drop)?

- A Venturi pipe is added to piping system.
- The throat of the Venturi pipe will cause a pressure difference which could be converted into voltage.

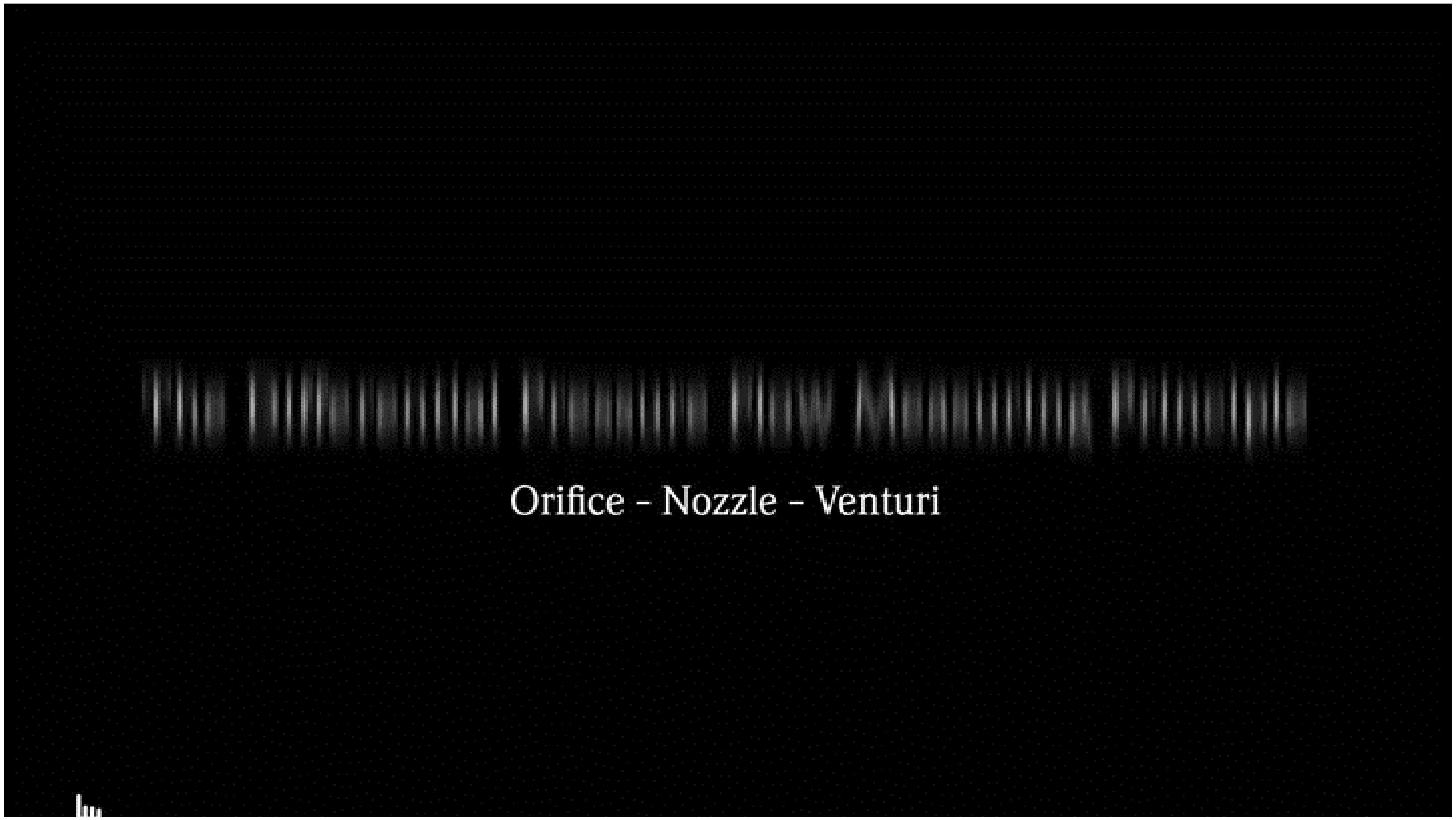
$$Q = A_1 v_1 = A_1 A_2 \sqrt{\frac{2(p_1 - p_2)}{\rho(A_1^2 - A_2^2)}}$$



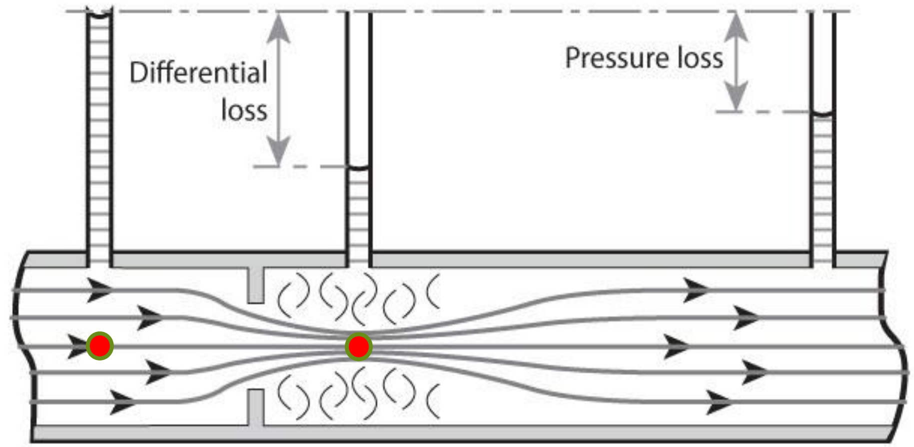
Resistance to fluid’s flow

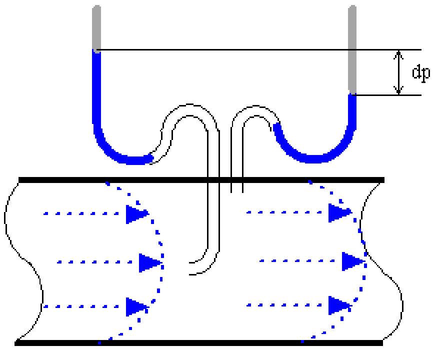
Pressure Drop

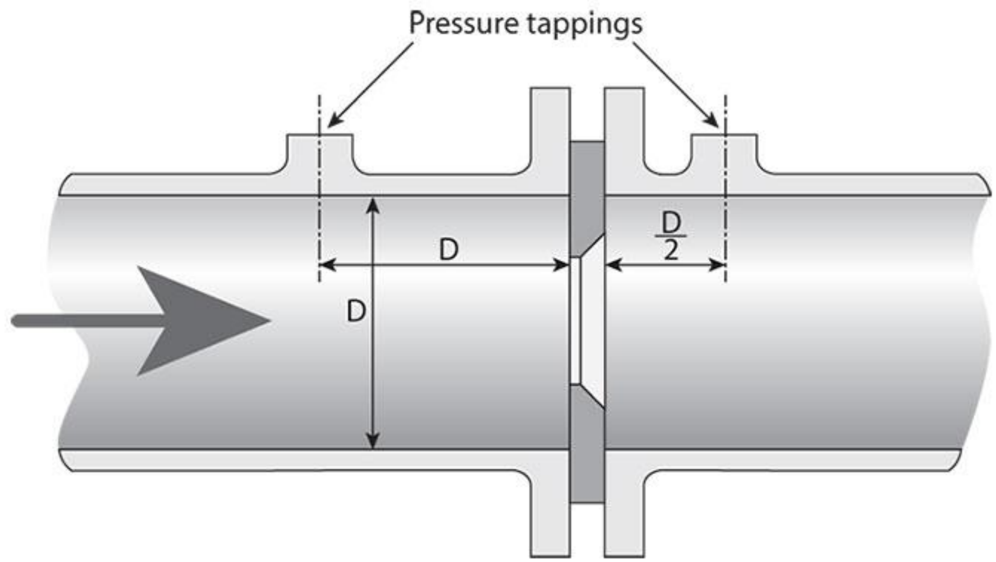
How to convert flowrate into differential pressures (or pressure drop)?

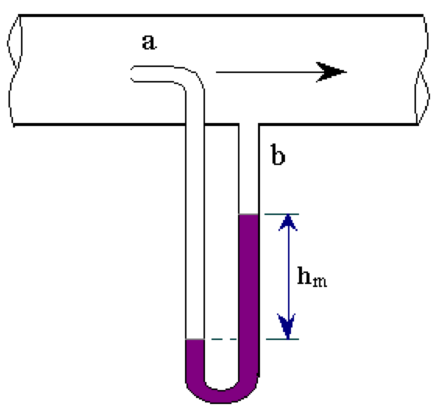


Other solutions for taping differential pressures …



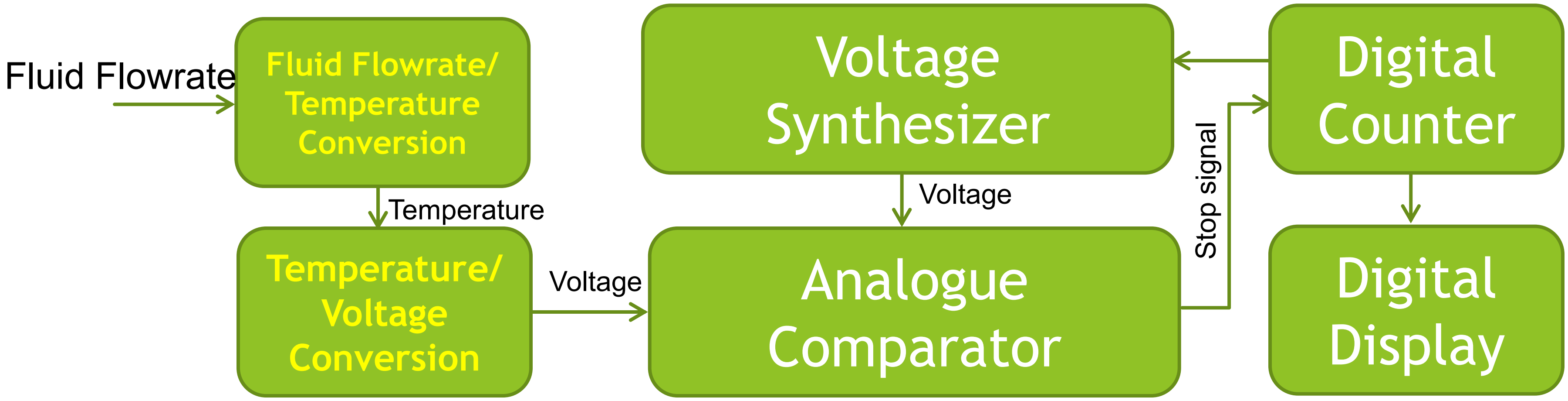






How to apply principle 3 to design digital measurement and sensing systems for fluid flowrate?

- Fluid flowrate is converted to temperature which is then converted to voltage. Finally, the voltage is measured by digital voltmeter (e.g. microcontrollers).

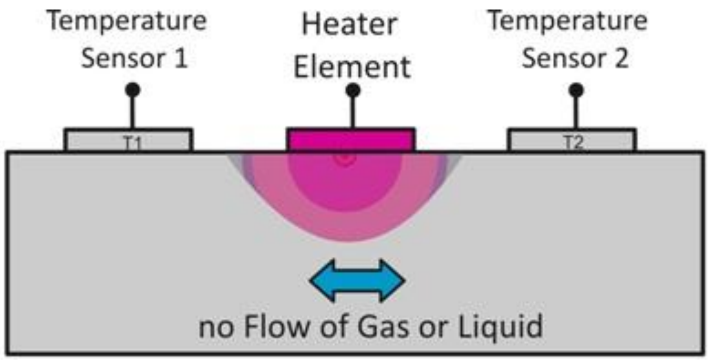


All microcontrollers are programmable digital sensors of voltage!

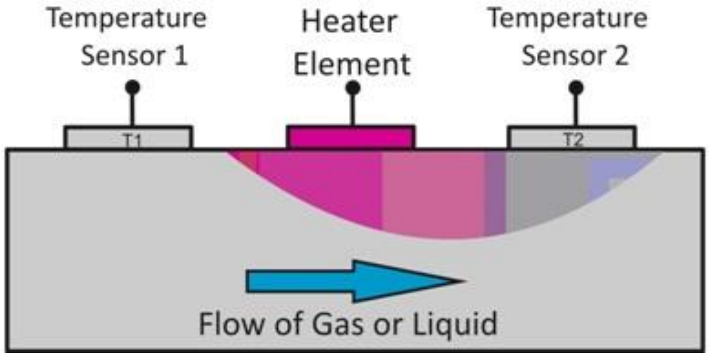
How to convert flowrate into temperature?

$$flow\ rate = f(\Delta T = T_2 - T_1)$$

- A heating element is placed onto a pipe together with two temperature sensors: one at upstream and the other at downstream.



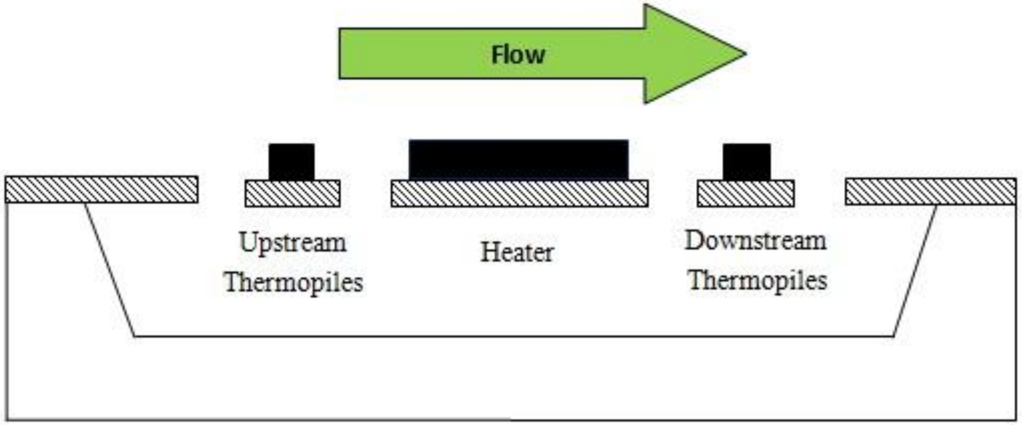
- The profile of temperature distribution is a function of fluid's flowrate.



Example of Implementation …

- Heater is outside the pipe …

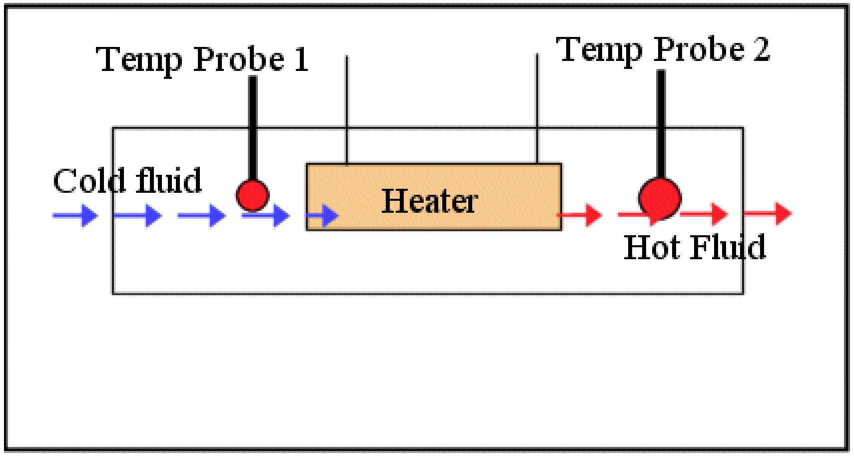
$$flowrate = f(\Delta T = T_2 - T_1)$$



Example of Implementation …

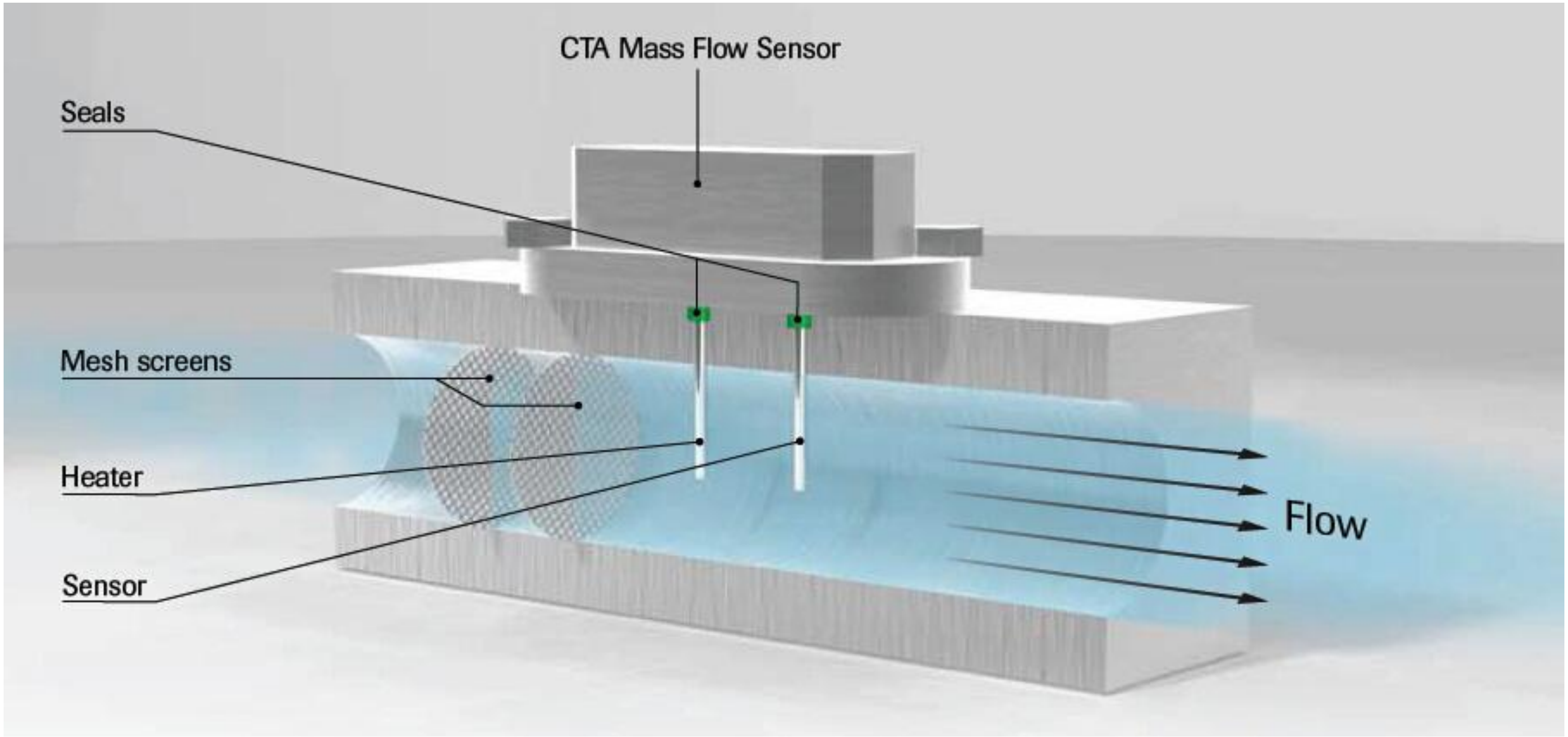
- Heater is inside the pipe …

$$flowrate = f(\Delta T = T_2 - T_1)$$

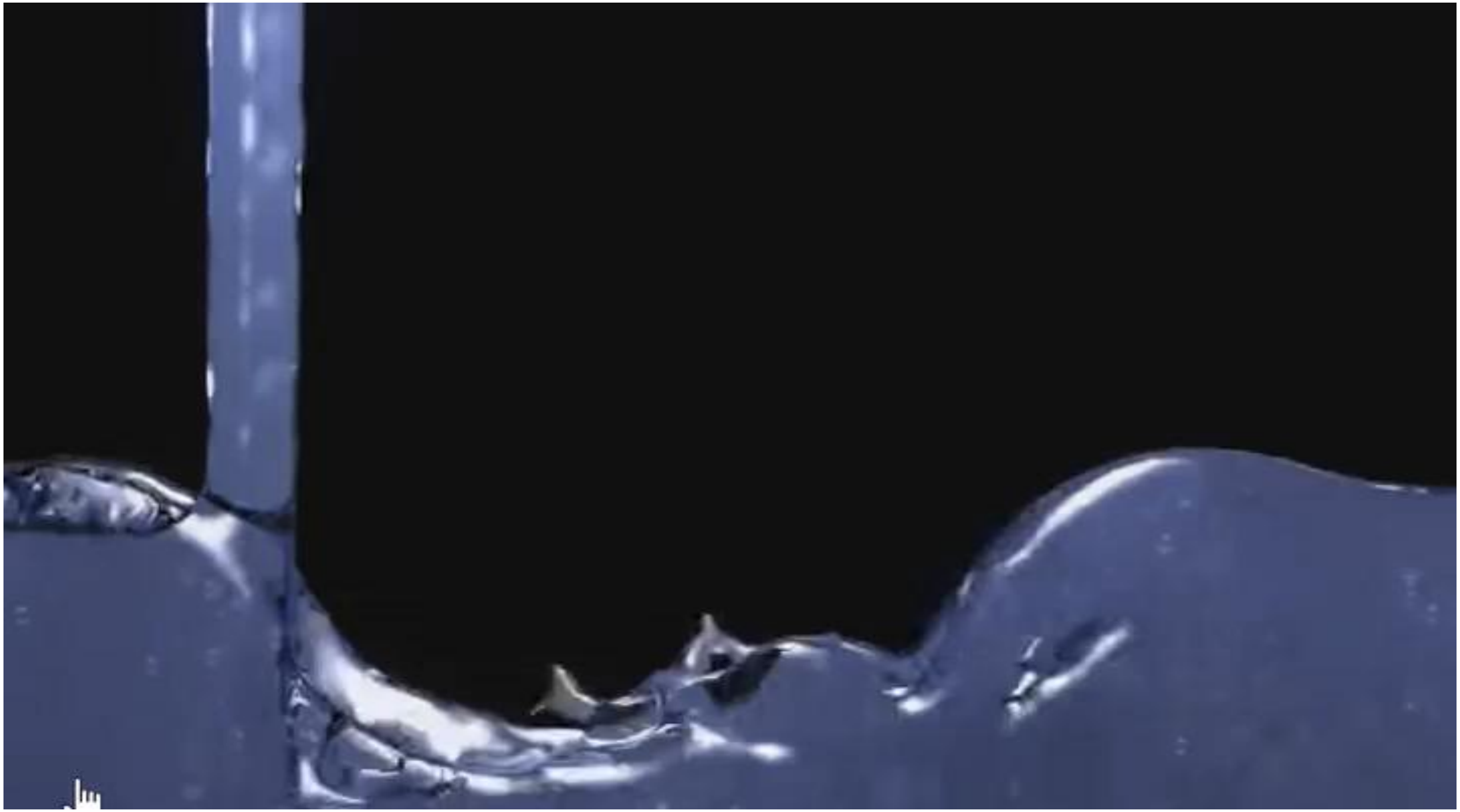


Example of Implementation …

- Heater is inside the pipe …

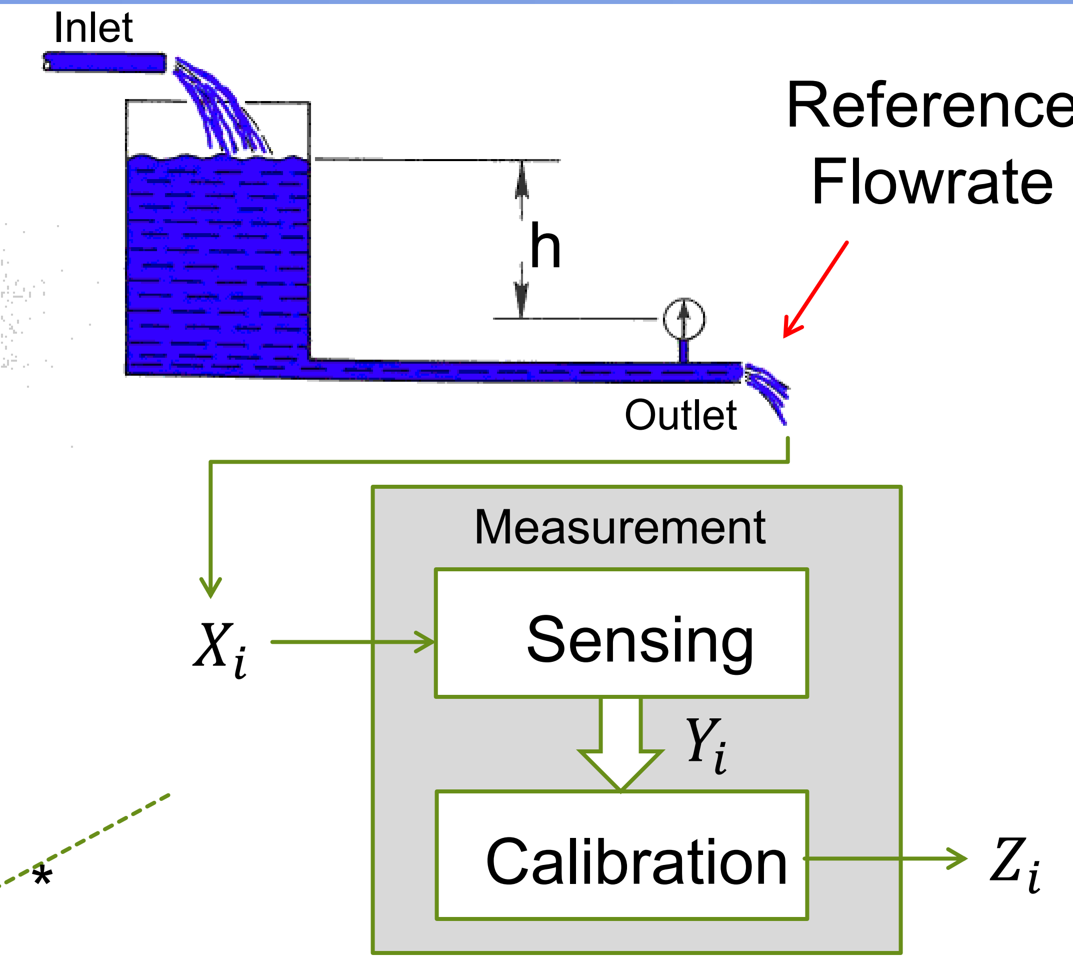


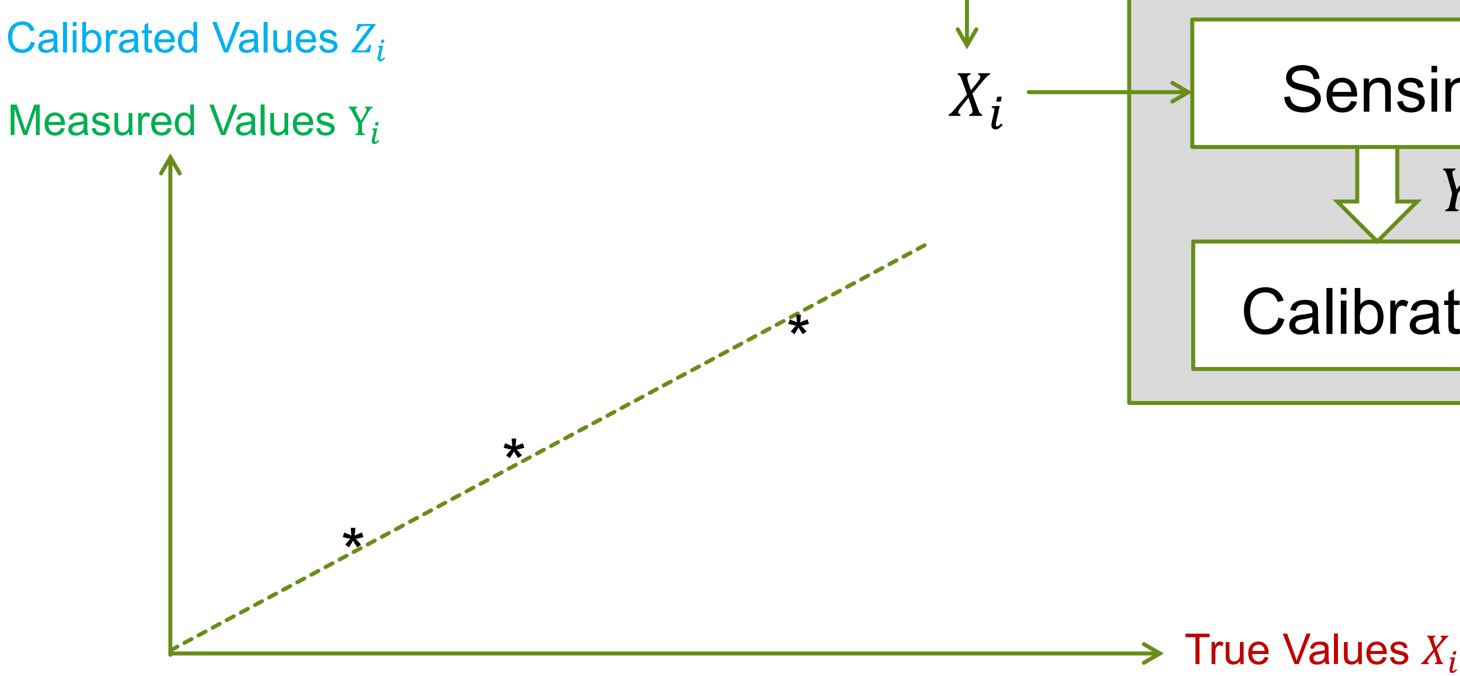
How to convert flowrate into temperature?



Remember to Do Calibration

- Curve fitting for calibration:
  - Yi is produced by Xi
  - Zi is computed from Yi
  - Zi must be equal to Xi

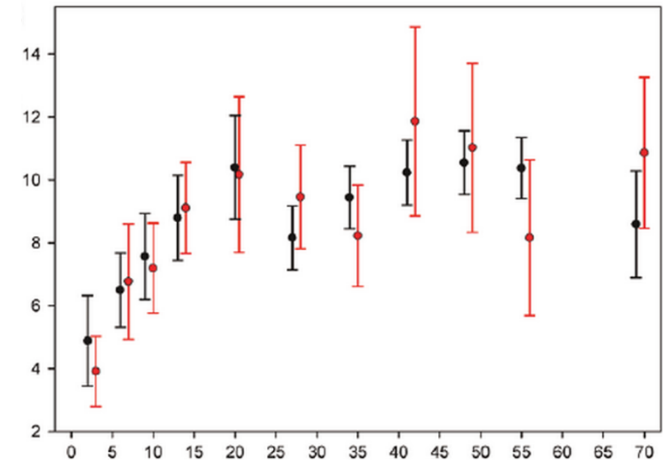


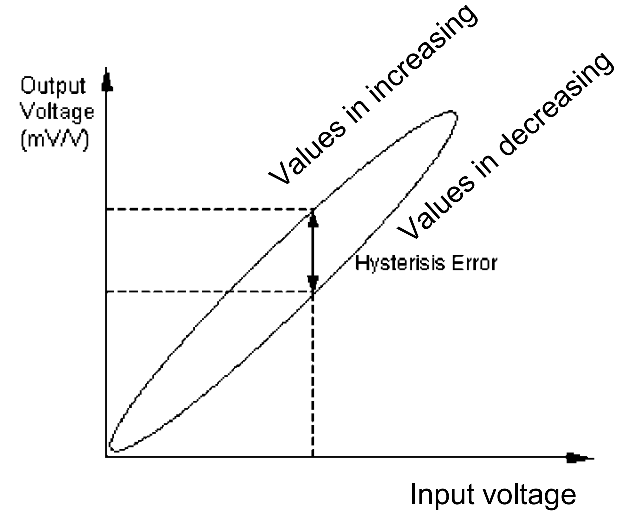


Remember to Do Error Analysis

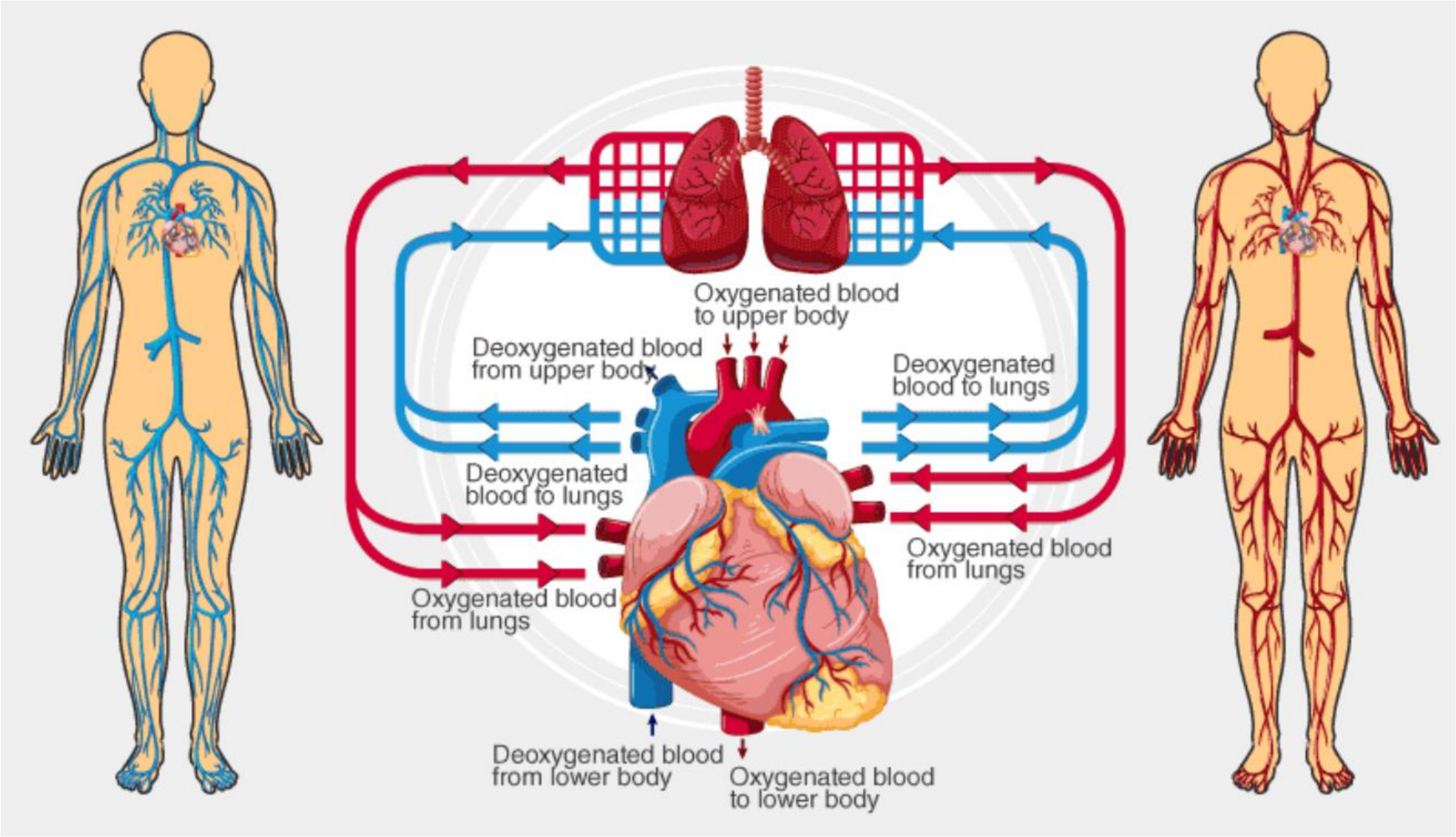
- Systematic error = mean value – true value
- Repeatability error = value with maximum error – mean value
- Accuracy = value with minimum error – mean value
- Hysteresis error = |measured value in increasing – measured value in decreasing|

For each true value, we can do error analysis



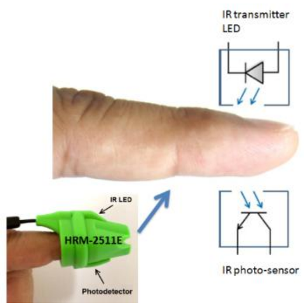


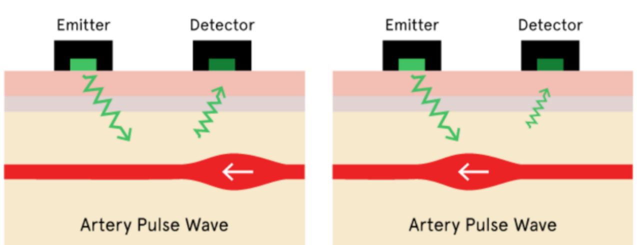
Discussion: What is the primary purpose of Blood Flow Systems in Human Body?



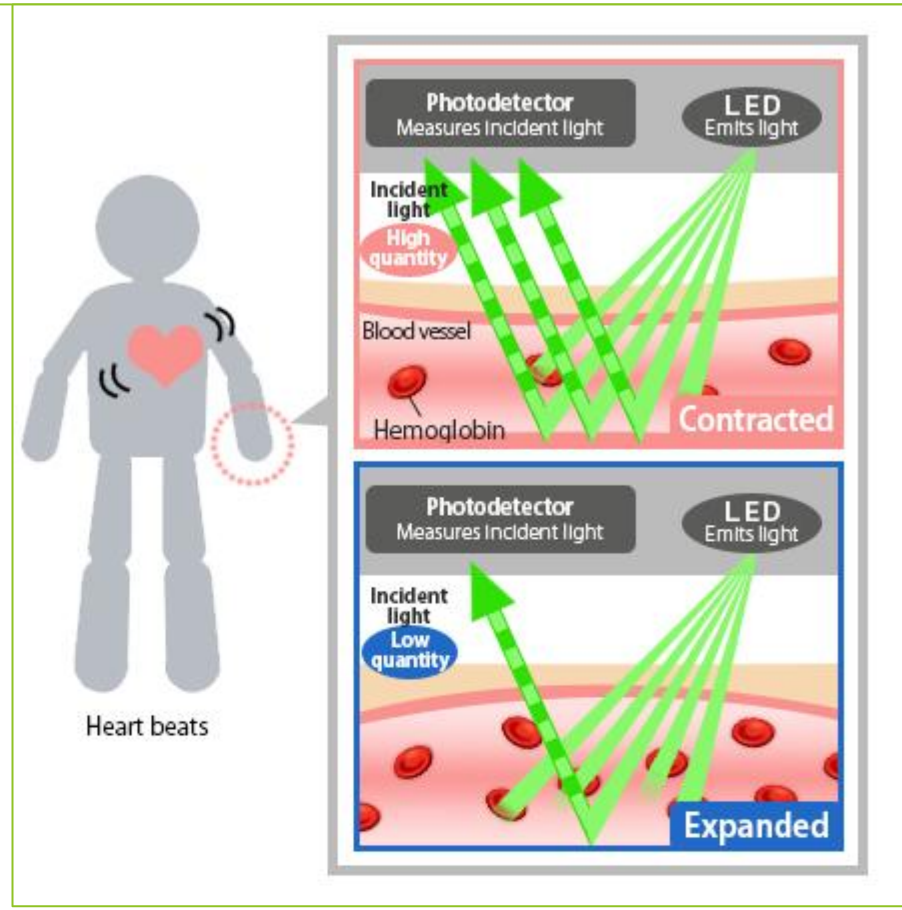
Discussion

- Can we consider the pulsed wave of human body's blood as discrete flow?
- Can we determine the average of flowrate from the number of pulses per second?



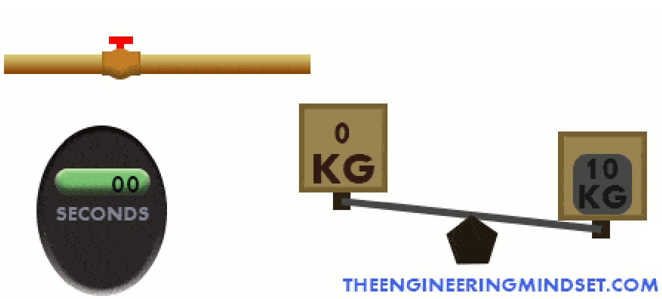


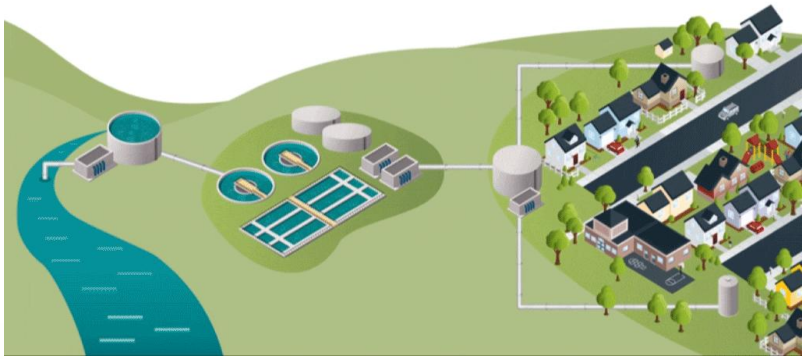
1. Hemoglobin absorbs lights.
2. Contracted vessel produces more reflected lights.
3. Expanded vessel produces less reflected lights.



Summary

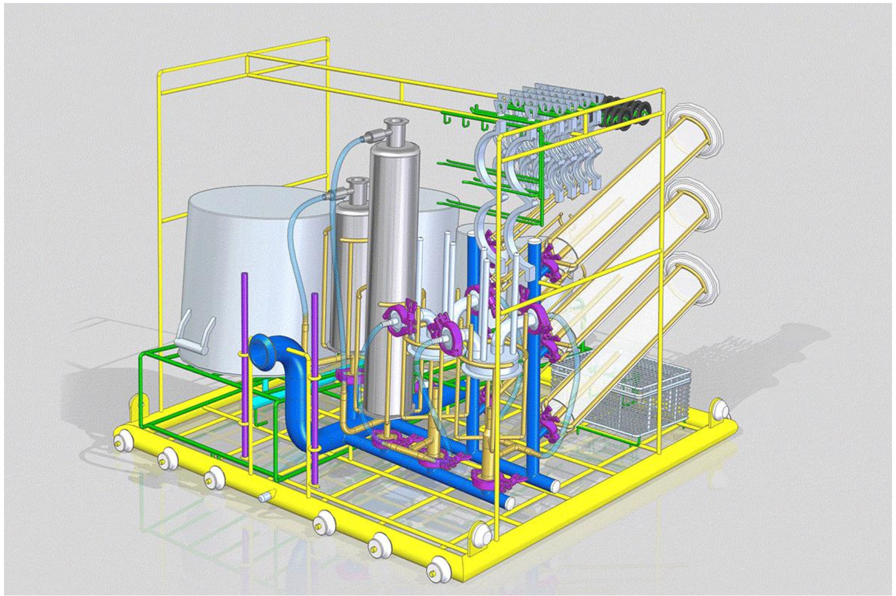
- Understanding of Flow Rate
- Computation of Flow Rate
- Measurement of Flow Rate





Outline of Module 5

- Lecture 1:
  - Measurement of Fluid Level
- Lecture 2:
  - Measurement of Flow Rate
- Lecture 3:
  - Measurement of Sound/Voice
- Lecture 4:
  - Measurement of Photometry
- Lecture 5:
  - Measurement of Geometry



Module 5 Lecture 3

MA4822

Measurement of Sound/Voice

Xie Ming, PhD (France)

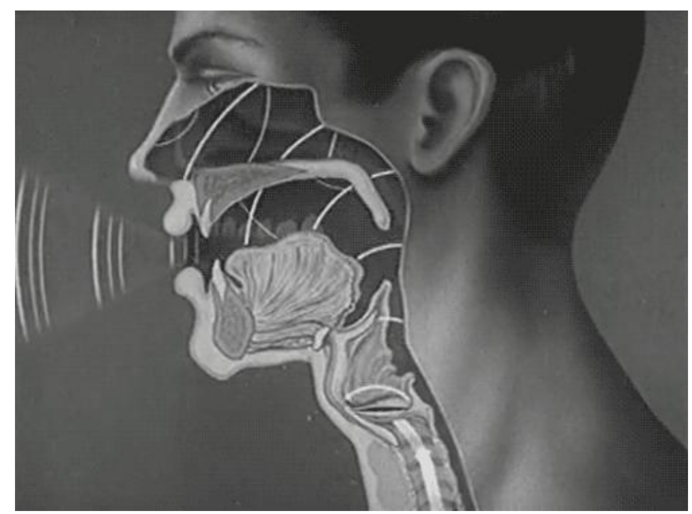
mmxie@ntu.edu.sg

http://personal.ntu.edu.sg/mmxie

Outline

- Understanding of Acoustic Signals
- Computation of Acoustic Signals
- Measurement of Acoustic Signals

Processing of Acoustic Signals

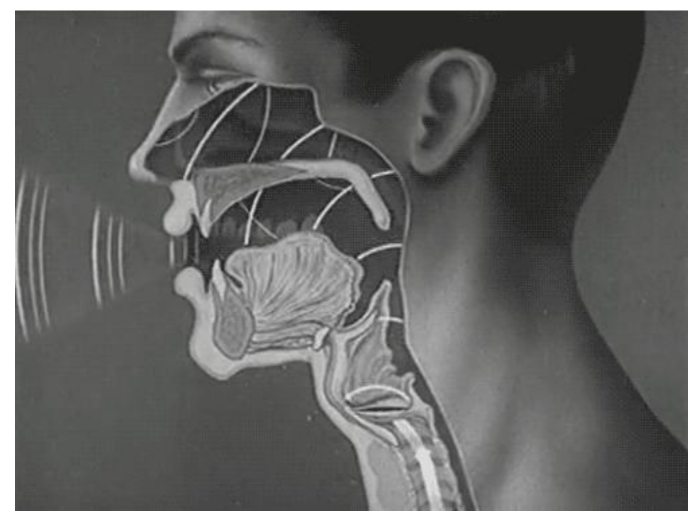


Outline

- Understanding of Acoustic Signals
- Computation of Acoustic Signals
- Measurement of Acoustic Signals

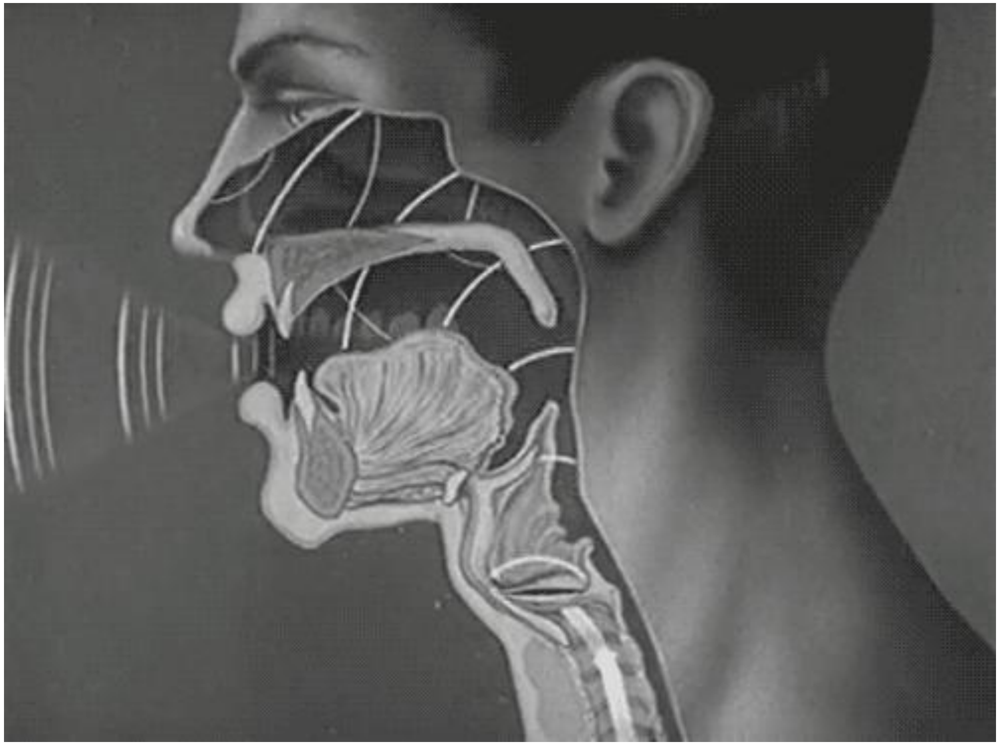
⇩

Processing of Acoustic Signals



What is sound or voice?

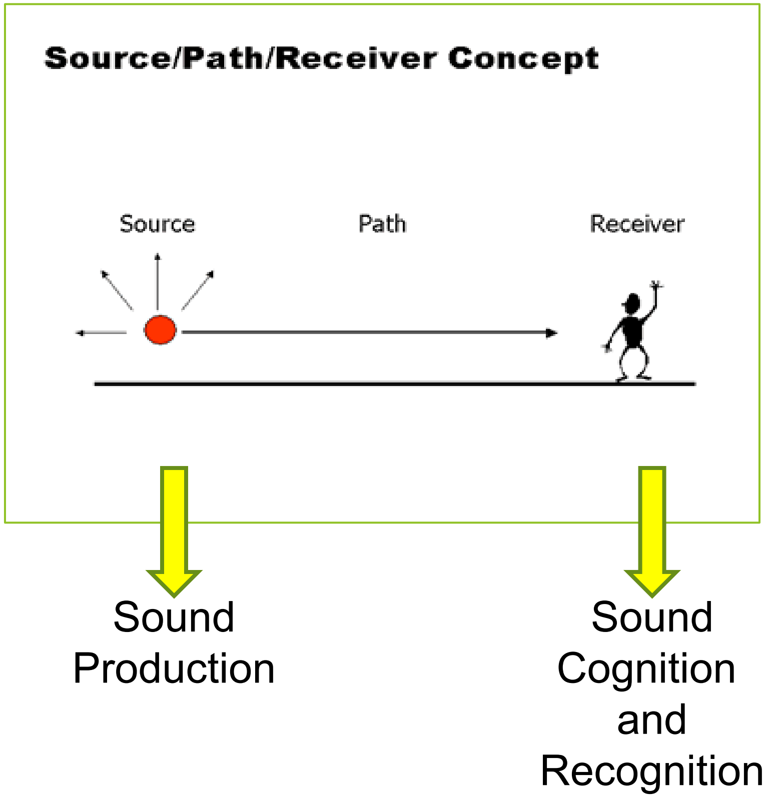
- Audible acoustic signals are called sounds or voices.



How to understand sound or voice?

Focus on:

- Sound/Voice Source
- Sound/Voice Path
- Sound/Voice Receiver

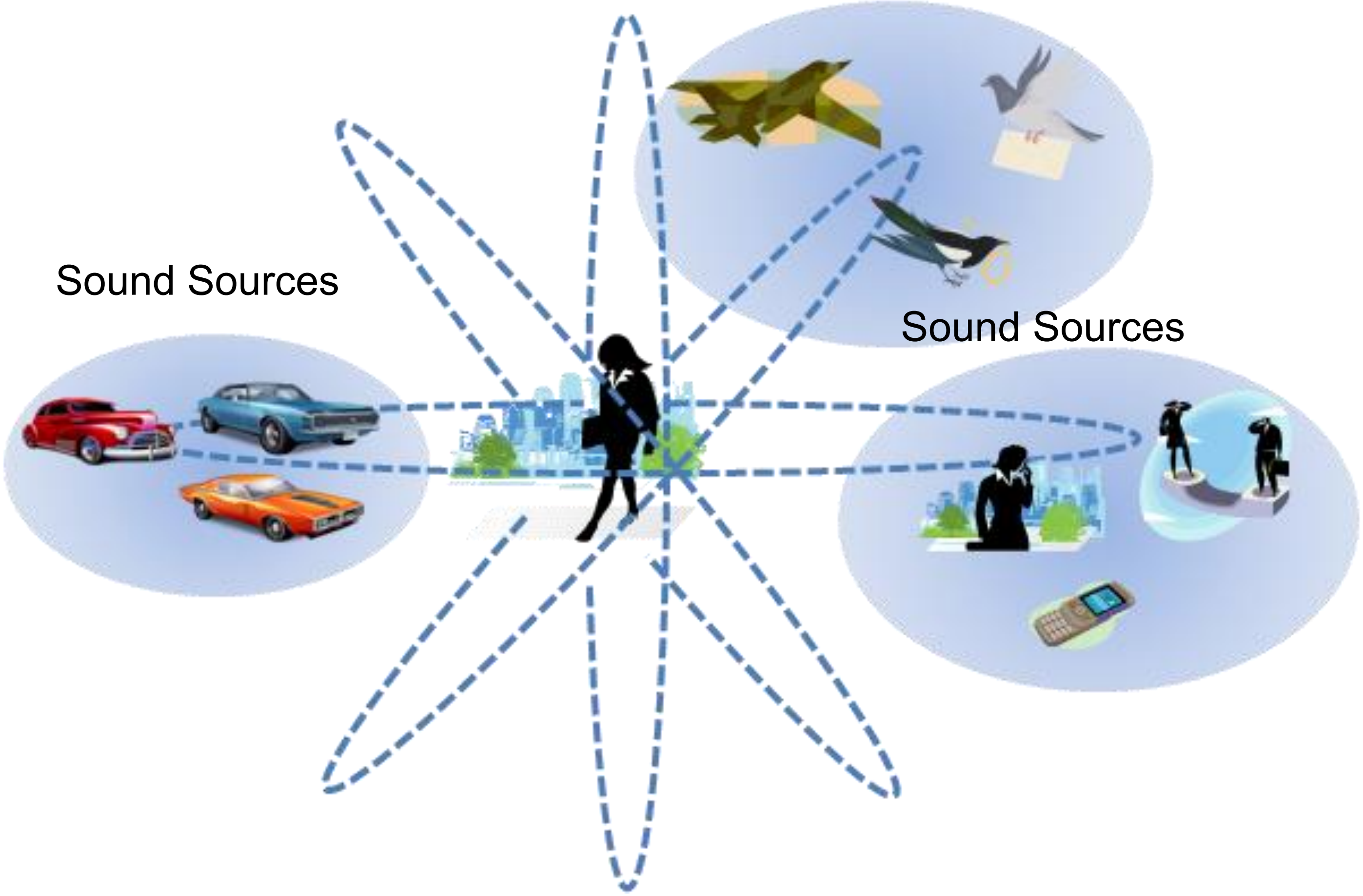


Understanding Sound Sources (1)

- Mechanical vibrations cause vibrations of air. And, periodic vibrations of air, in return, produce sounds.

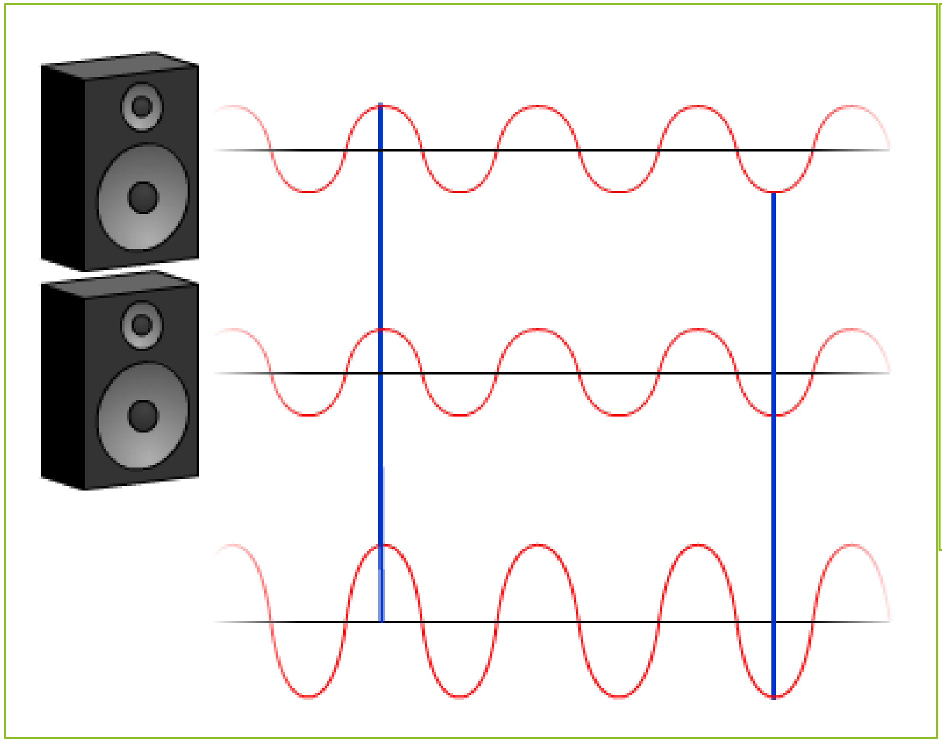
Understanding Sound Sources (2)

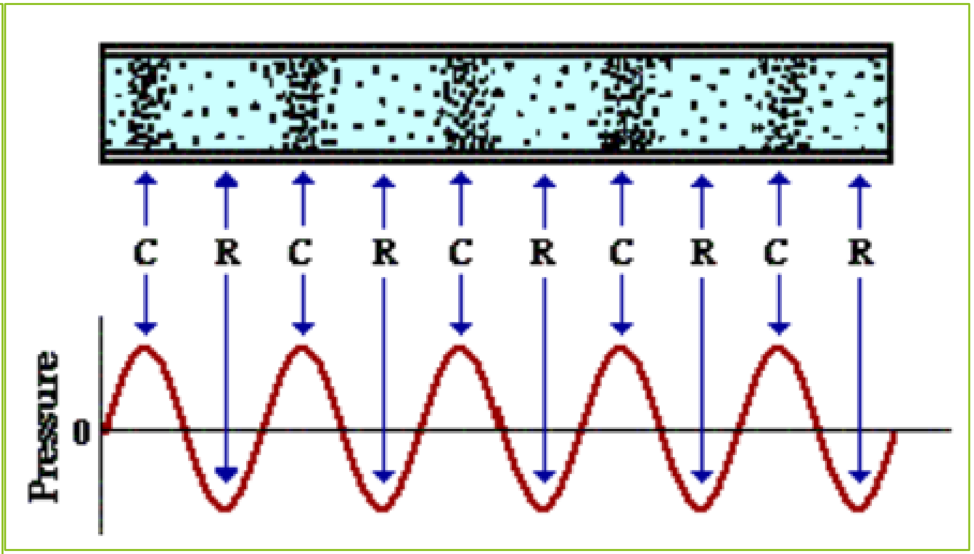
- Mechanical vibrations cause vibrations of air. And, periodic vibrations of air in return produce sounds.



Understanding Sound Sources (3)

- Sound source emits energy, which manifests in the form of pressure waves.

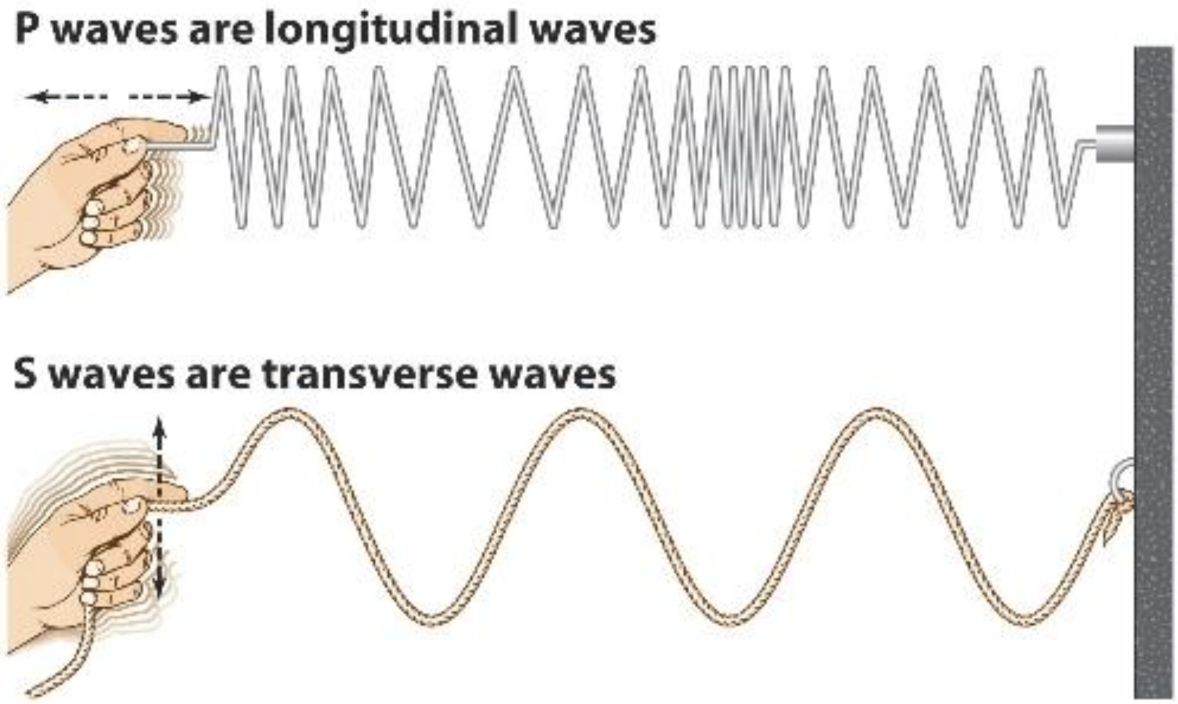




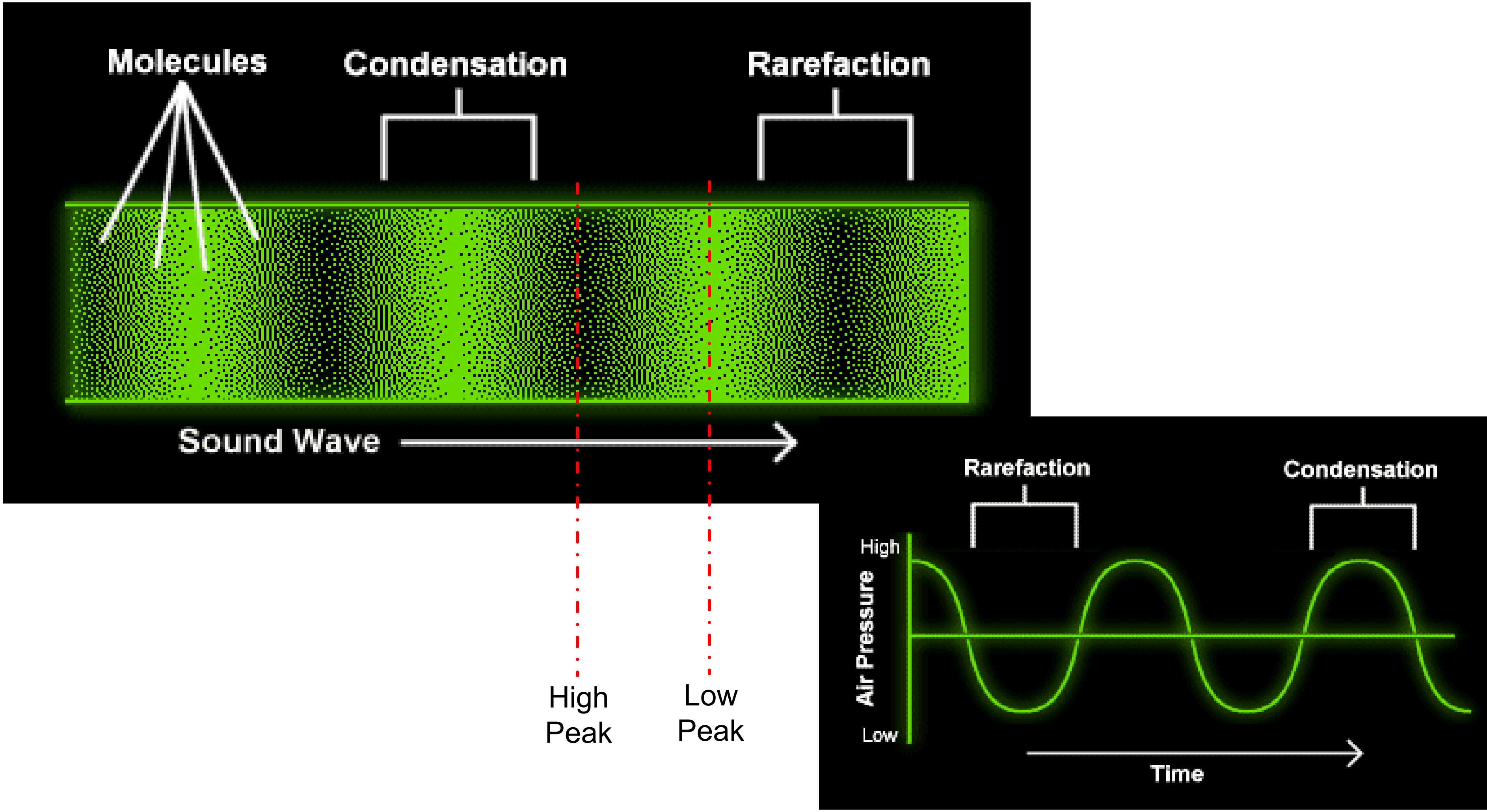
- Condensation
- Rarefaction

Understanding Sound Sources (3)

- Sound waves are P Waves.

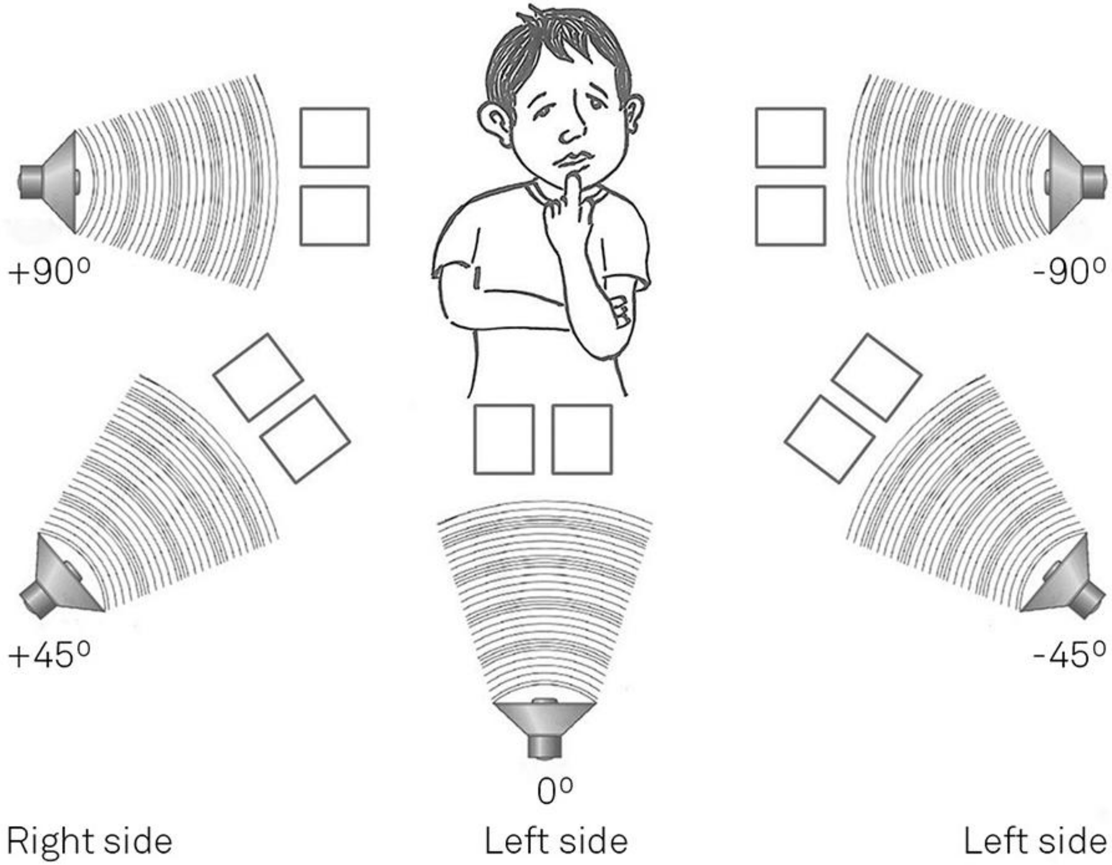


Example of P Waves …



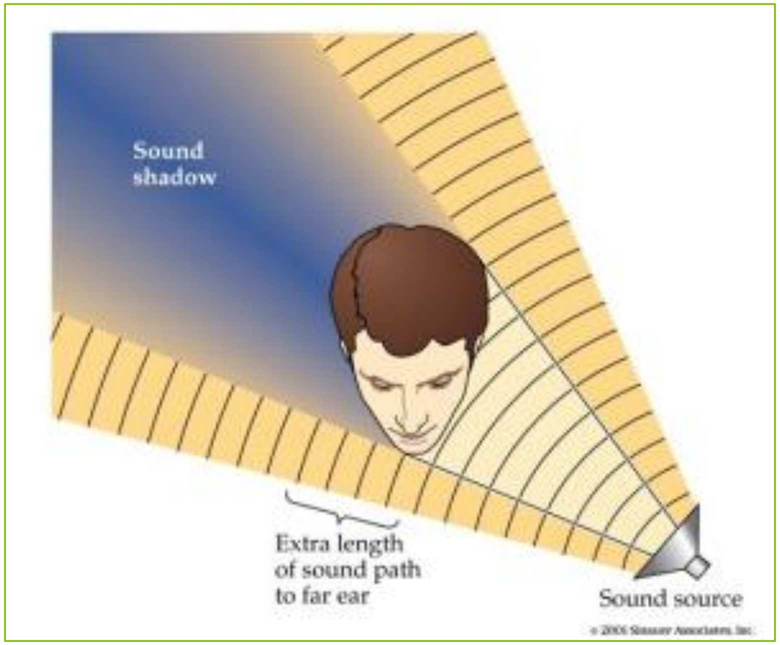
Understanding Sound Paths (1)

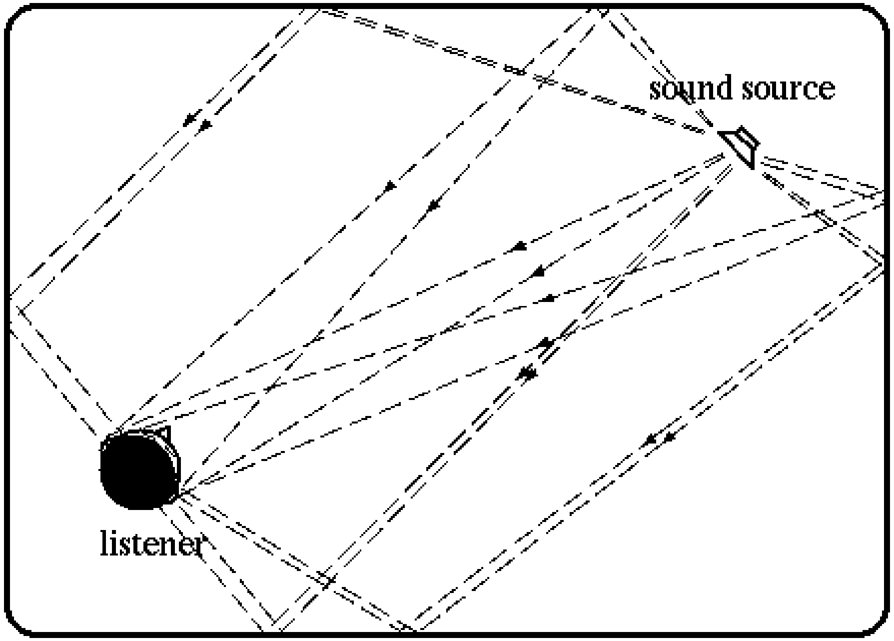
- Sound waves can come from everywhere.



Understanding Sound Paths (2)

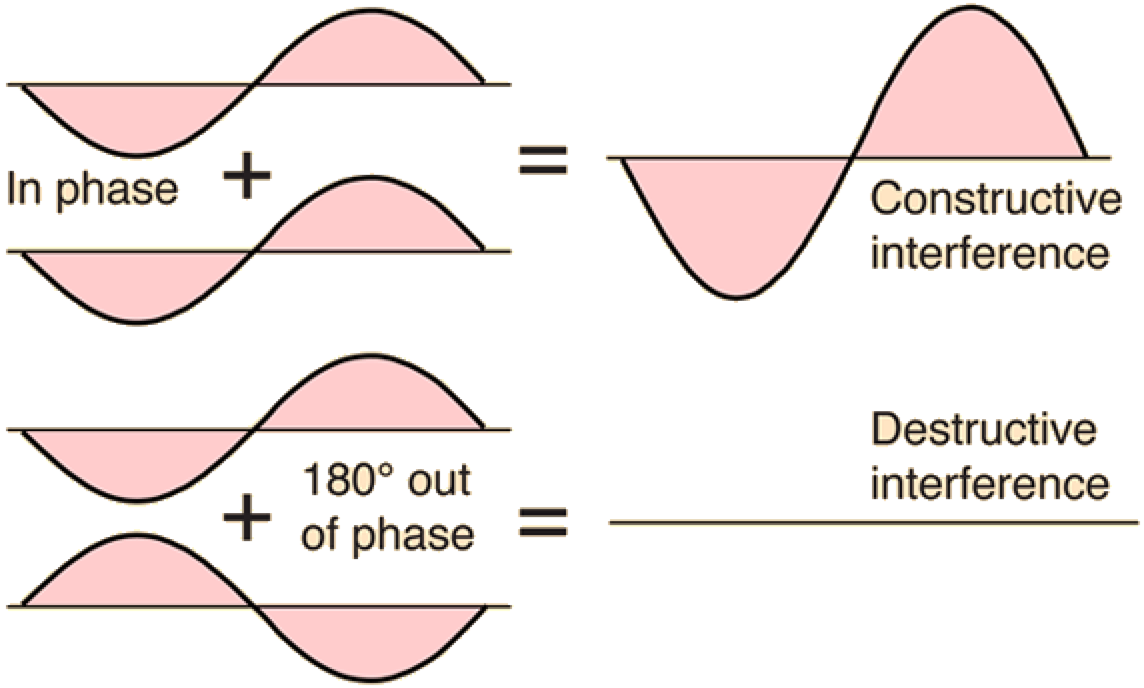
- Sound waves propagate in straight lines from sound sources, and change directions due to reflections.



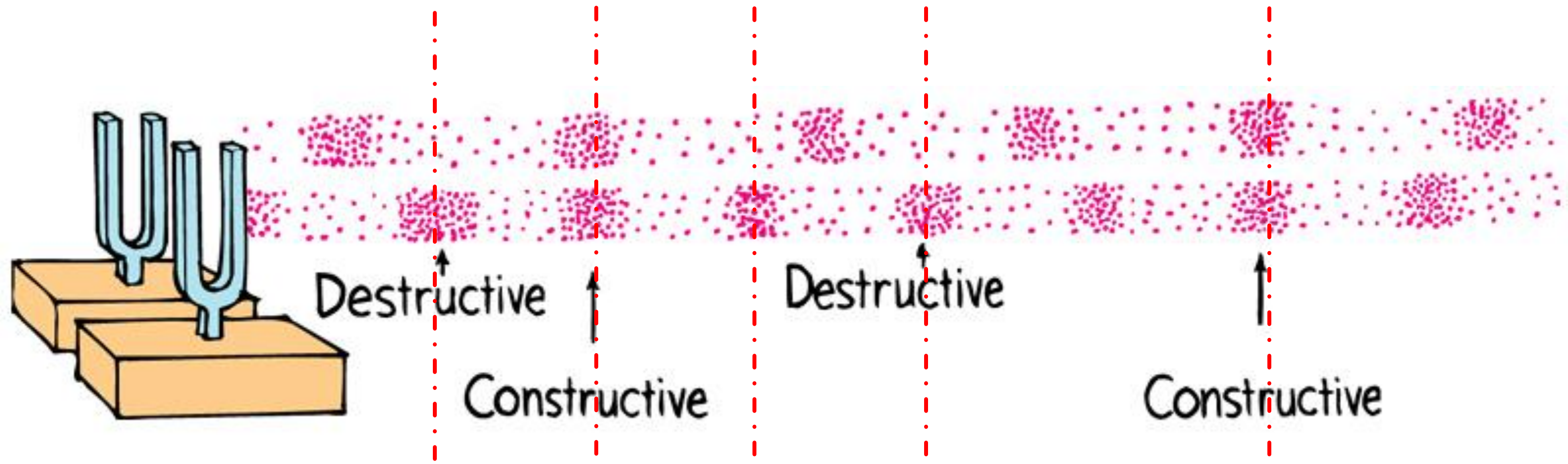


Understanding Sound Paths (3)

- When sound waves meet in space, interferences occur. Two basic modes of interference are
  - a) constructive interference and
  - b) destructive interference.



Example of Sound Interferences …

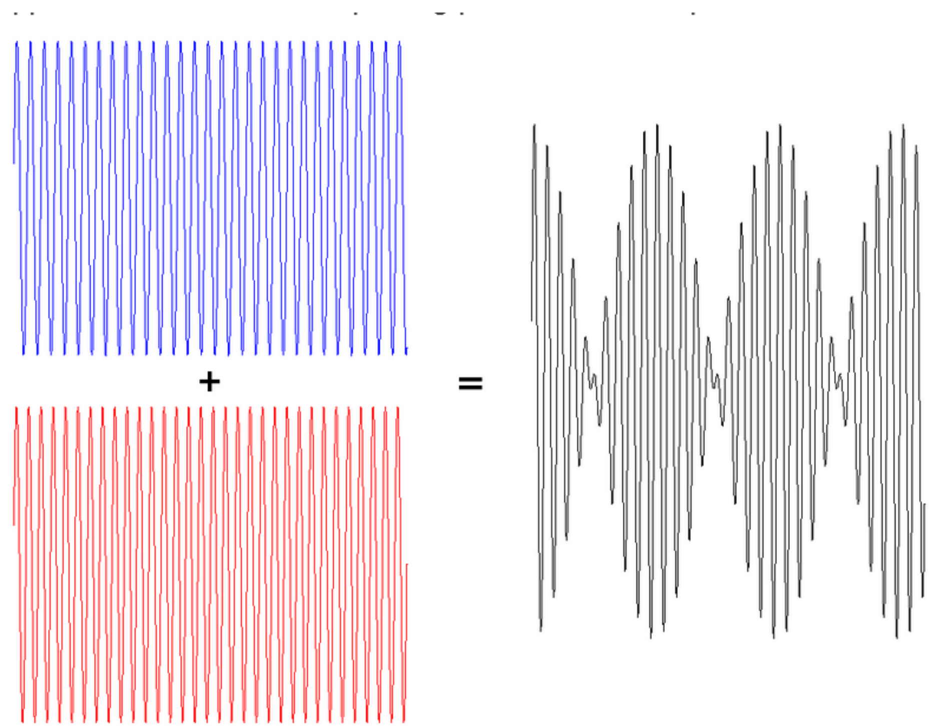


Example of Sound Interferences …

- When a signal contains two frequencies that are close together, they can cause the signal to appear to have a series of 'beats' - a pulsing pattern in the amplitude.

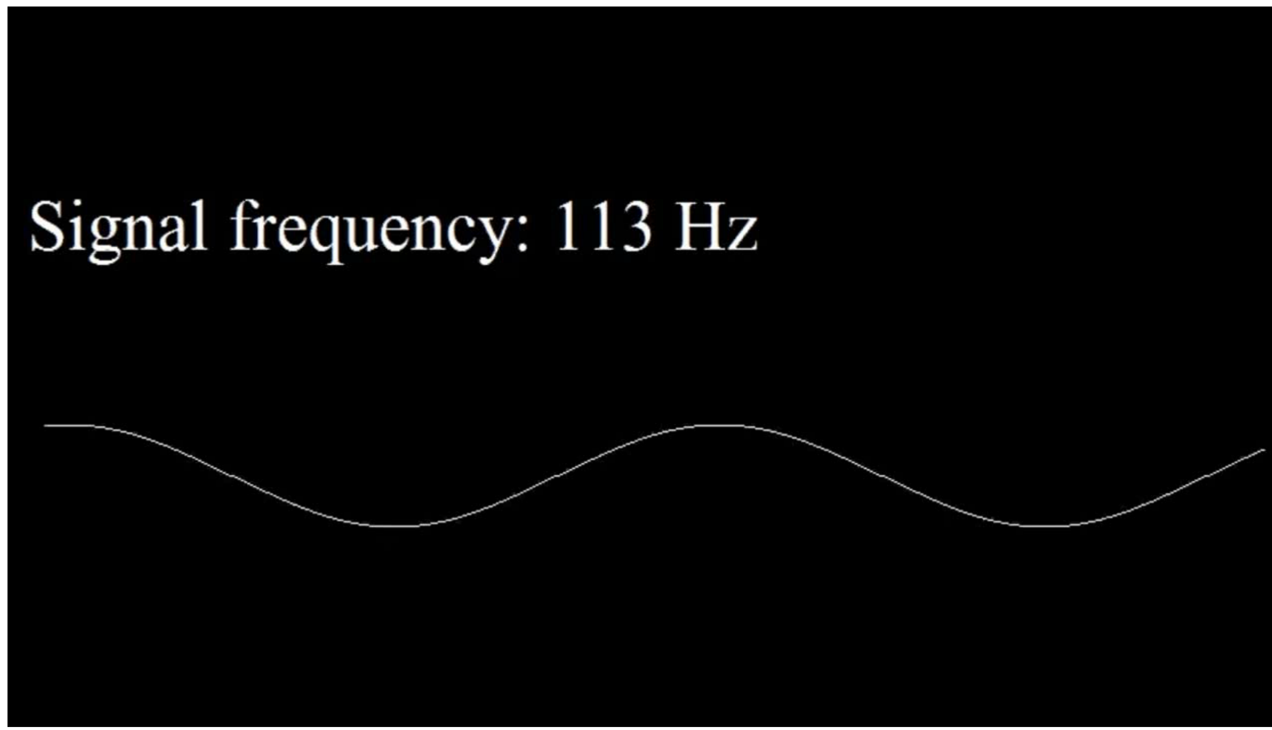
$$y = \sin(1.8 * 2\pi * t)$$

$$y = \sin(2.1 * 2\pi * t)$$

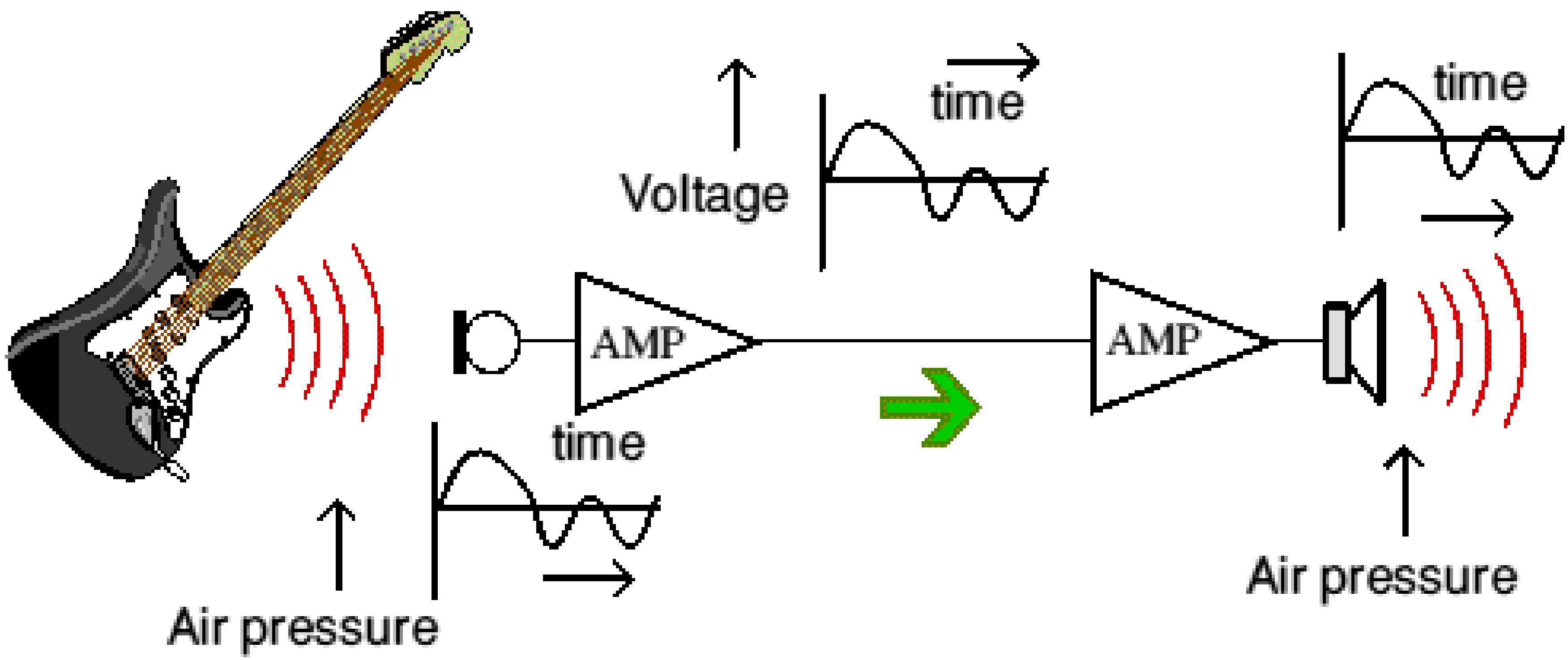


Understanding Sound Receivers (1)

- The input to, and output from, sound receivers are one-dimensional signals which are functions of time.

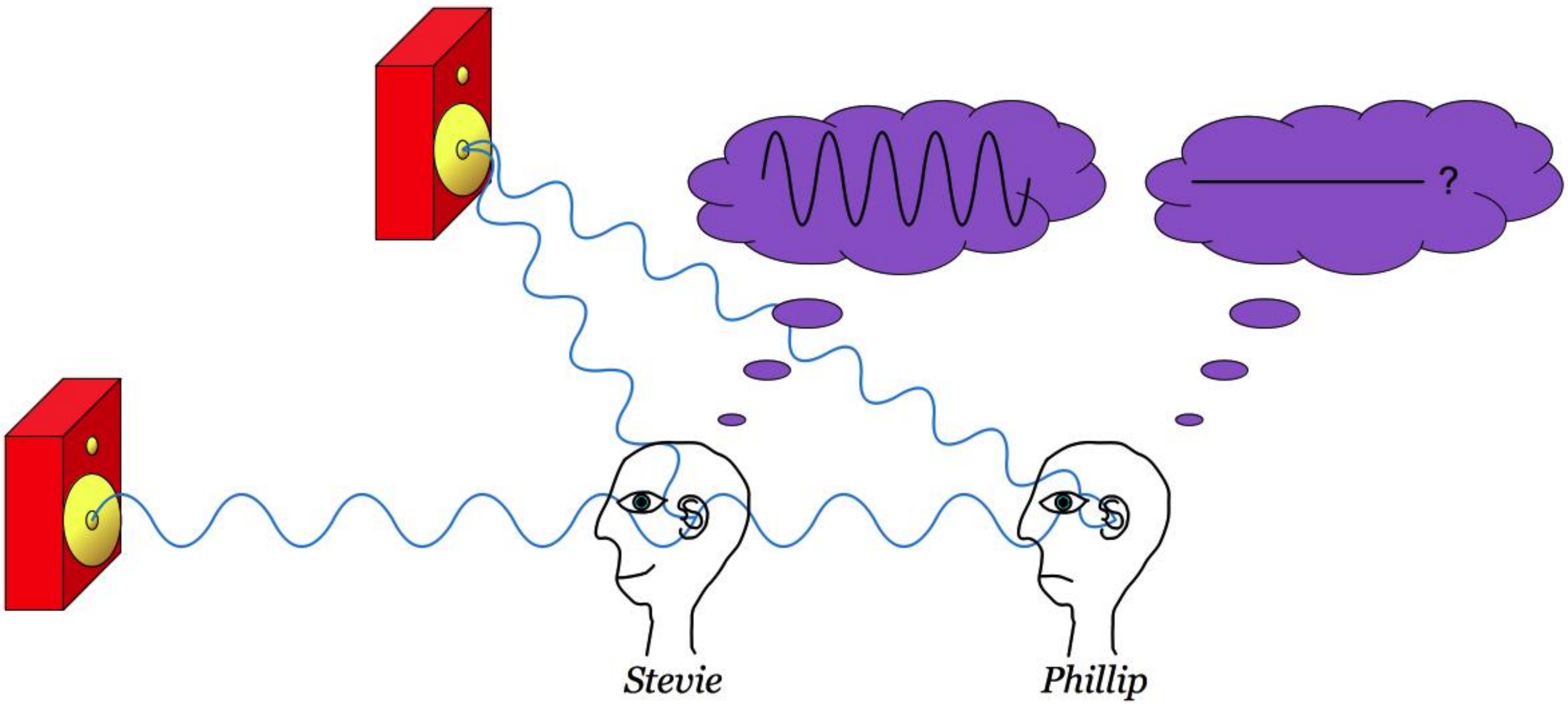


Example of Sound Receiver …



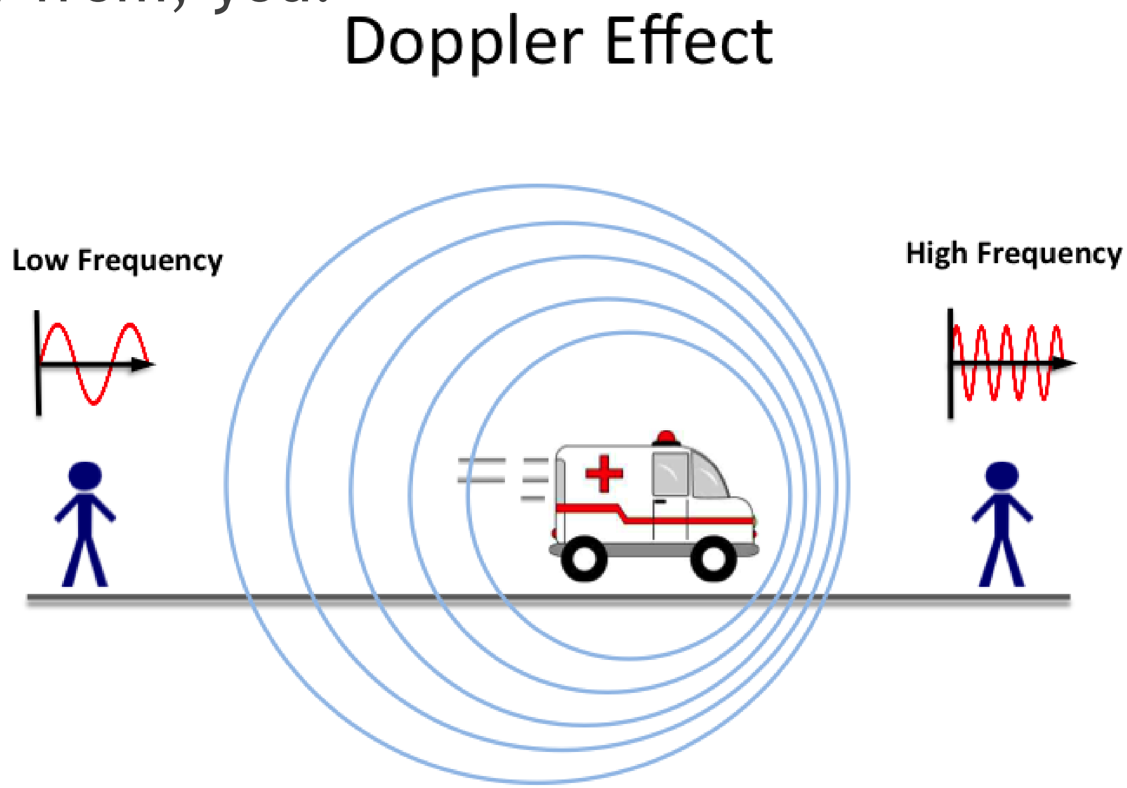
Understanding Sound Receivers (2)

- When you hear nothing, it does not mean that there is no sound.



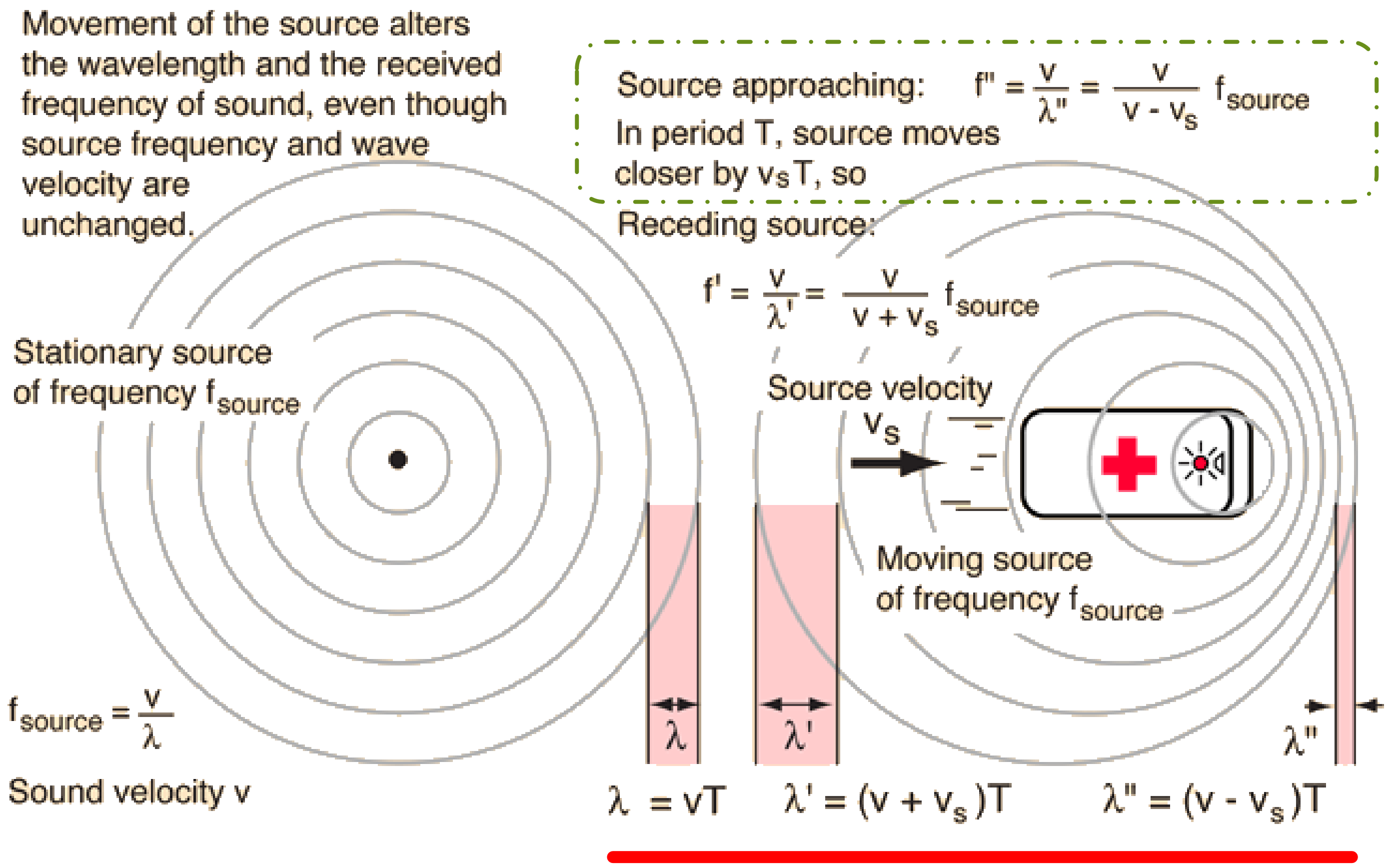
Understanding Sound Receivers (3)

- What you hear may not be exactly what the source emits if the source has a relative speed toward, or away from, you.

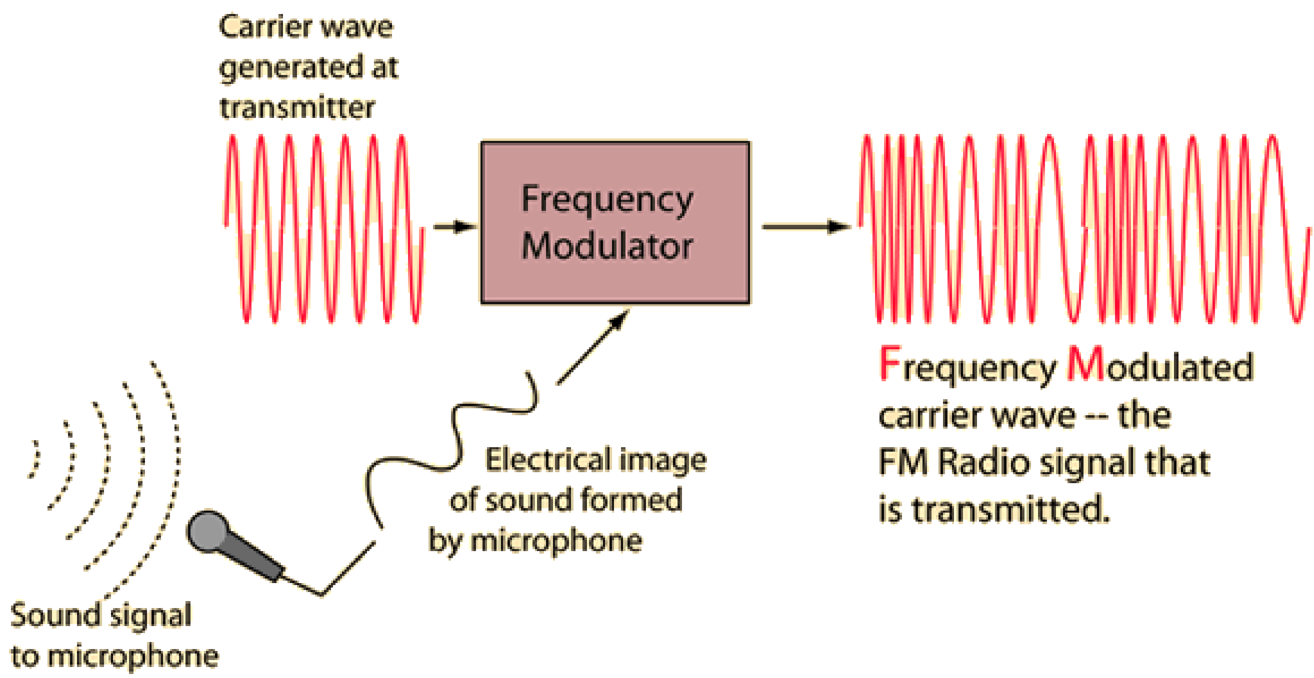


Understanding Sound Receivers (4)

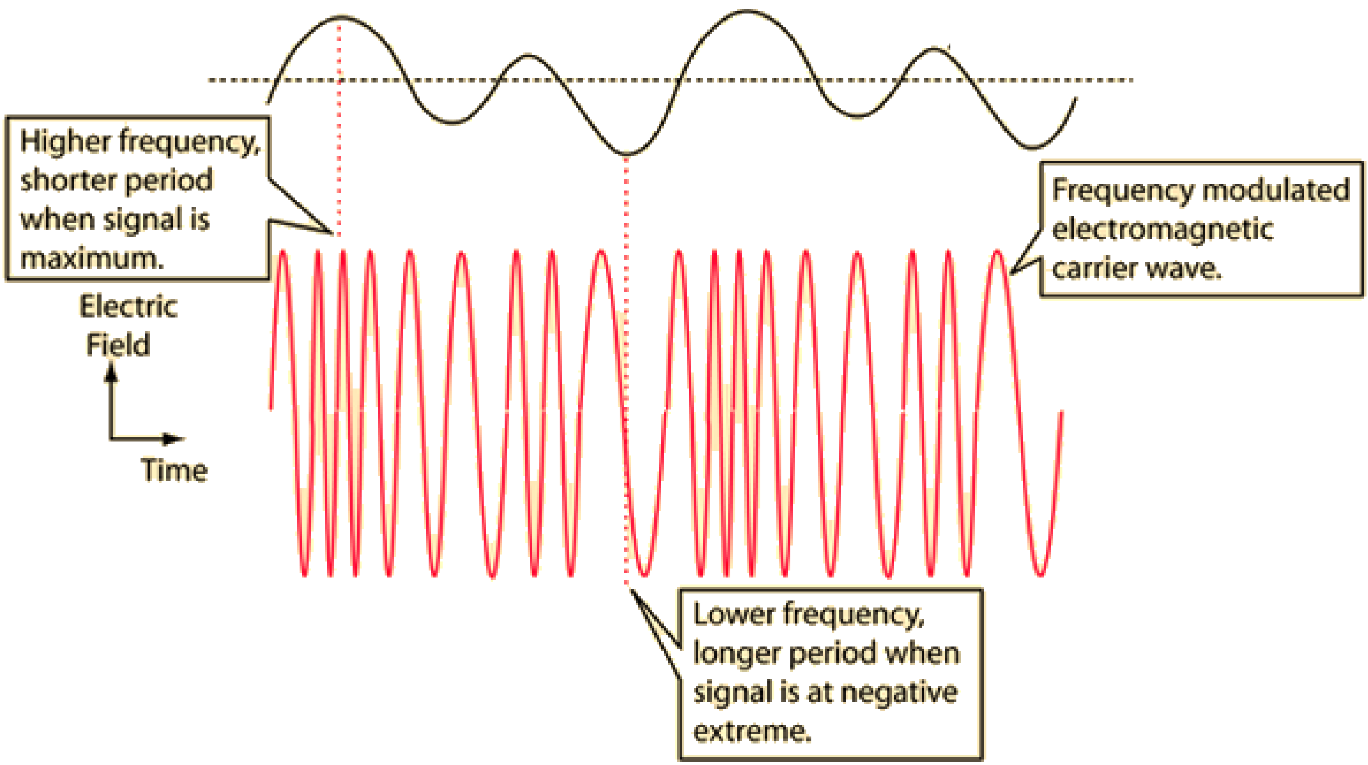
- The frequency of sound increases if the source approaches you. It reduces if the source moves away from you.



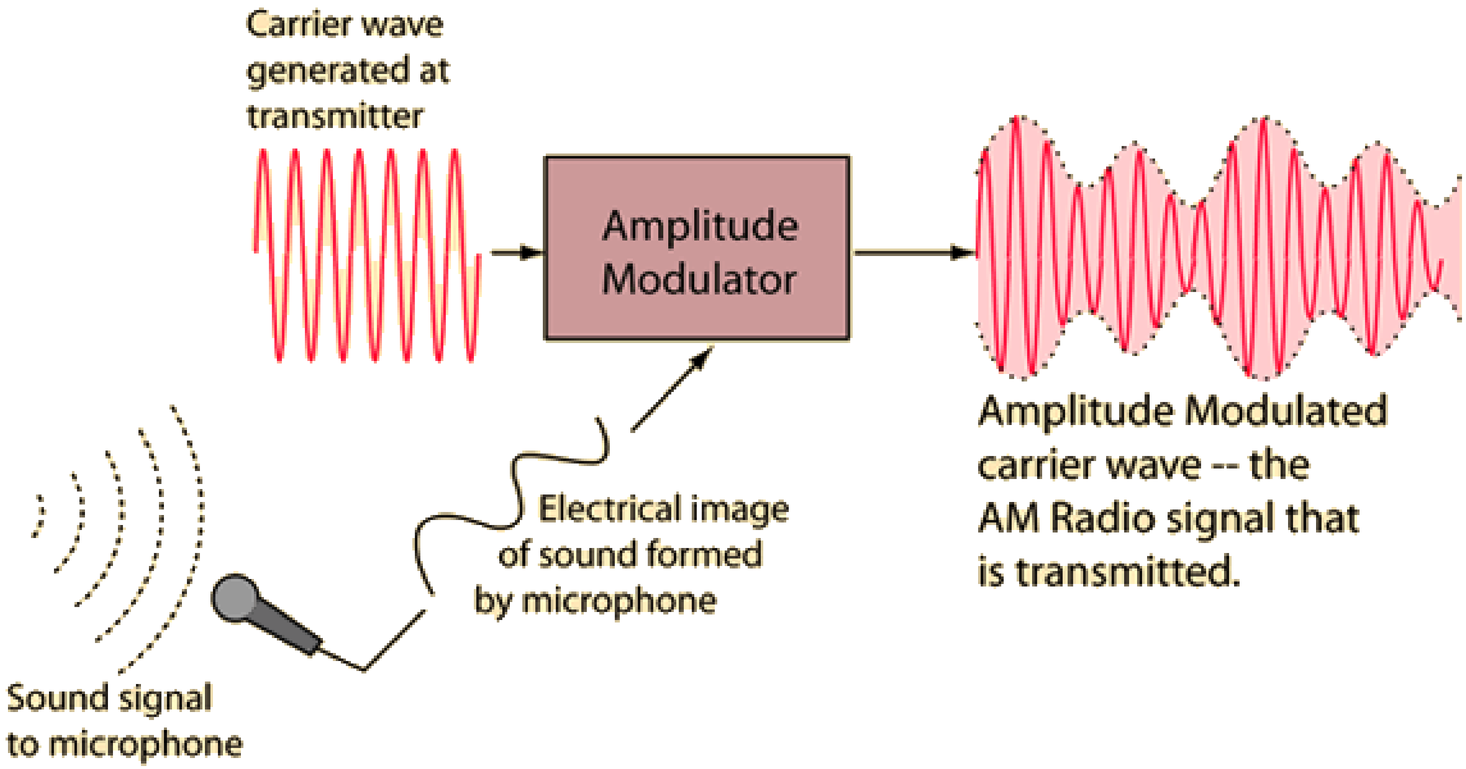
Sound Signal Could Be Used to Modulate The Frequency of Carrier Signal …



Example of Modulating Frequencies



Sound Signal Could Be Used to Modulate The Amplitude of Carrier Signal …

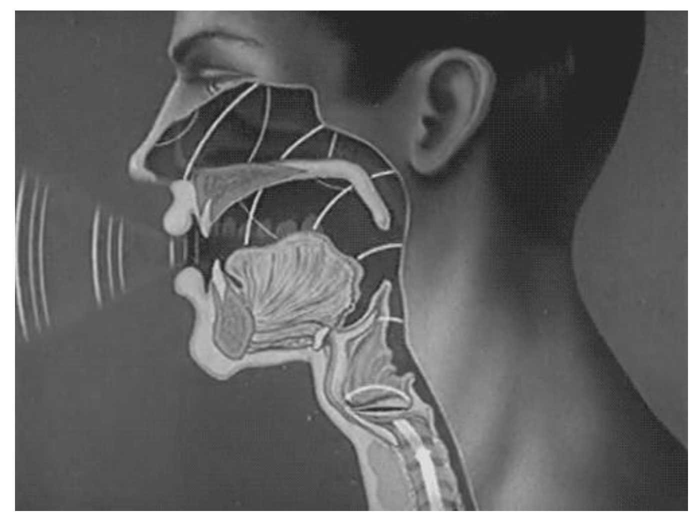


Outline

- Understanding of Acoustic Signals
- Computation of Acoustic Signals
- Measurement of Acoustic Signals

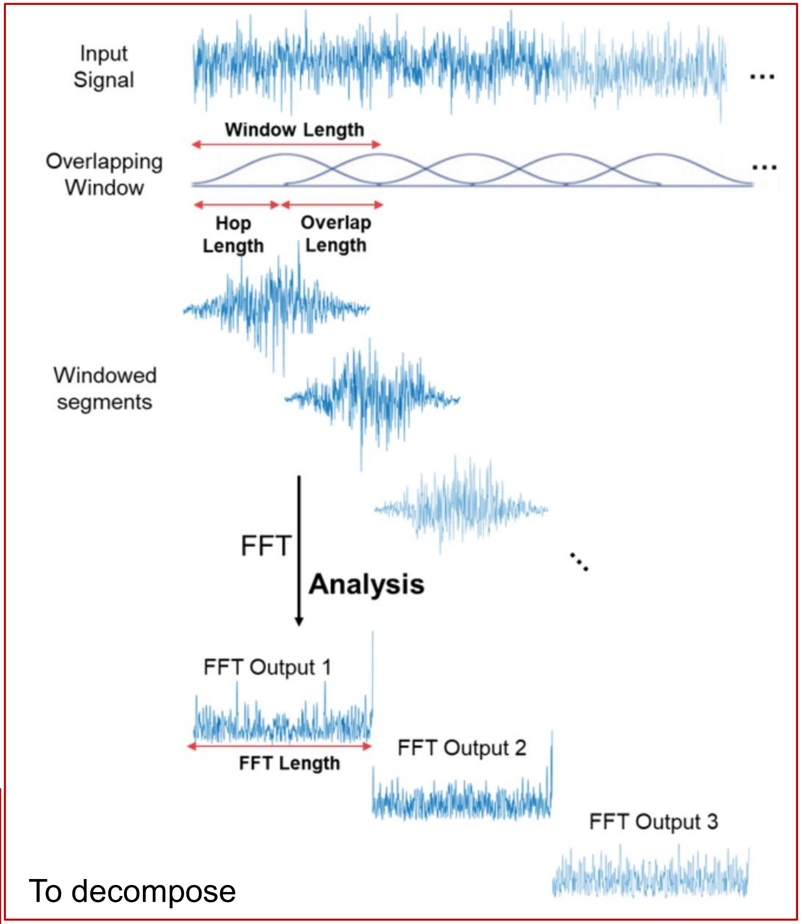
⇩

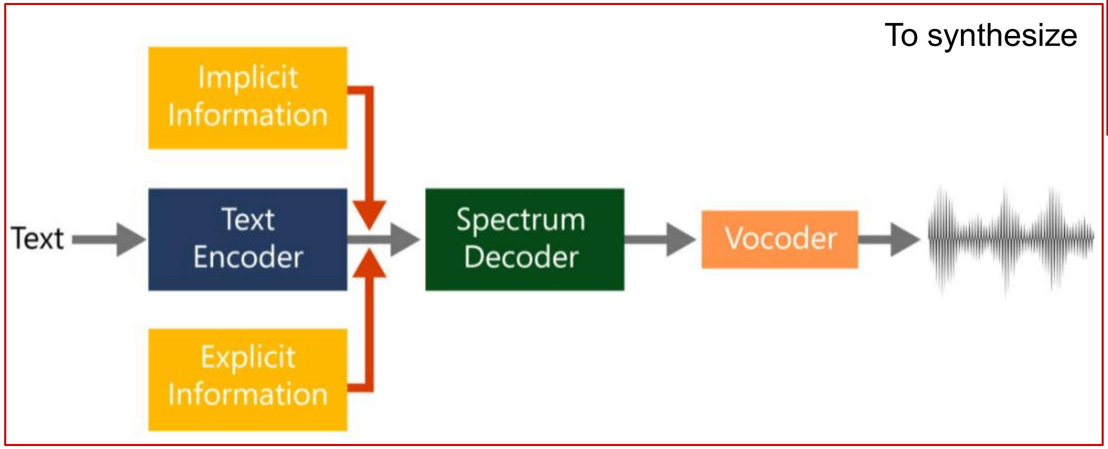
Processing of Acoustic Signals



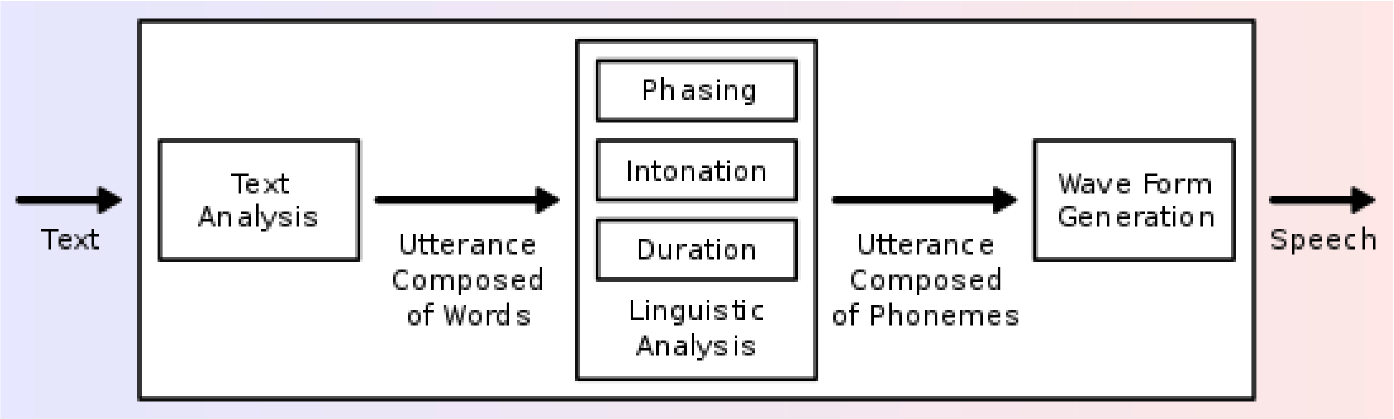
Why to do computation with sound waves?

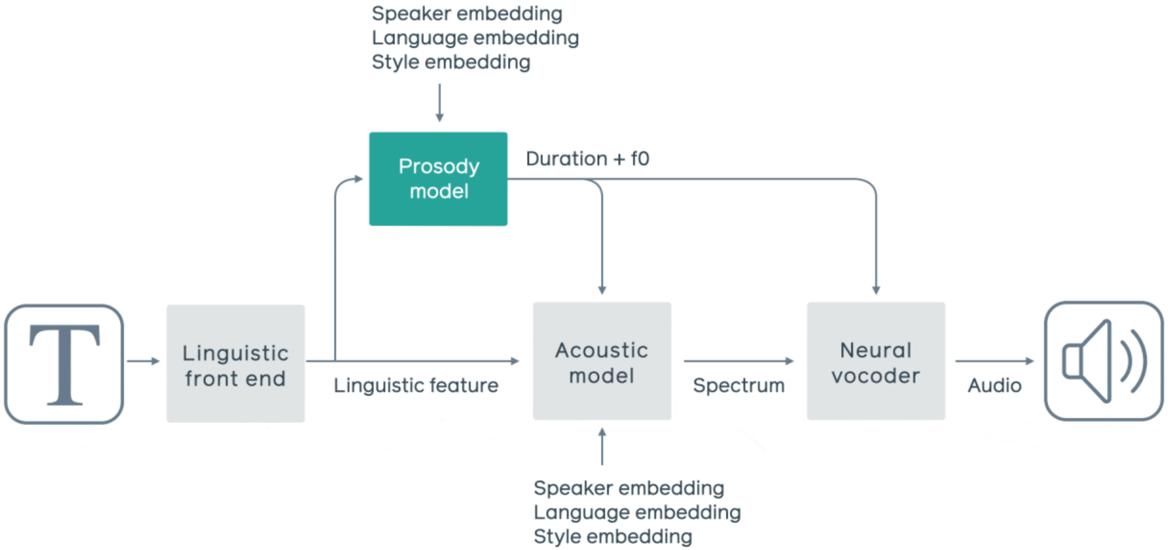
- To synthesize sound waves from sine waves or cloned samples of phonemes in a spoken language.
- To decompose sound waves into sine waves or cloned samples of phonemes in a spoken language.



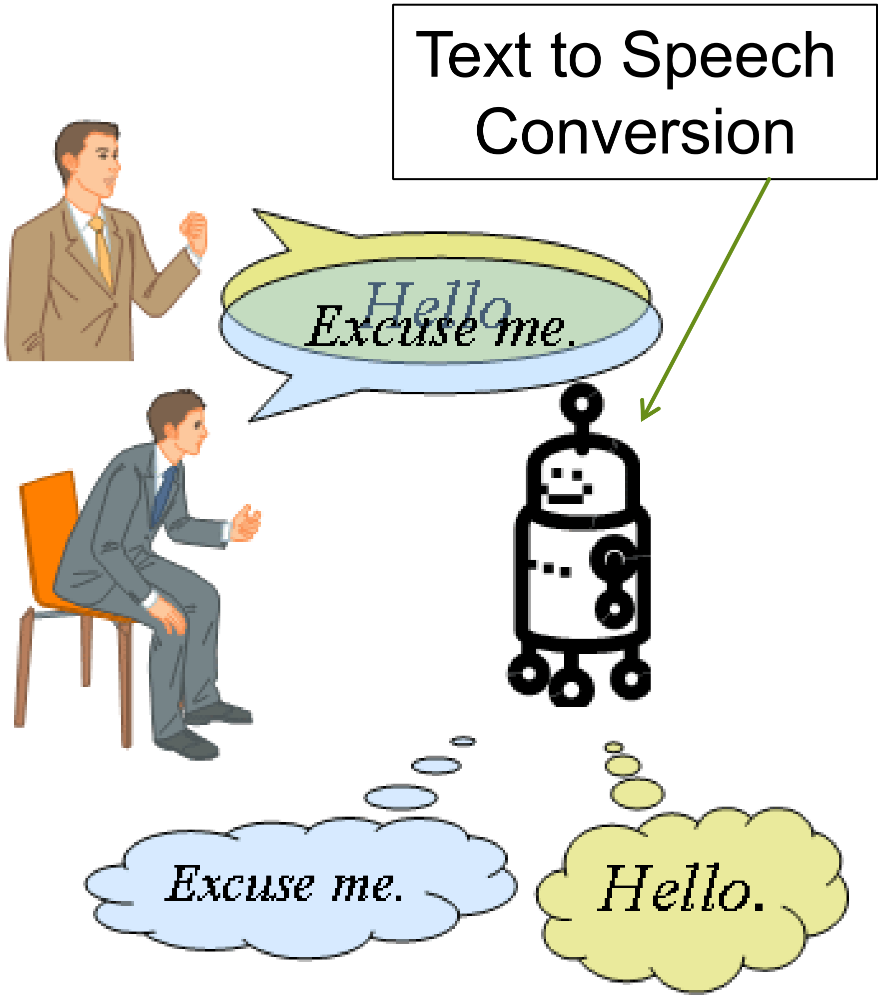


Text to Voice Synthesis …





Voice Synthesis by Robots



Example of Phonemes in English …

In English, there are 44 phonemes, or word sounds that make up the language. They're divided into:

- 19 consonants,
- 7 digraphs,
- 5 'r-controlled' sounds,
- 5 long vowels,
- 5 short vowels,
- 2 'oo' sounds,
- 2 diphthongs.

AI Research

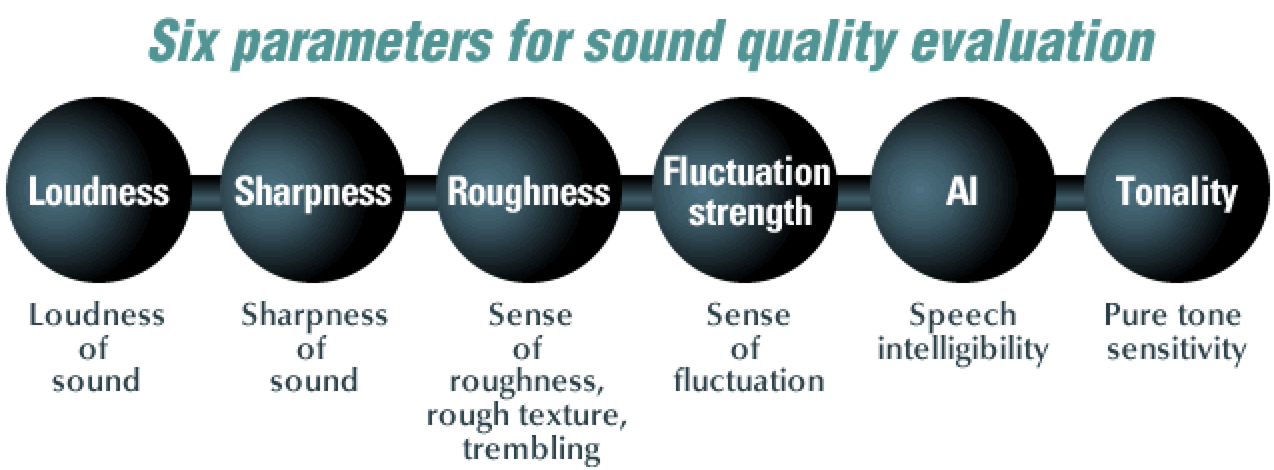
How to construct a large database of phonemes?

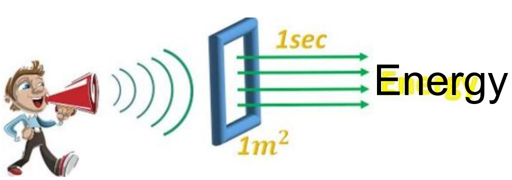
What can be computed from sound waves?

- Energy
- Frequency
- Amplitude

- Loudness: Energy
- Sharpness: Frequency Distribution
- Roughness: Amplitude Fluctuation
- Fluctuation Strength: Roughness below 20 Hz.
- Intelligibility: Degree of Being Comprehensible.
- Tonality: Patterns (pitches/chords) of sounds

$$s(t) = \sum A \sin(2\pi f t + \varphi)$$



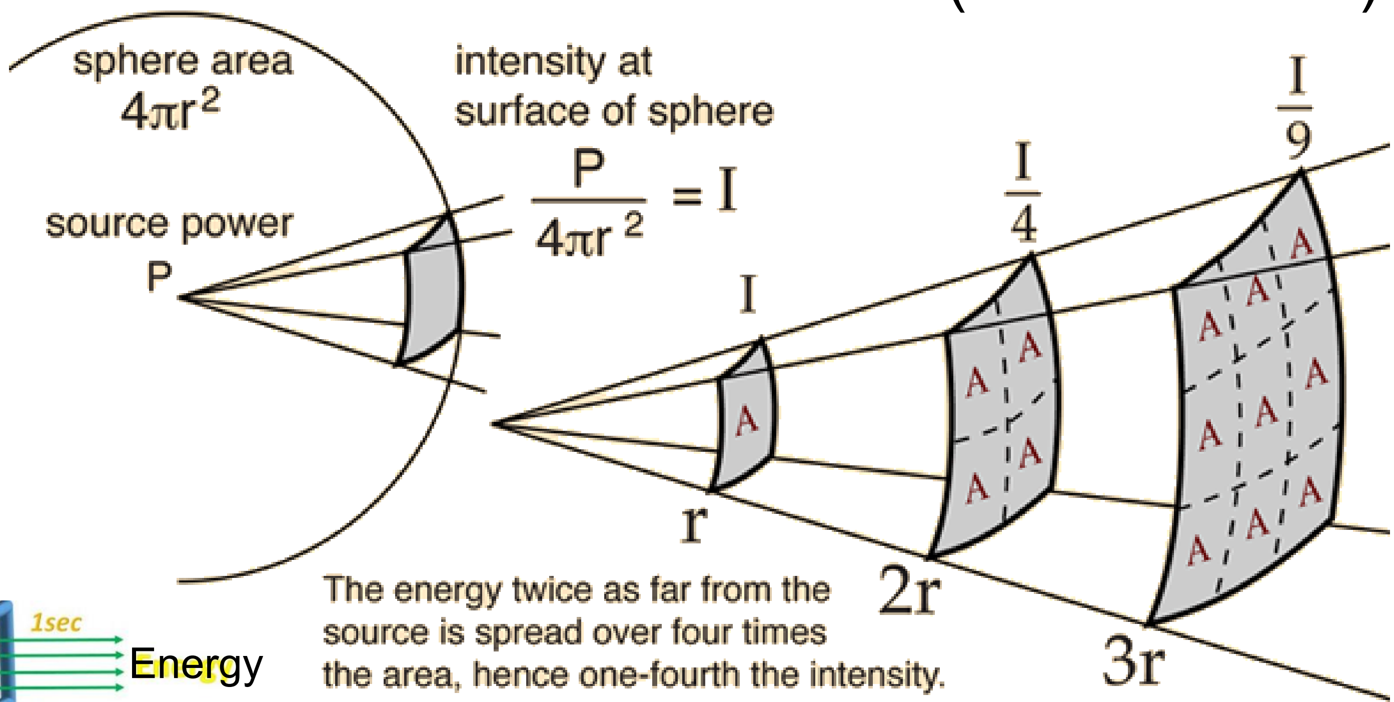


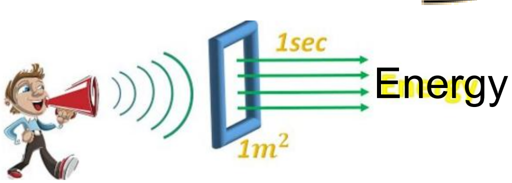
Energy of Sound Wave

$$\text{Loudness} = \text{I} = \frac{P}{4\pi r^2}$$

$$\text{Level} = 10 \times \log_{10}\left(\frac{P}{4\pi r^2}\right) \text{ (decibel)}$$

(absolute level)



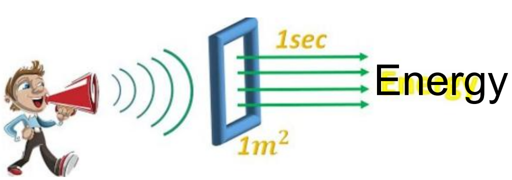


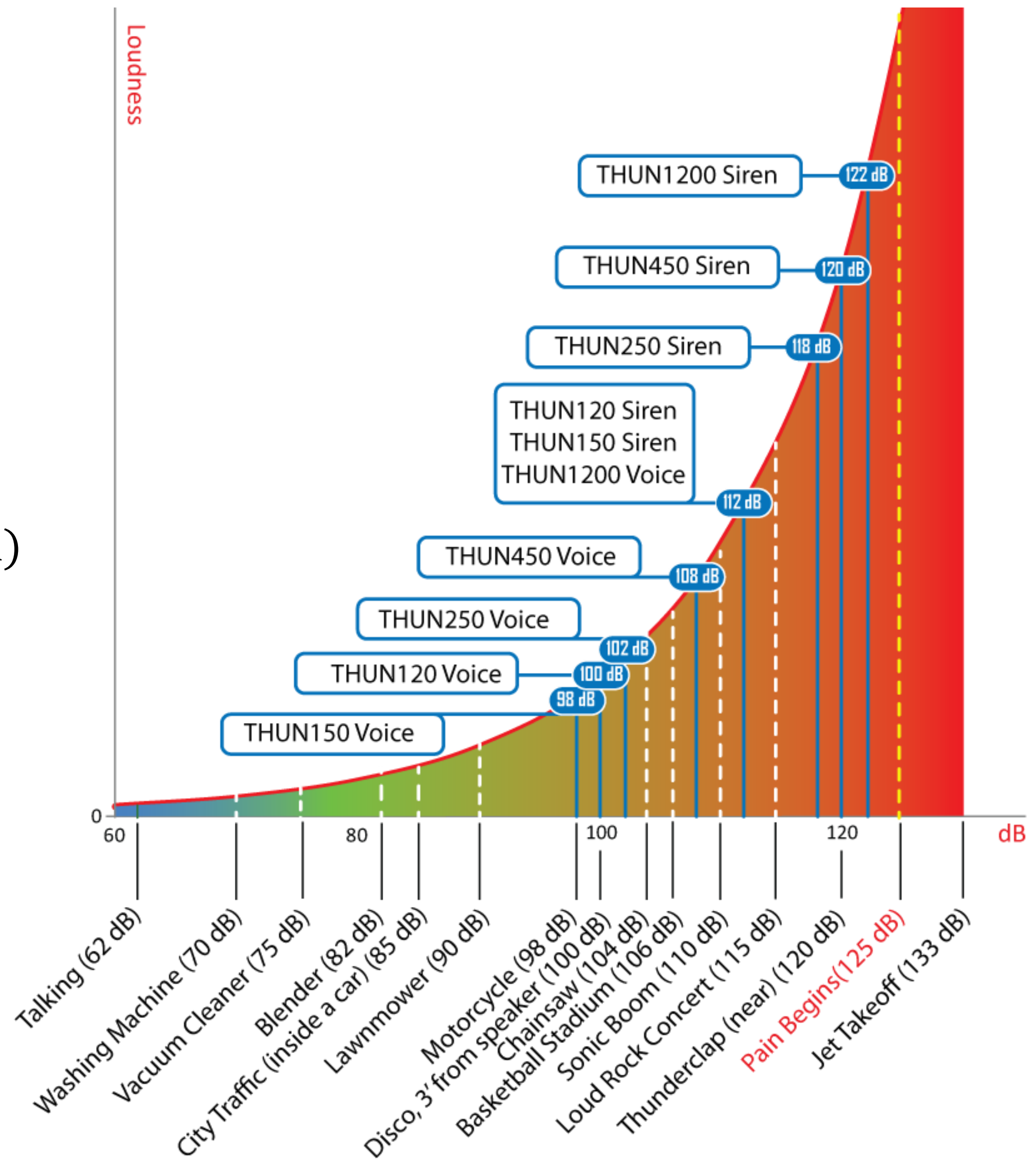
Levels of Loudness

$$\text{Loudness} = I = \frac{P}{4\pi r^2}$$

$$\text{Level} = 10 \times \log_{10}\left(\frac{P}{4\pi r^2}\right) \text{ (decibel)}$$

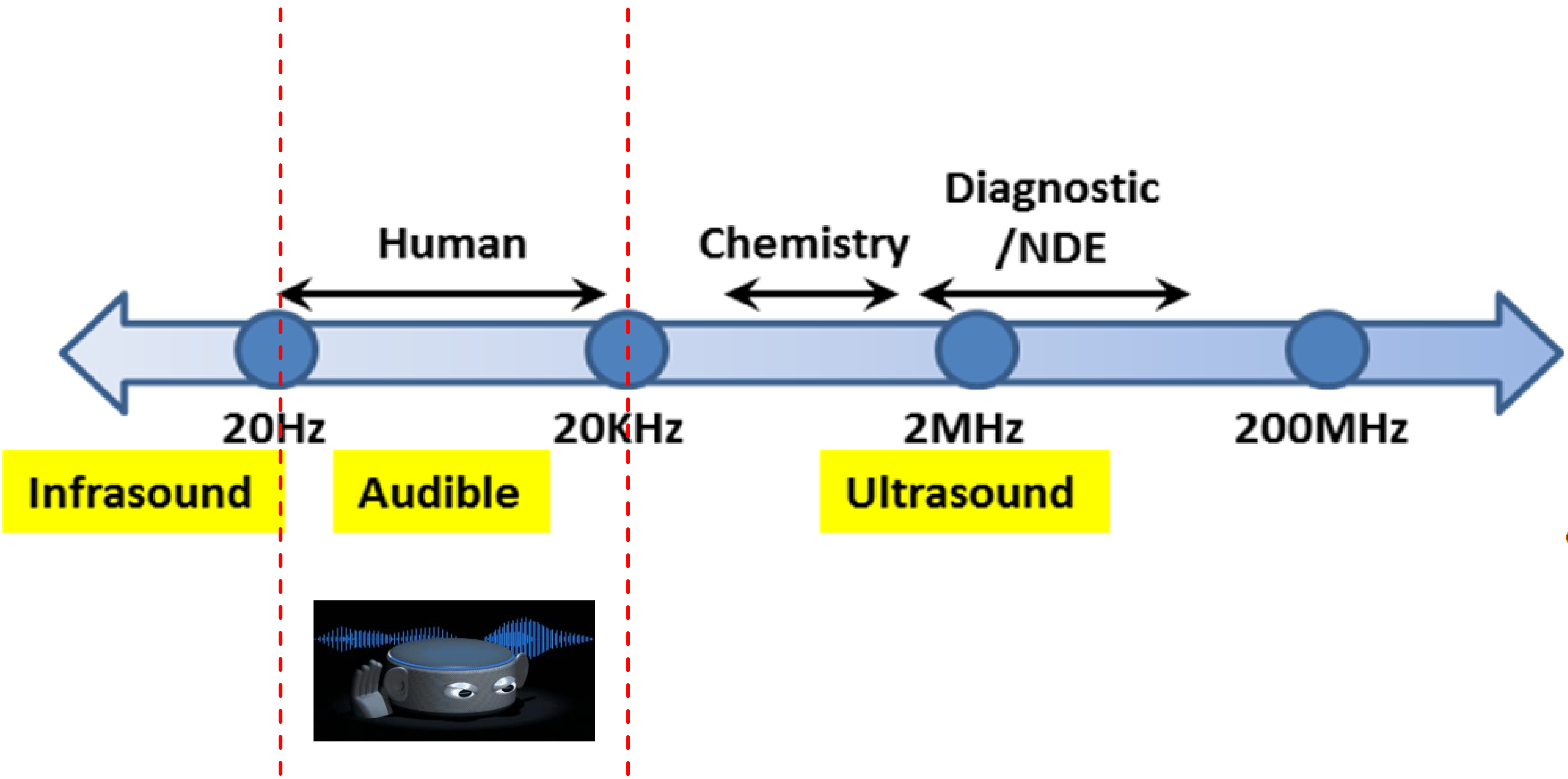
(absolute level)





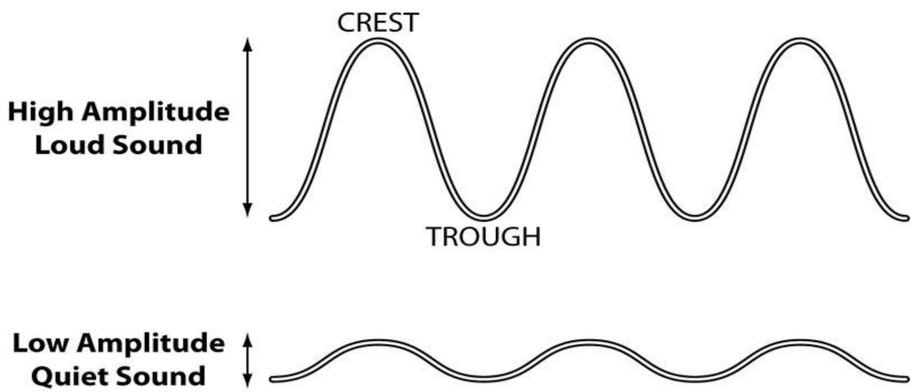
Frequency Range of Sound Signals …

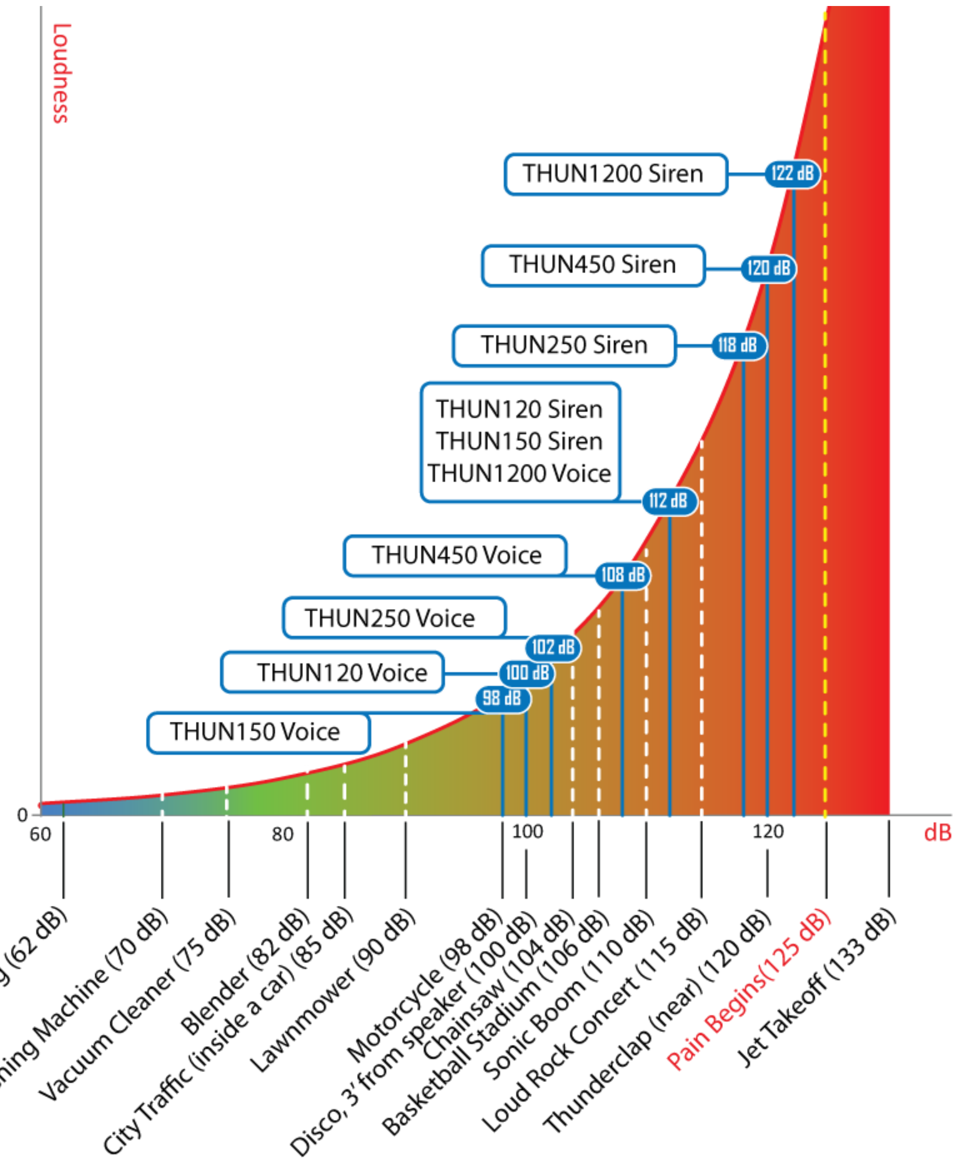
$$s(t) = \sum A \sin(2\pi f t + \varphi)$$



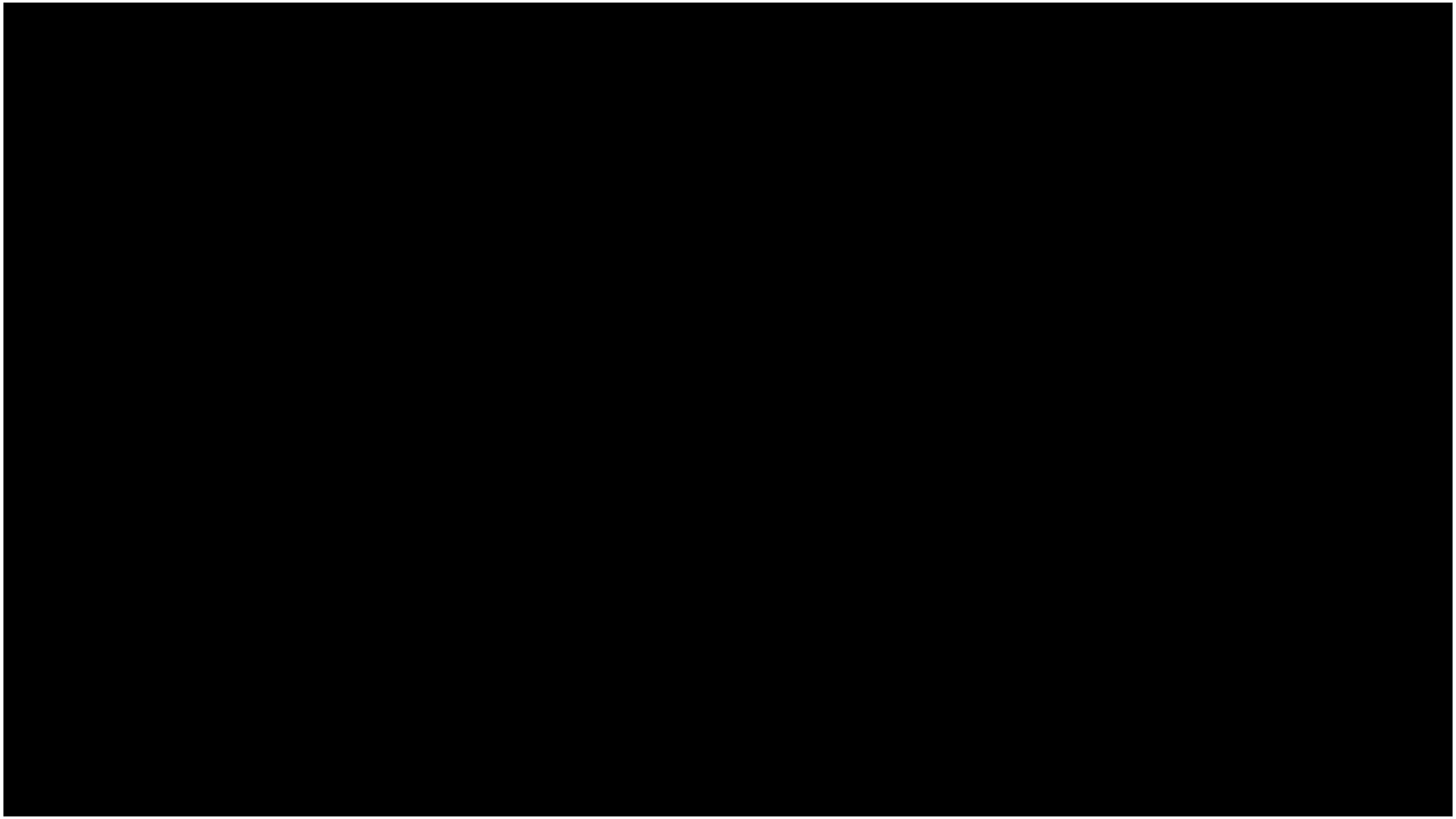
Amplitude Range of Sound Signals …

$$s(t) = \sum A \sin(2\pi f t + \varphi)$$

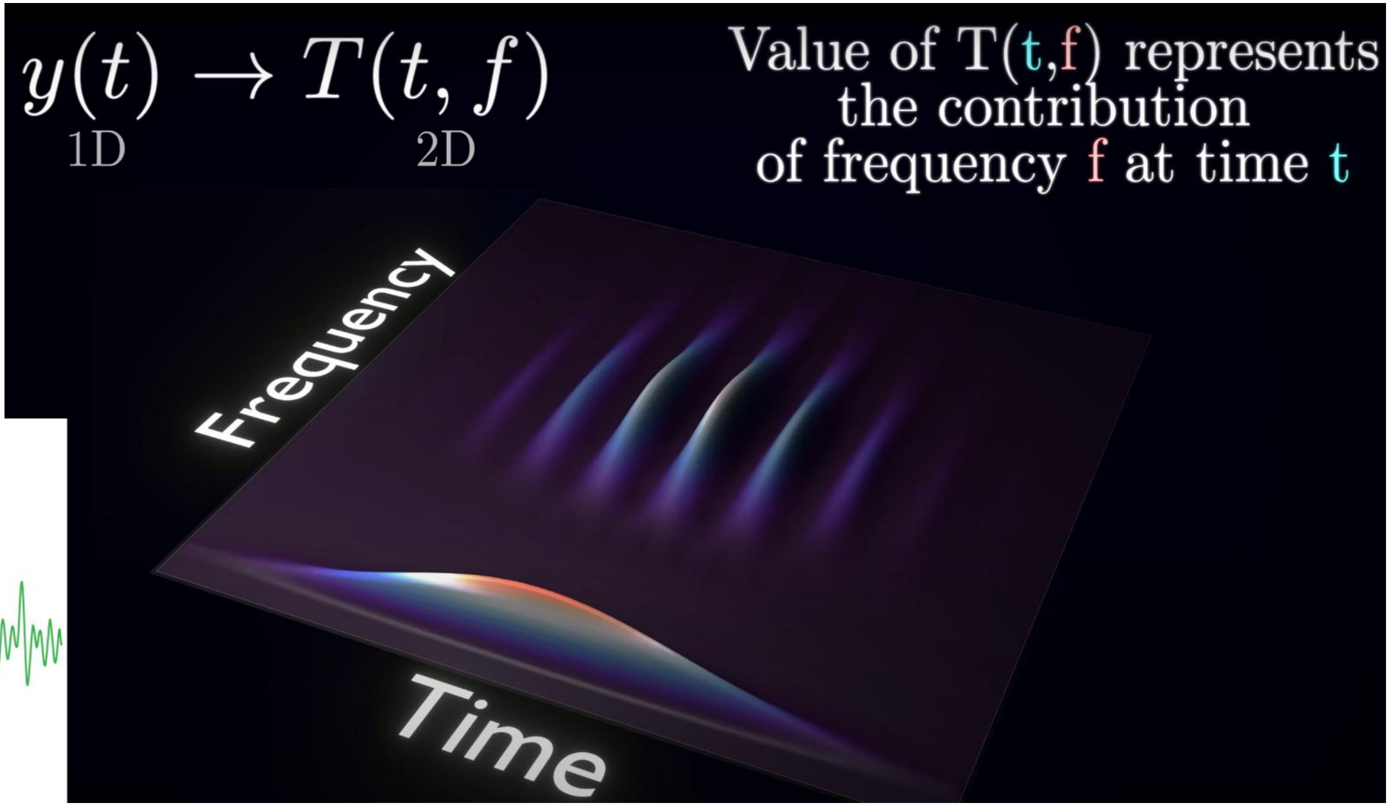




How to compute frequency information?

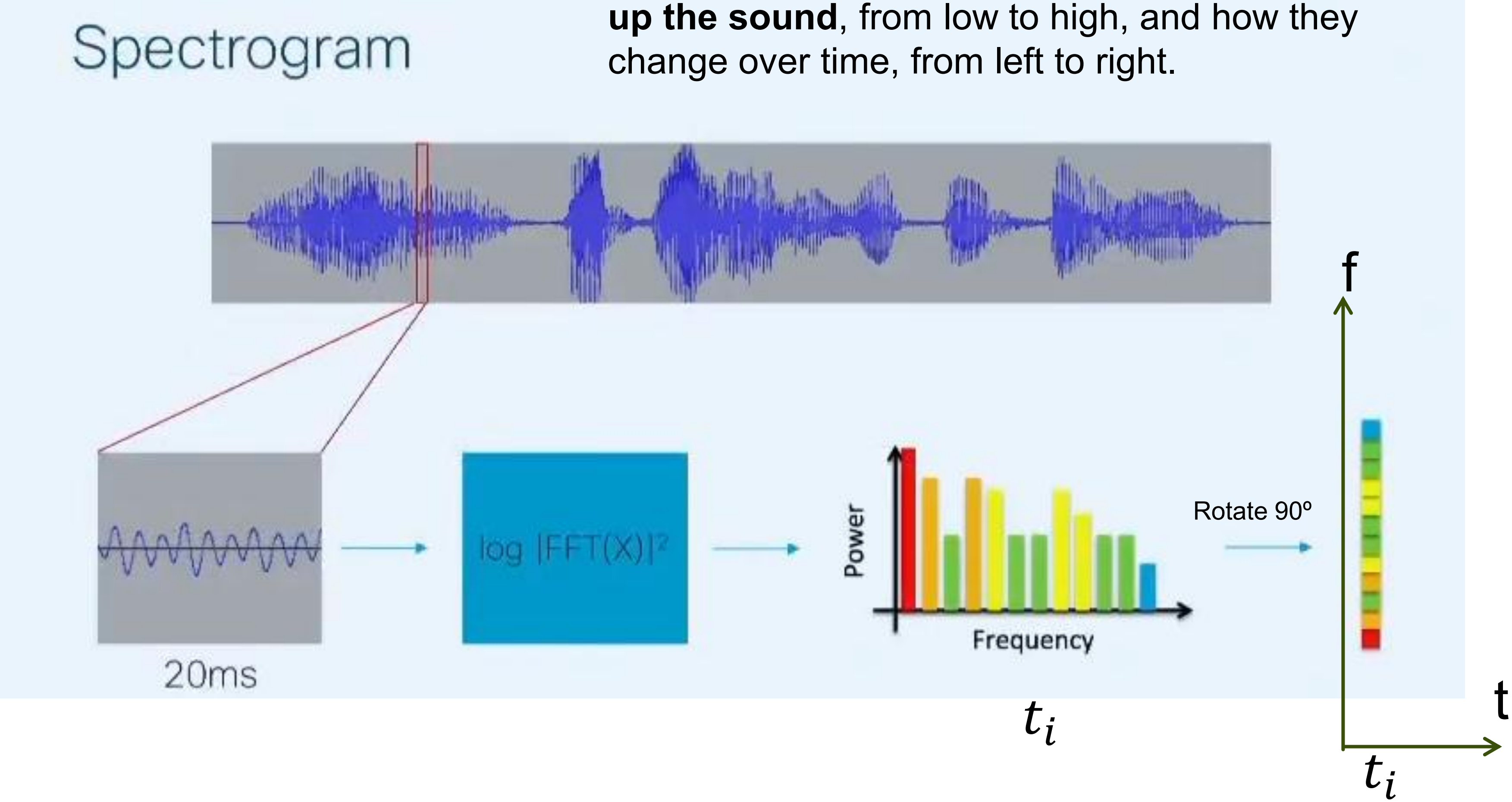


How to preserve time information?

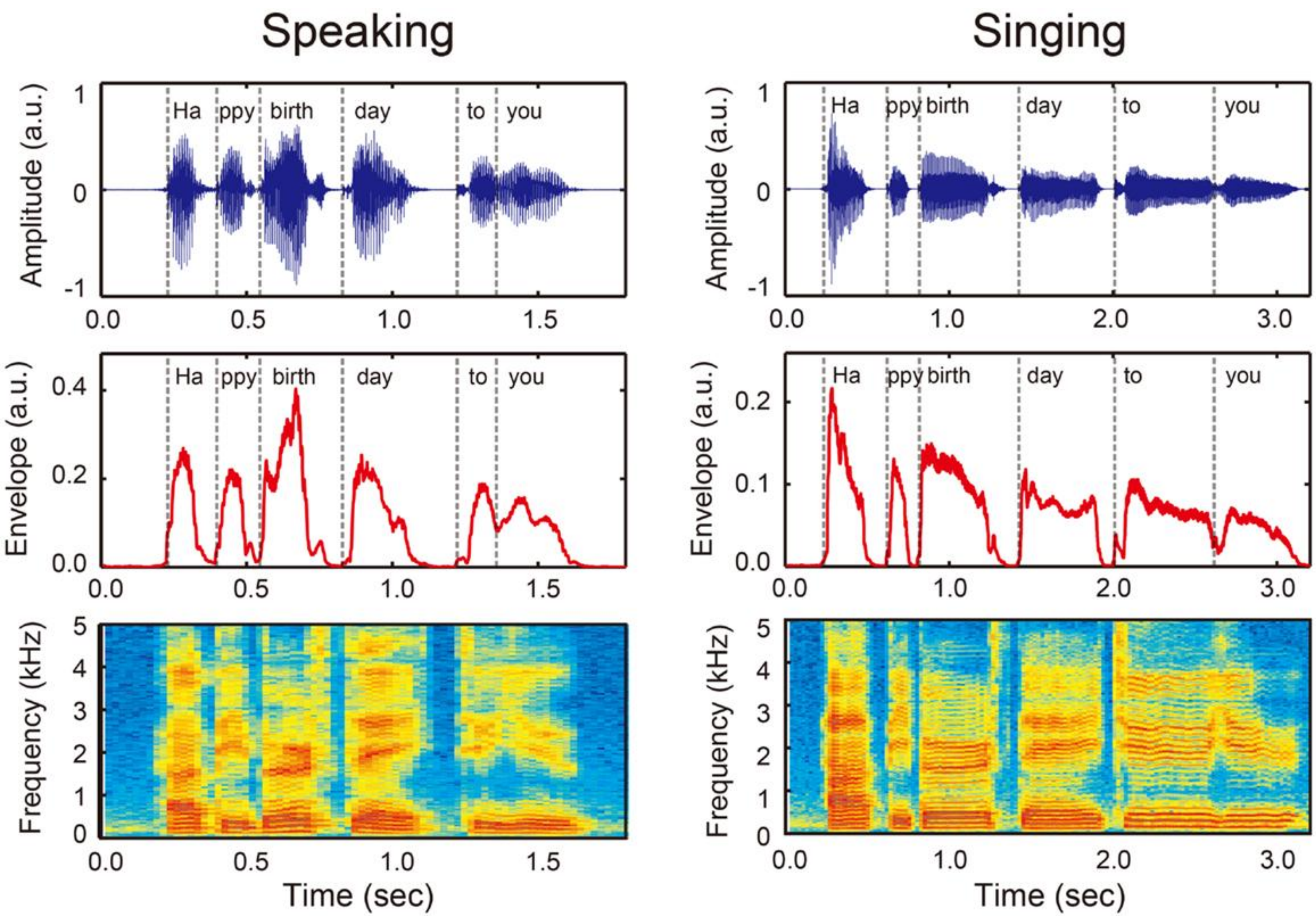


What is spectrogram of sound?

A spectrogram **shows the frequencies that make up the sound**, from low to high, and how they change over time, from left to right.

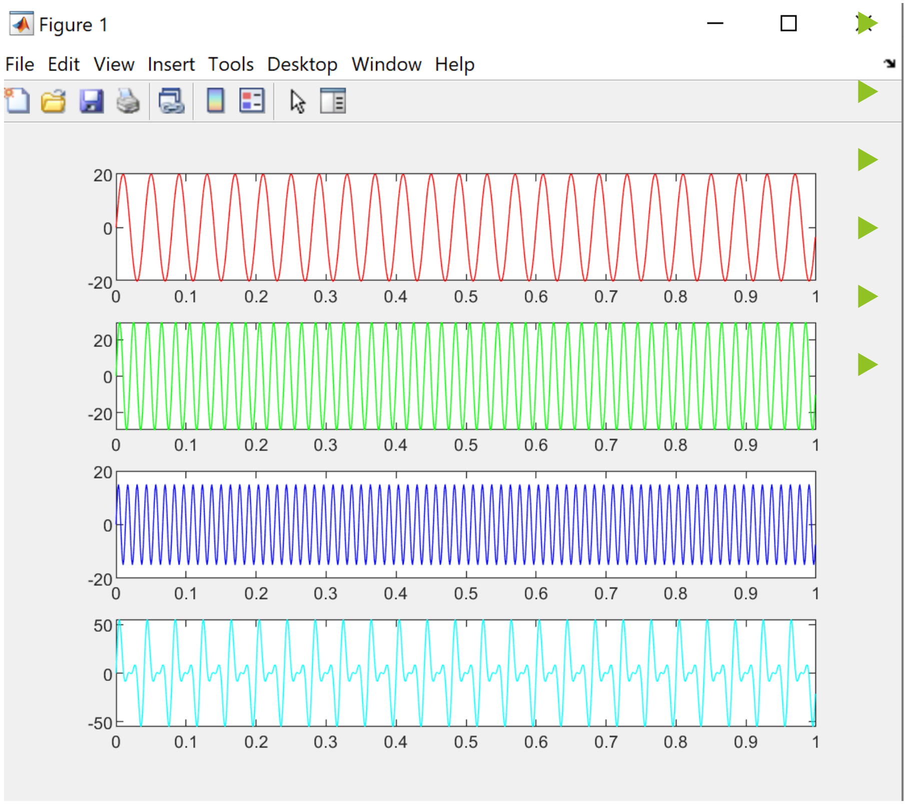


Example of Voice's Spectrogram

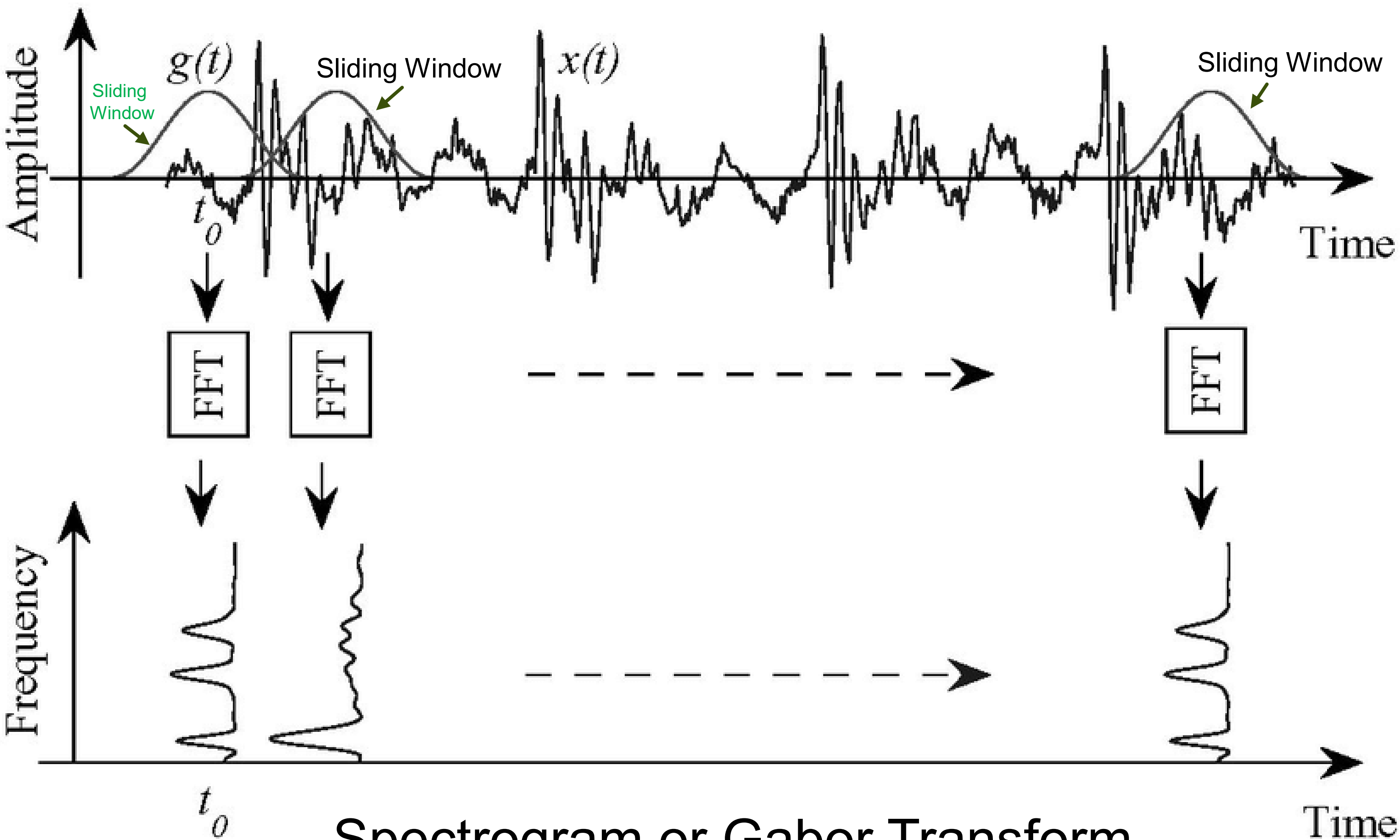


Practice with MATLAB …

```
fs = 900; ts = 1/fs;
dt = 0:ts:1-ts;  % have 900 discrete times
f1 = 25; f2 = 50;  f3 = 75;
s1= 20.0*sin(2*pi*f1*dt);
s2 = 30.0*sin(2*pi*f2*dt) ;
s3 = 15.0*sin(2*pi*f3*dt);
s  = s1 + s2 + s3;
subplot(4, 1, 1); plot(dt, s1, 'r');
subplot(4, 1, 2); plot(dt, s2, 'g');
subplot(4, 1, 3); plot(dt, s3, 'b');
subplot(4, 1, 4); plot(dt, s, 'c') ;
```

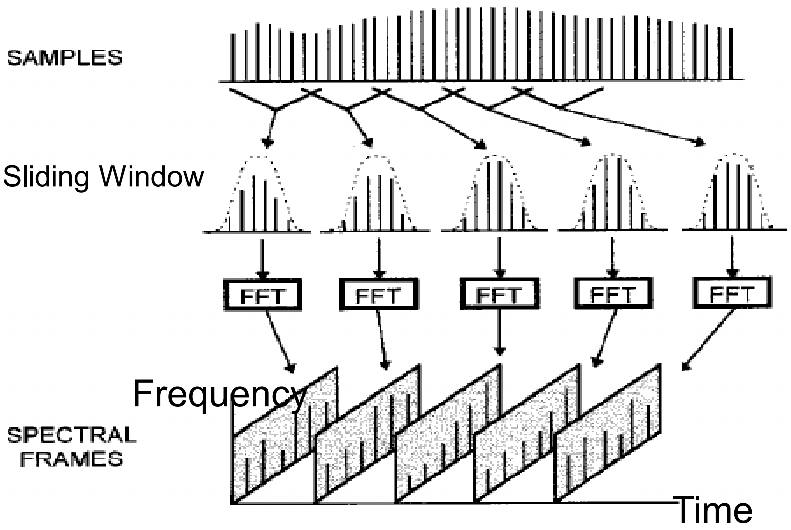


Decomposing Sound/Voice to Sine Signals ...



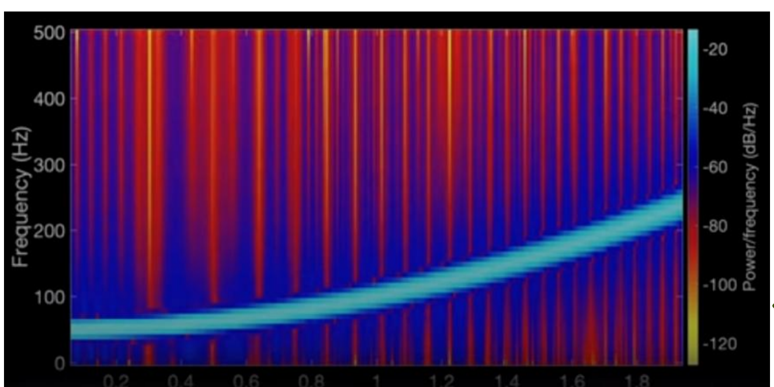
Spectrogram or Gabor Transform

More Illustration …



Sample Program in MALAB

```
clear all, close all, clc

dt=0.001;
t = 0:dt:2;
f0 = 50;
f1 = 250;
t1 = 2;
x = chirp(t,f0,t1,f1,'quadratic');
x = cos(2*pi*t.*(f0 + (f1-f0)*t.^2/(3*t1^2)));

sound(4*x,1/.001)
plot(t,x)
%%

% There is a typo in Matlab documentation...
% ... divide by 3 so derivative amplitude matches frequency

spectrogram(x,128,120,128,1e3,'yaxis')
colormap jet

set(gca,'LineWidth',1.2,'FontSize',36);
set(gcf,'Position',[2500 100 1550 800]);
```



A Practice of FFT with MATLAB …

```
fs = 900; ts = 1/fs;
dt = 0:ts:1-ts;  % have 900 discrete times
f1 = 25; f2 = 50;  f3 = 75;
s1= 20.0*sin(2*pi*f1*dt);
s2 = 30.0*sin(2*pi*f2*dt) ;
s3 = 15.0*sin(2*pi*f3*dt);
s  = s1 + s2 + s3;
slength = length(s);
slengthtopowertwo = 2^nextpow2(slength);
ftdatafull = fft(s, slengthtopowertwo);
ftdatahalf = ftdatafull(1:slengthtopowertwo/2);
subplot(2, 1, 1); plot(abs(ftdatafull),'r');
subplot(2, 1, 2); plot(abs(ftdatahalf), 'g');
```

Result ...

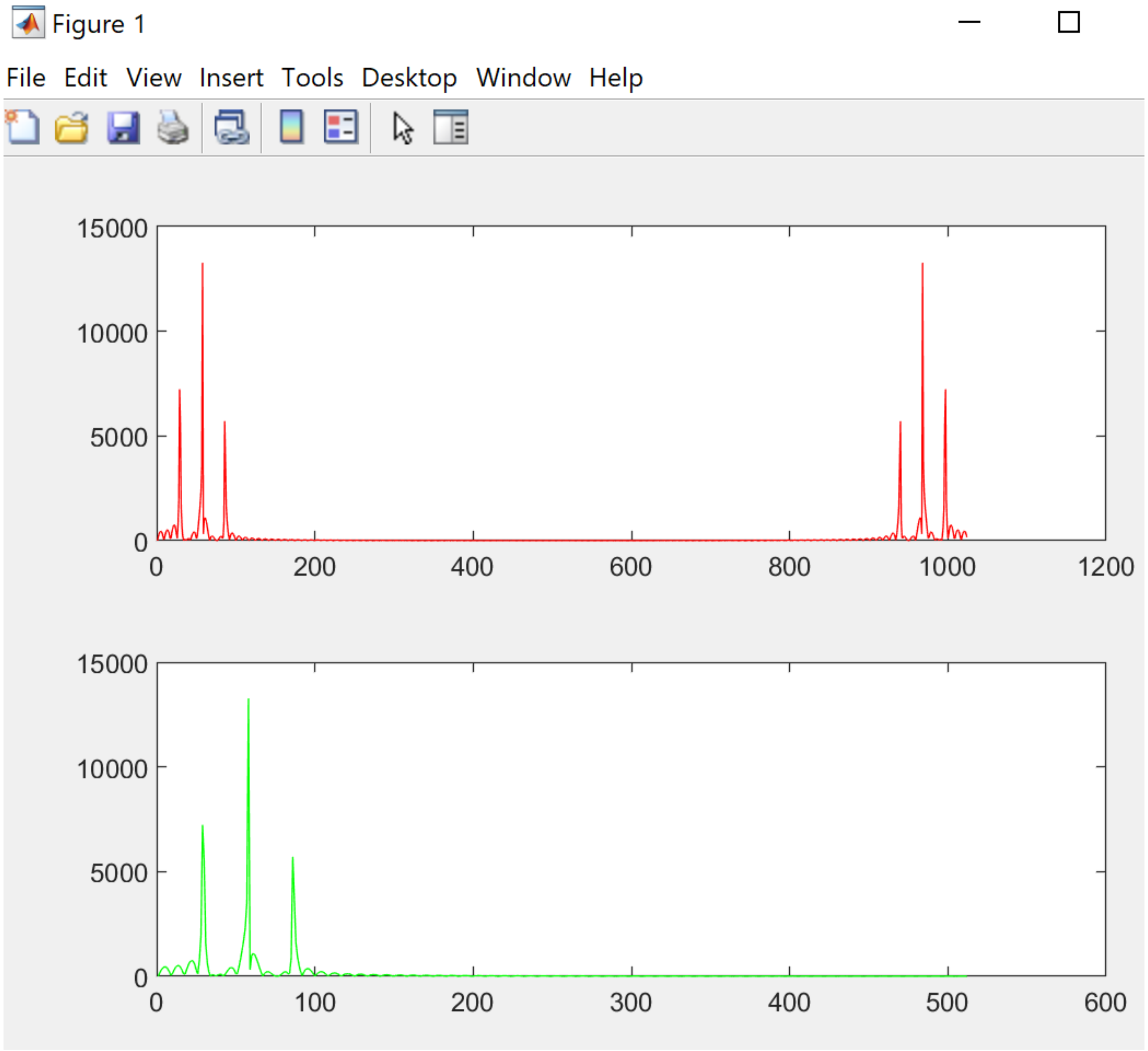
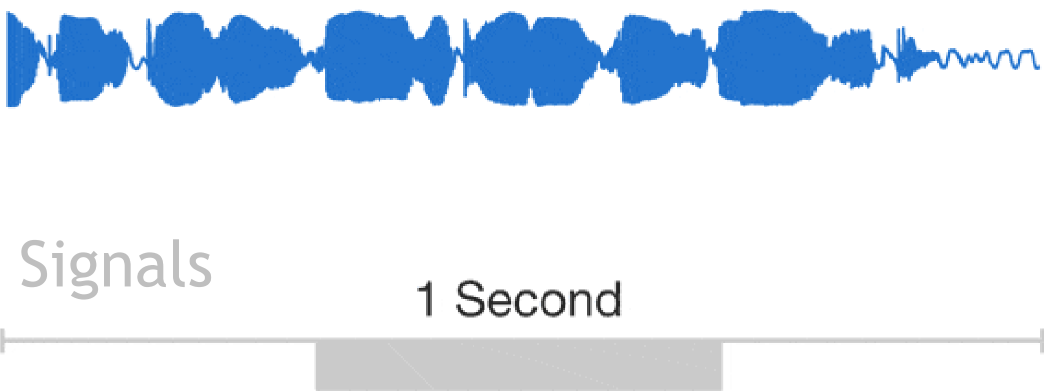


Figure 1
File Edit View Insert Tools Desktop Window Help
15000
10000
5000
0
0
200
400
600
800
1000
1200
15000
10000
5000
0
0
100
200
300
400
500
600

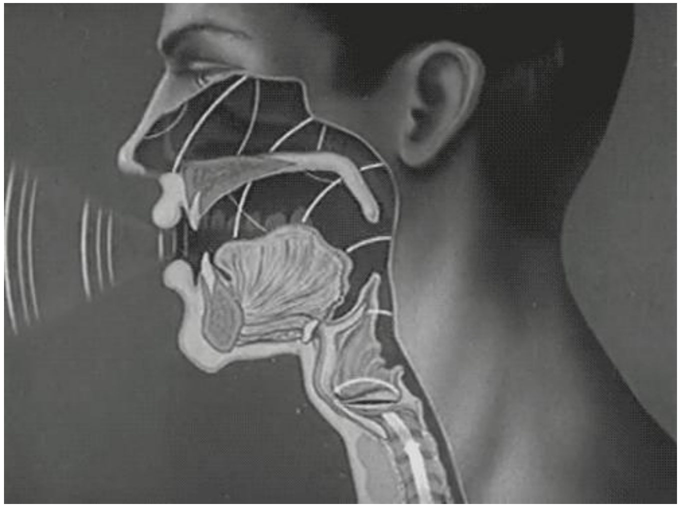
Outline



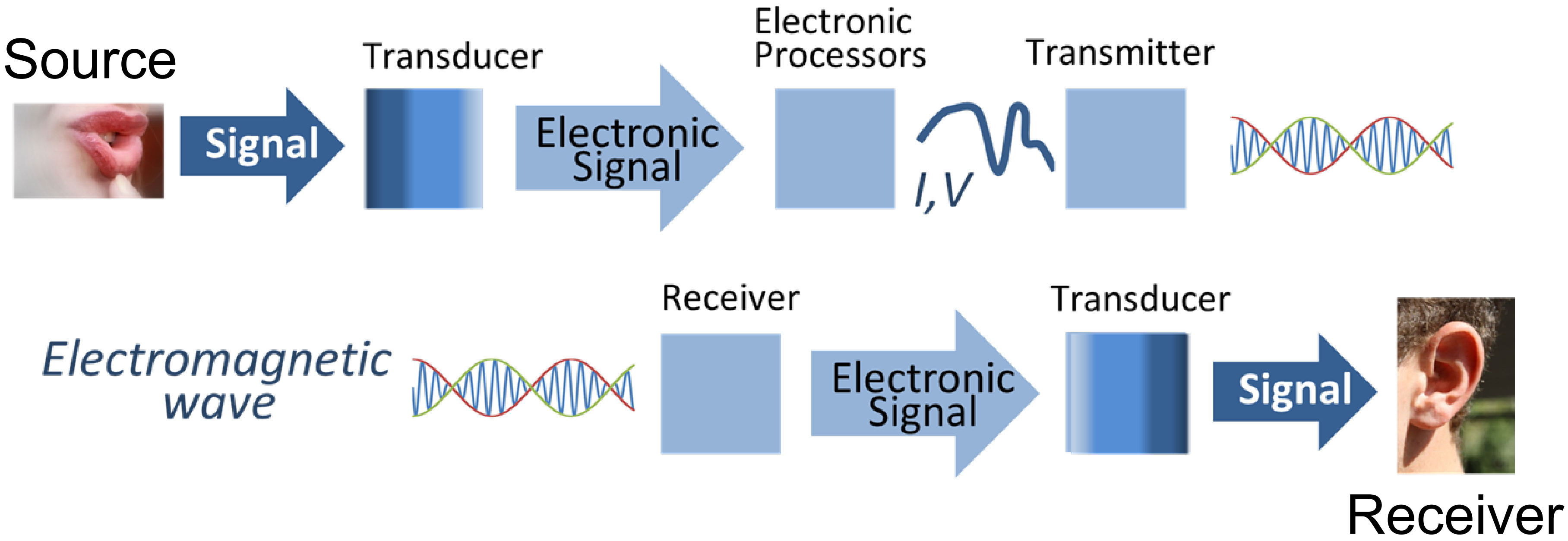
- Understanding of Acoustic Signals
- Computation of Acoustic Signals
- Measurement of Acoustic Signals

⇩

Processing of Acoustic Signals

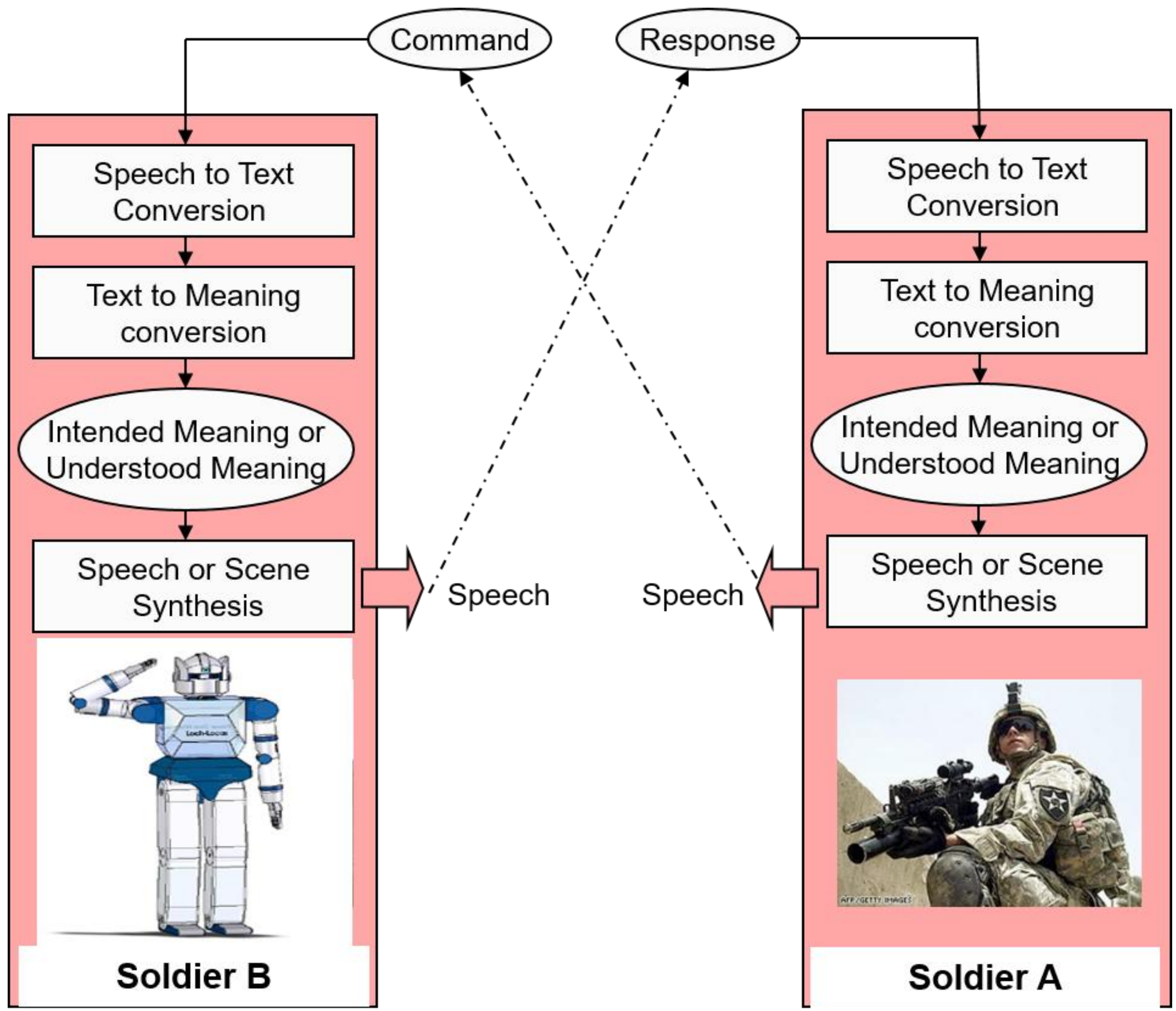


Sound/voice enable conversational dialogues among human beings …

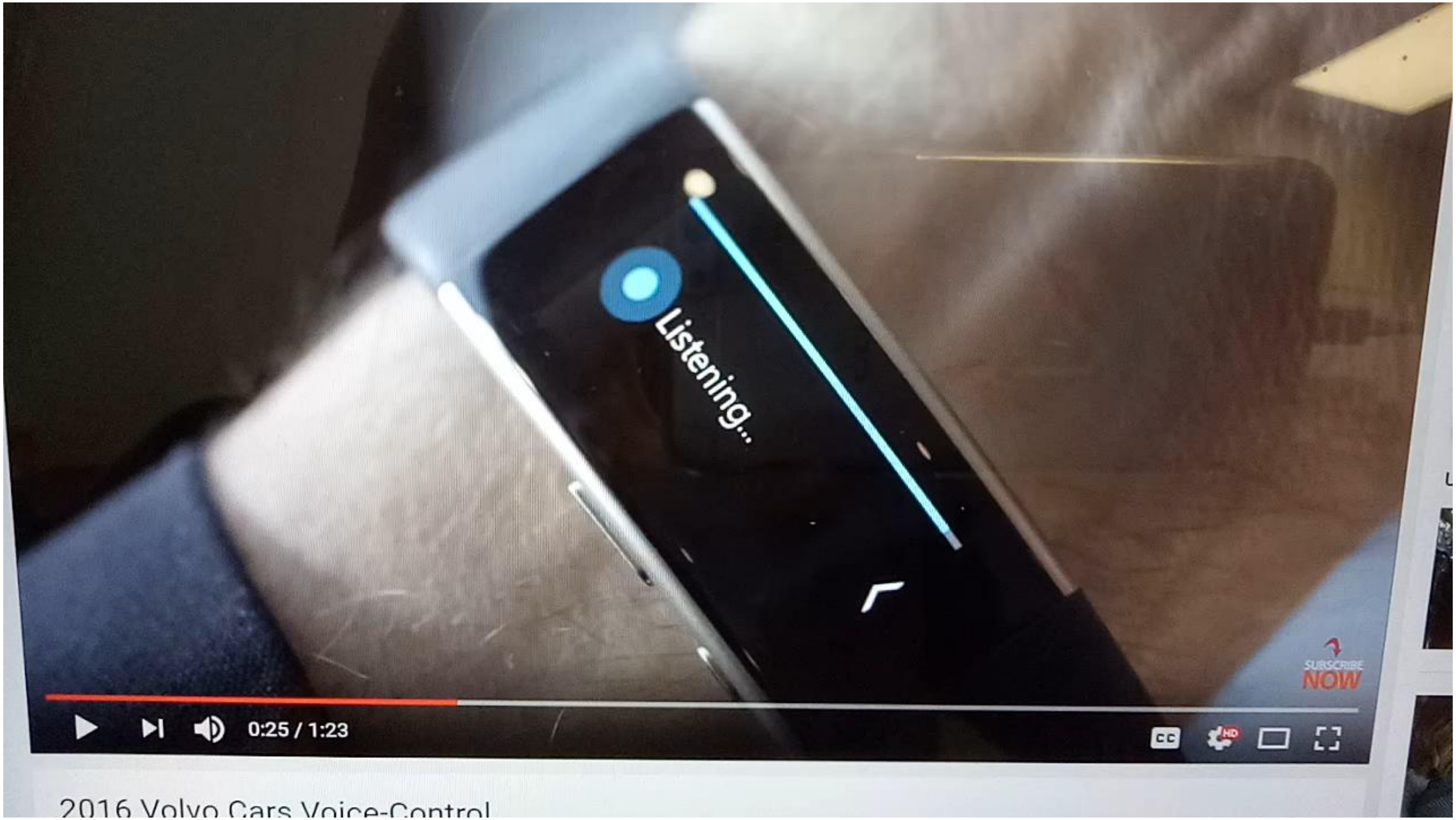


Sound/voice enable conversational dialogues between human being and robot …

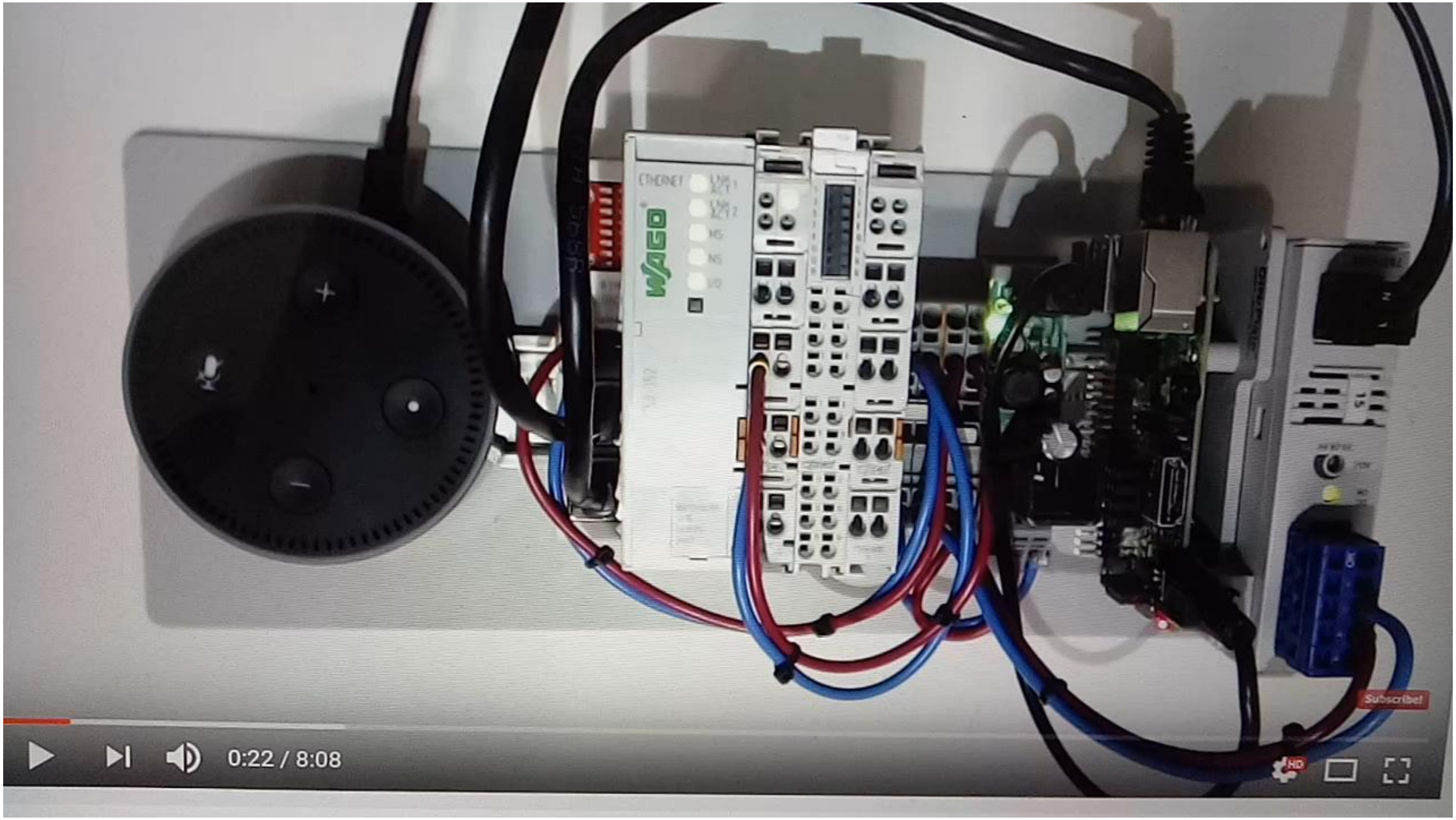
From Our 2008's Project



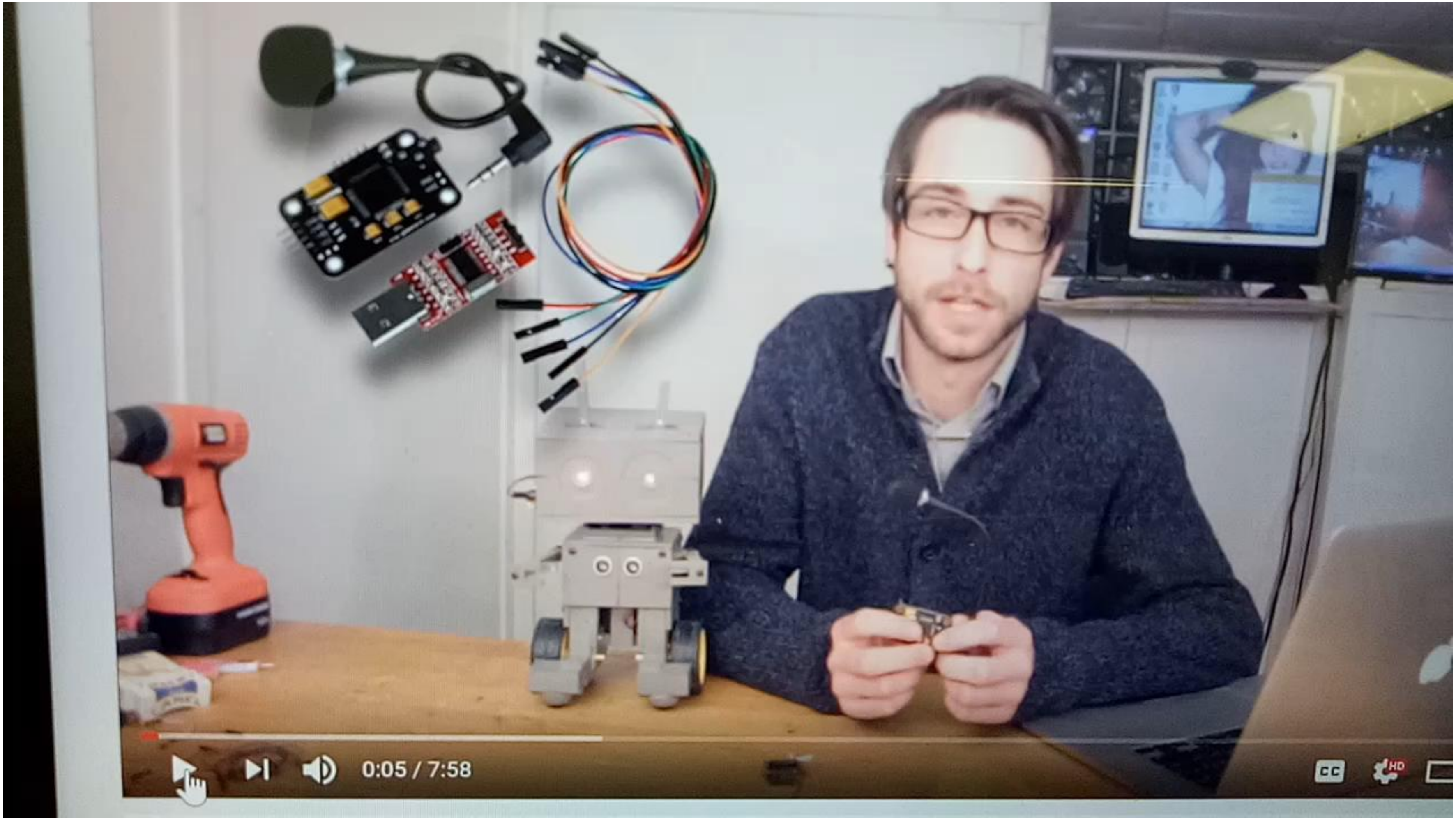
Applications in Transportation …



Applications in Automation …



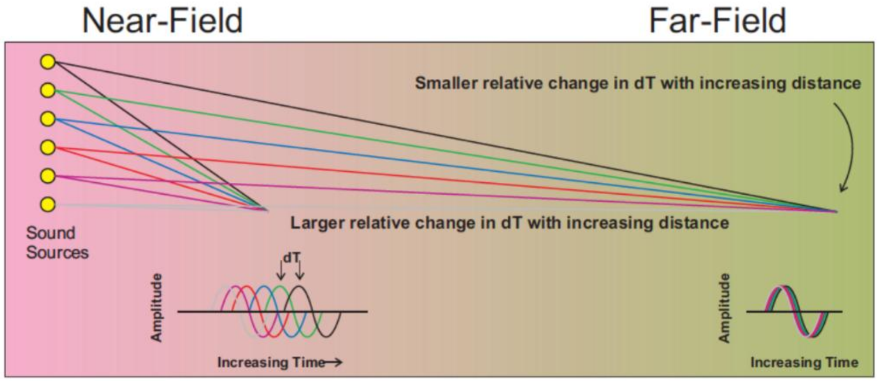
Applications in Robotics …

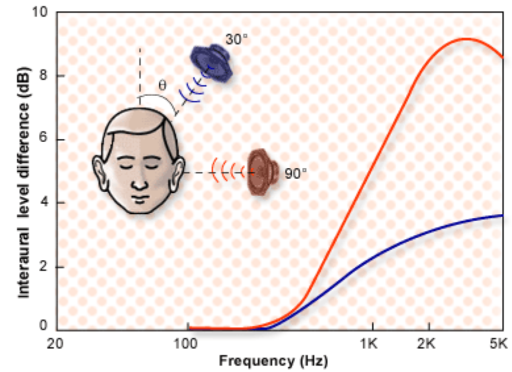


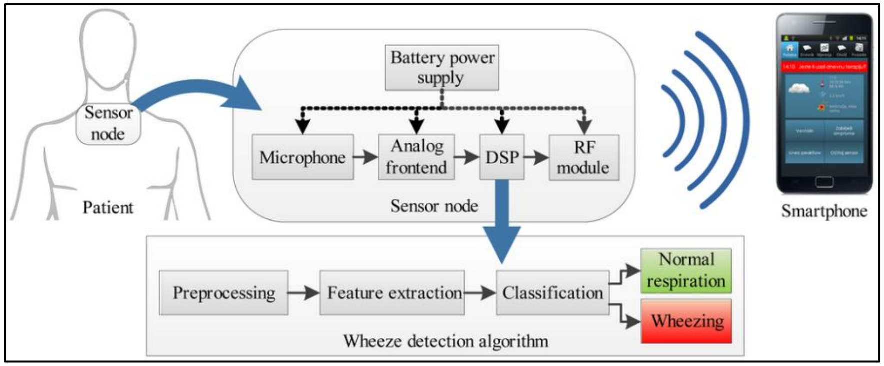
Applications in Medical Field …

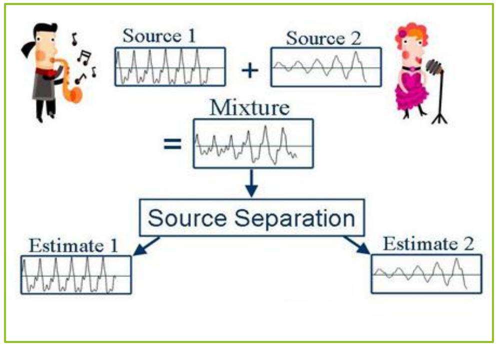
Applications in Medical Field …

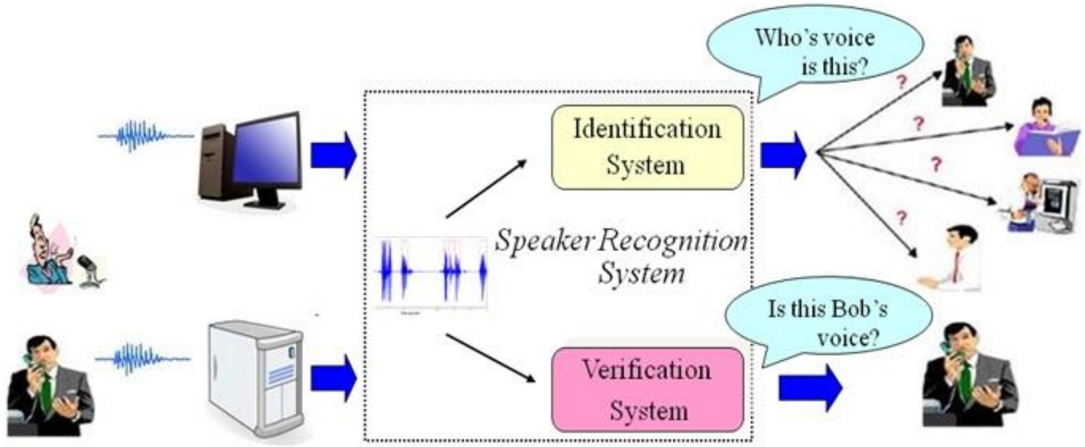
Many Other Possible Applications





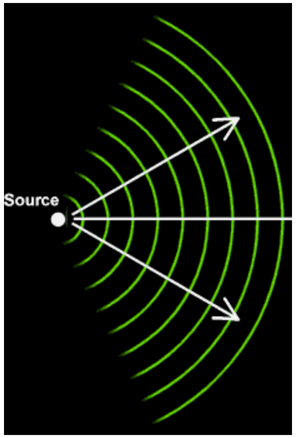


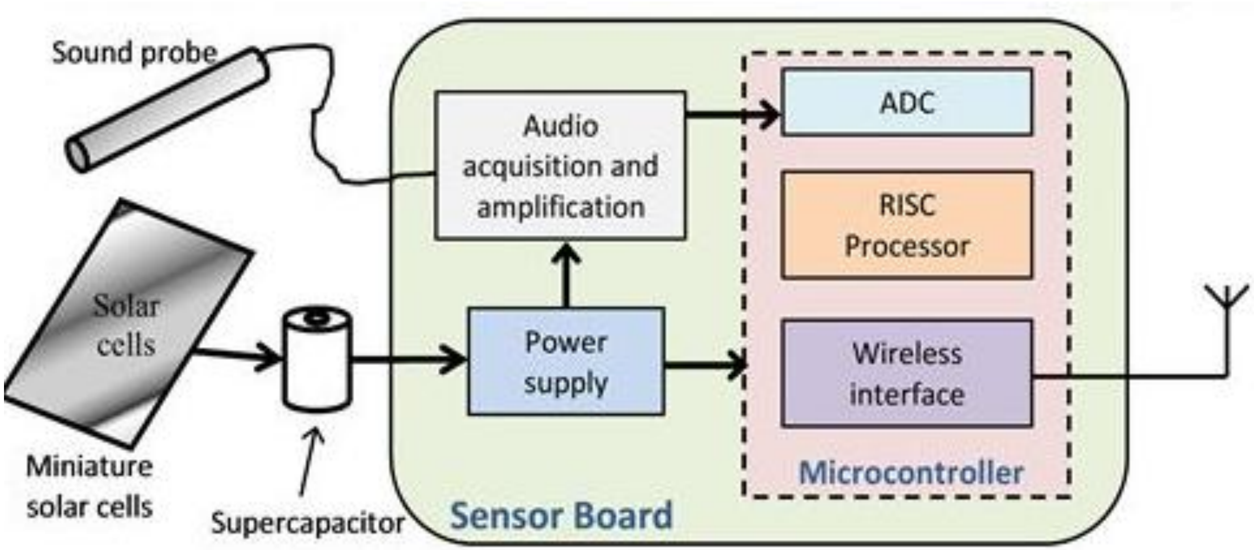




Principles of Measurement

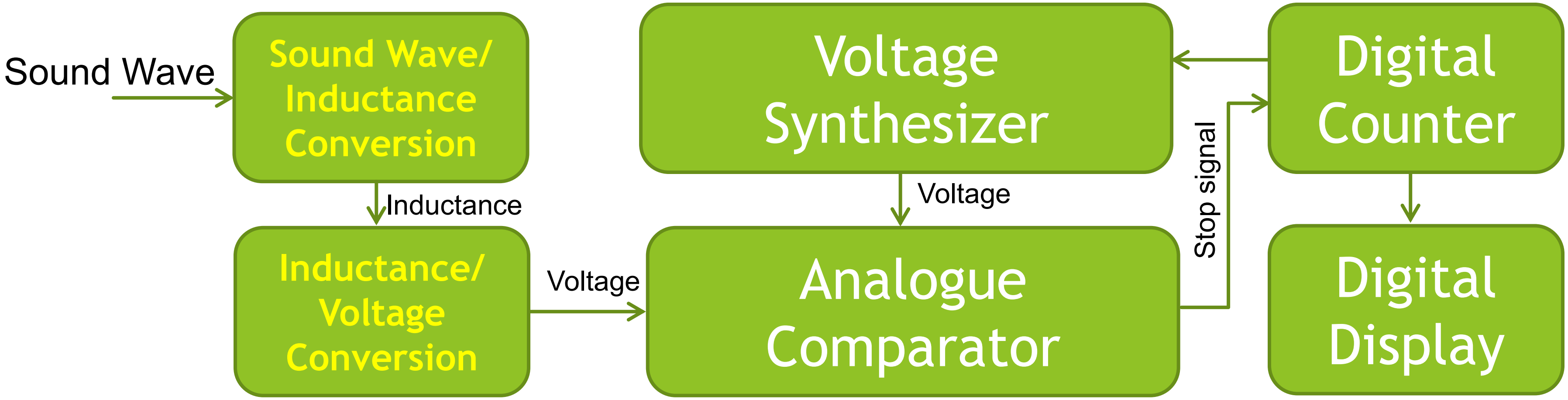
- Principle 1: Sound wave is converted into variations of inductance, which are then converted into time signals of voltage. The voltage signal could be measured automatically.
- Principle 2: Sound wave is converted into variations of capacitance, which are then converted into time signals of voltage. The voltage signal could be measured automatically.
- Principles 3: Sound wave is directly converted into time signals of voltage, which could be measured automatically.





How to apply principle 1 to design digital measurement and sensing systems for acoustic signals?

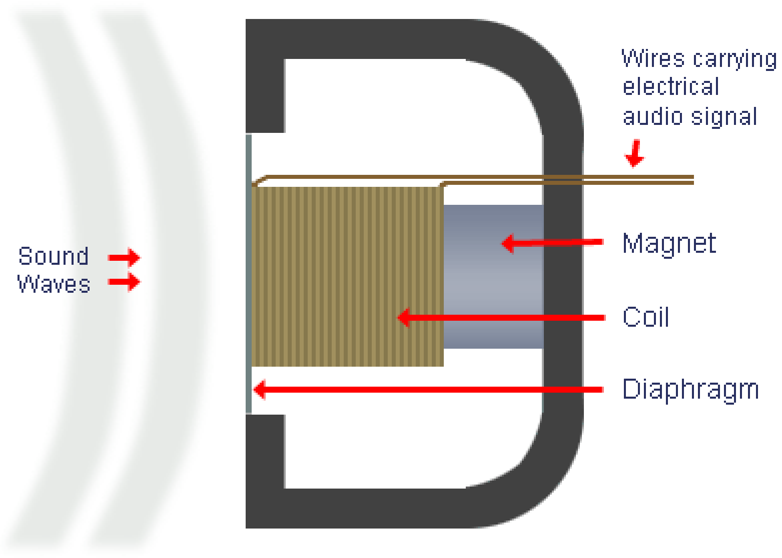
- Sound wave is converted into variations of inductance, which are then converted into time signals of voltage. Voltage signal is measured by digital voltmeter (e.g. microcontrollers).



All microcontrollers are programmable digital sensors of voltage!

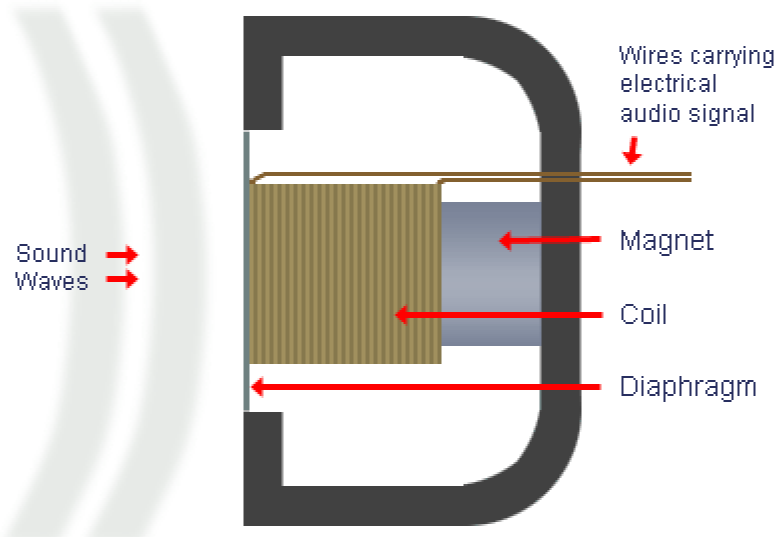
How to convert sound wave to variations of inductance?

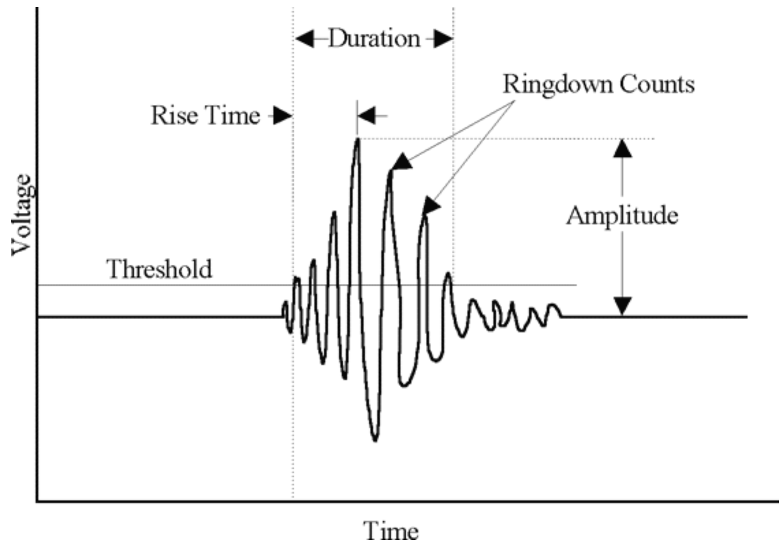
- Air pressure acts on the diaphragm and makes it vibrate.
- The vibration of diaphragm makes the voice coils to vibrate.
- The motion of voice coils makes the inductance of the coils to change.



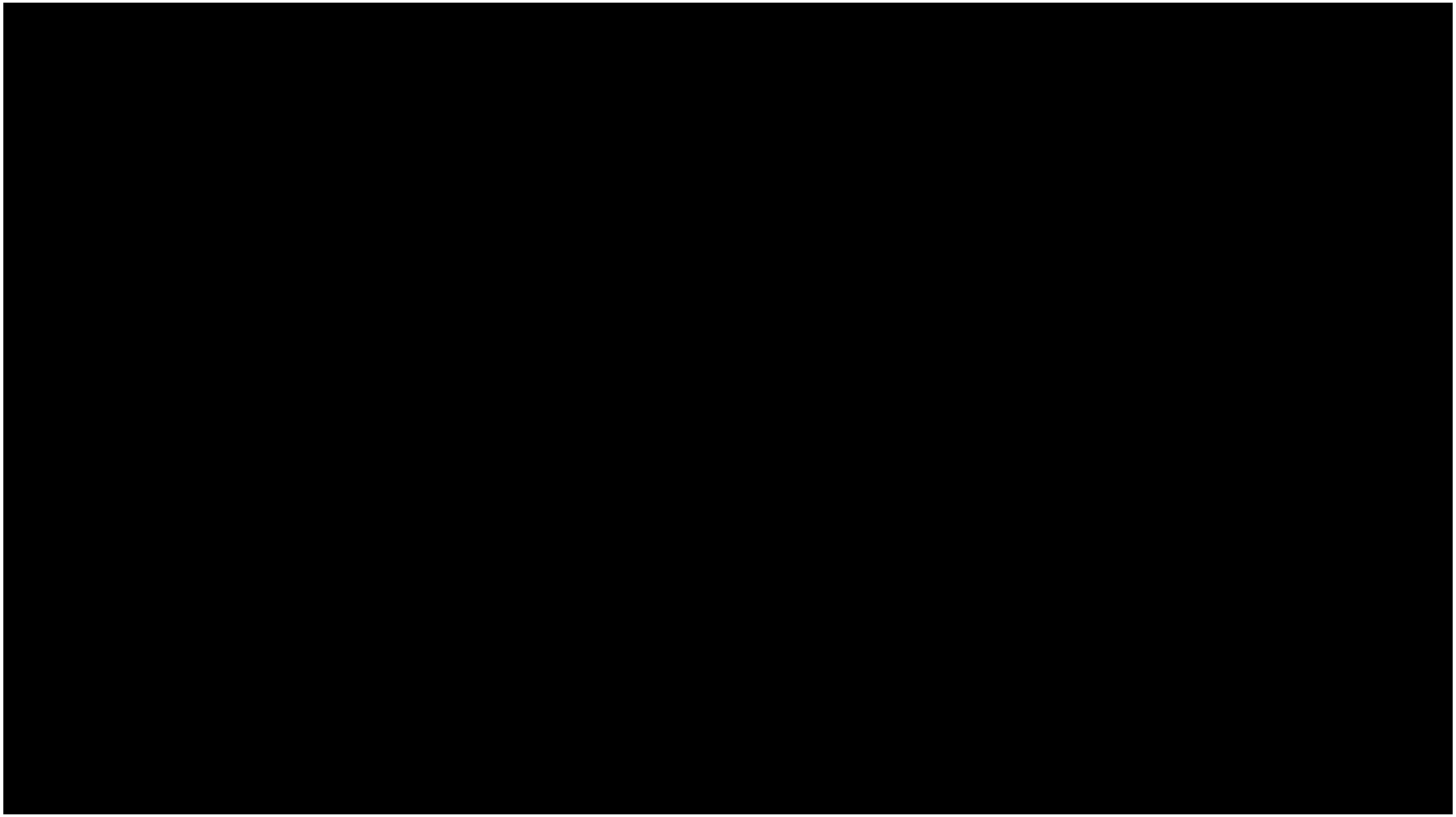
How to convert variations of inductance into voltage signals?

- A permanent magnet is placed inside the voice coils.
- When the voice coils vibrate, the magnetic flux inside the voice coils changes.
- Such changes of magnetic flux will produce electric charges in voice coils.



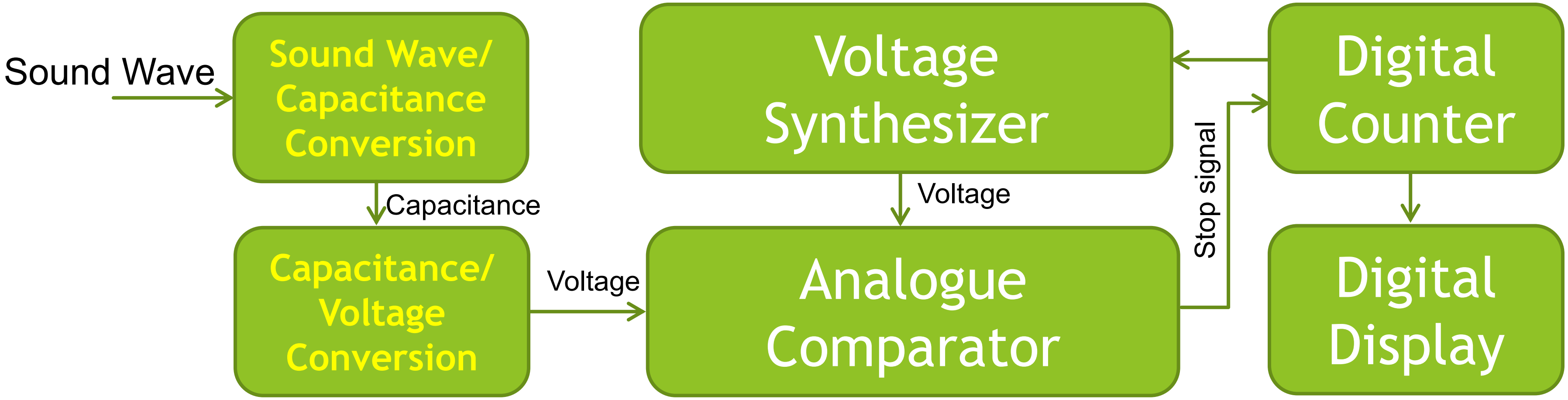


Example of Implementation …



How to apply principle 2 to design digital measurement and sensing systems for acoustic signals?

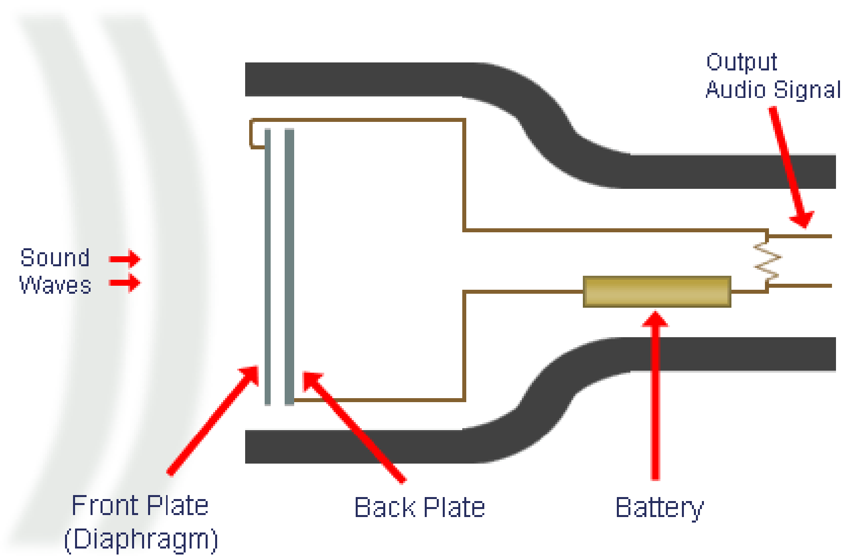
- Sound wave is converted into variations of capacitance, which are then converted into time signals of voltage. Voltage signal is measured by digital voltmeter (e.g. microcontrollers).



All microcontrollers are programmable digital sensors of voltage!

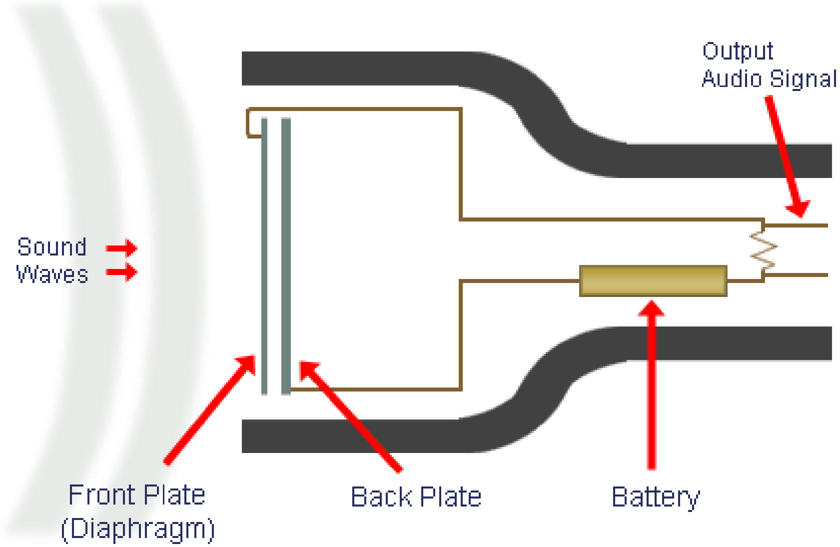
How to convert sound wave into variations of capacitance?

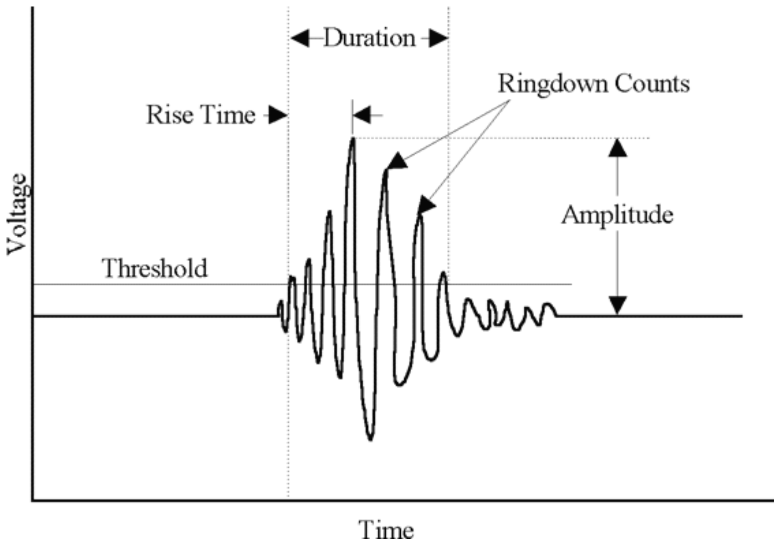
- Air pressure acts on the diaphragm and makes it vibrate.
- The vibration of diaphragm makes one plate to vibrate.
- The motion of the plate changes the capacitance.



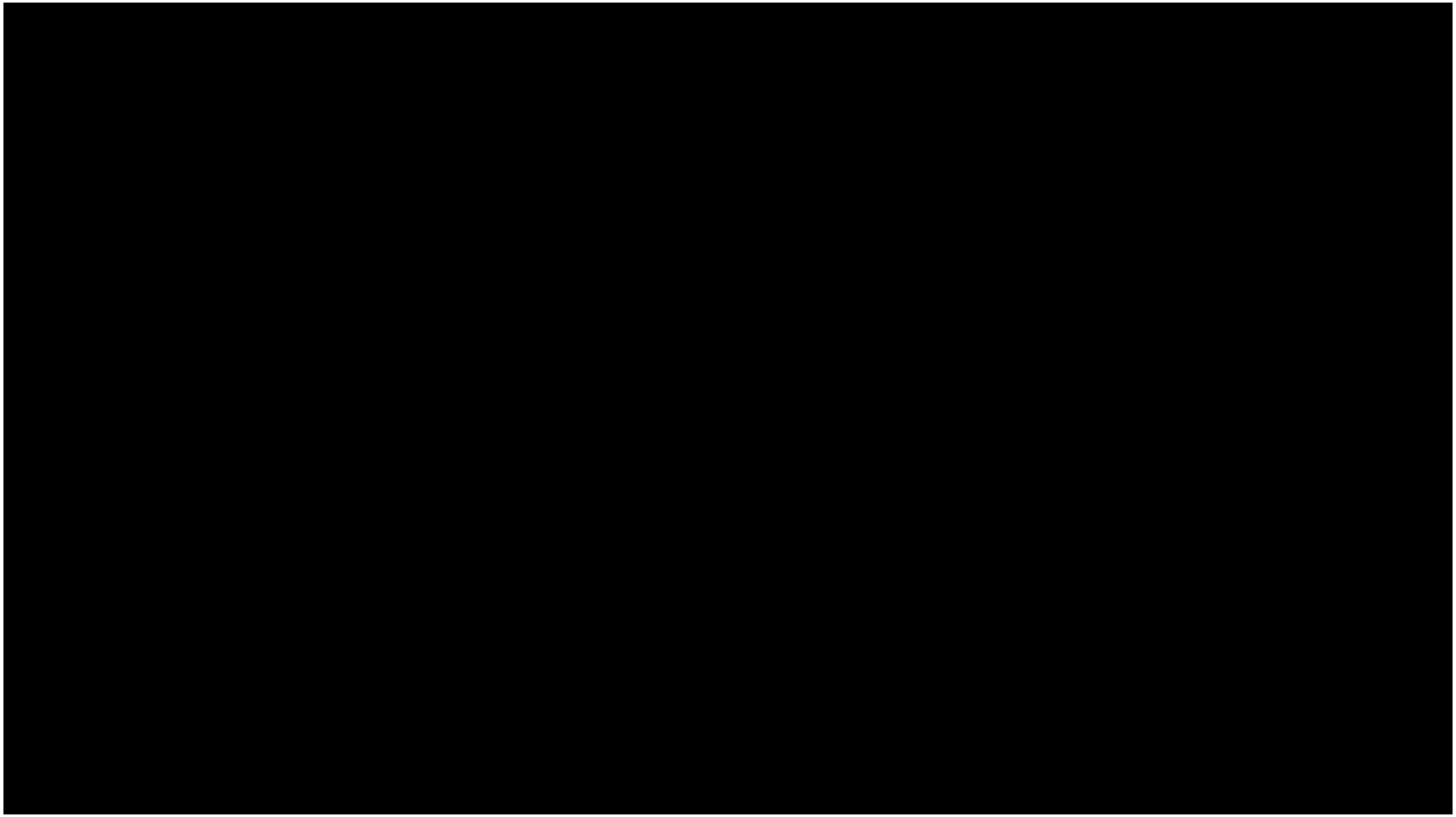
How to convert variations of capacitance into voltage signal?

- The capacitor together with a resistor forms a RC circuit.
- The RC circuit is powered by a constant DC source.
- When the capacitance changes, there will be a flow of electrons inside the RC circuit, which will produce voltage signal across the resistor.



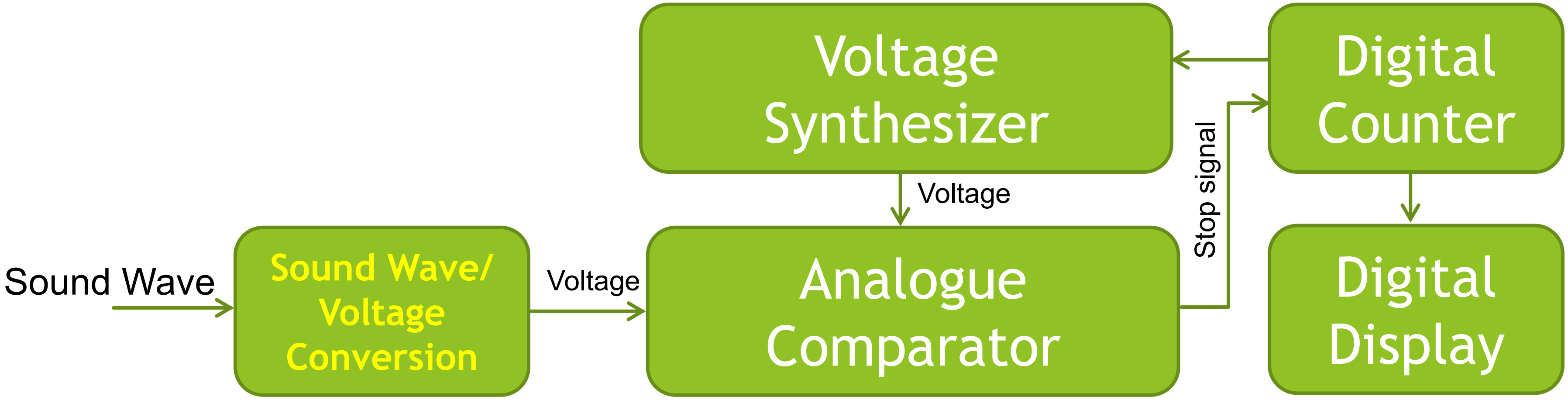


Example of Implementation …



How to apply principle 3 to design digital measurement and sensing systems for acoustic signals?

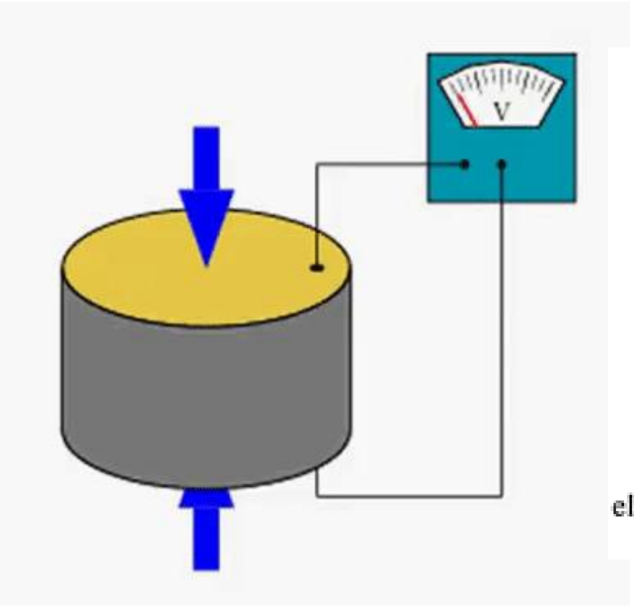
- Sound wave is directly converted into signals of voltage. Then, voltage signal is measured by digital voltmeter (e.g. microcontrollers).

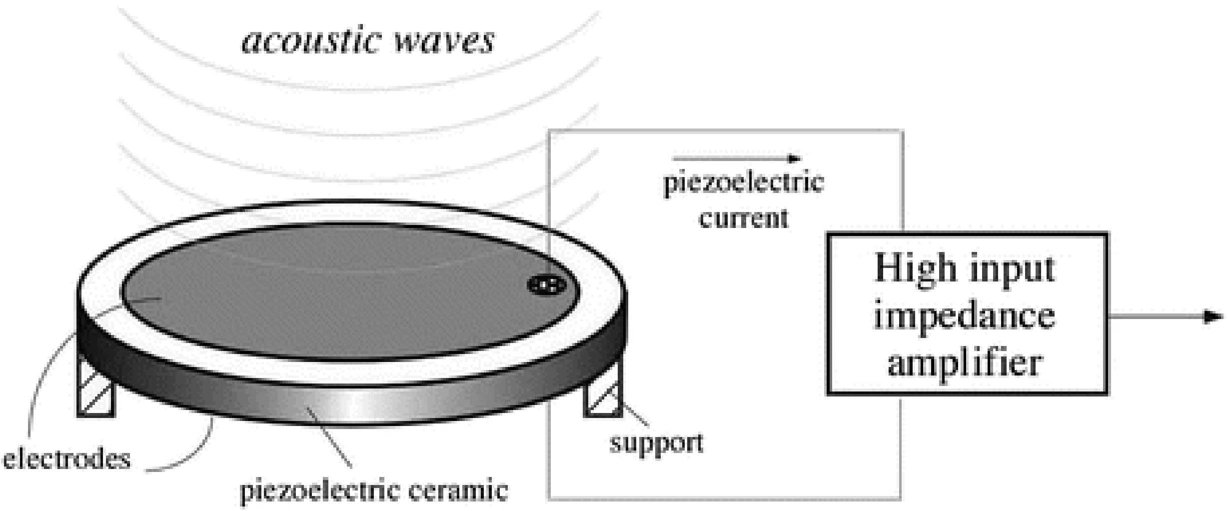


All microcontrollers are programmable digital sensors of voltage!

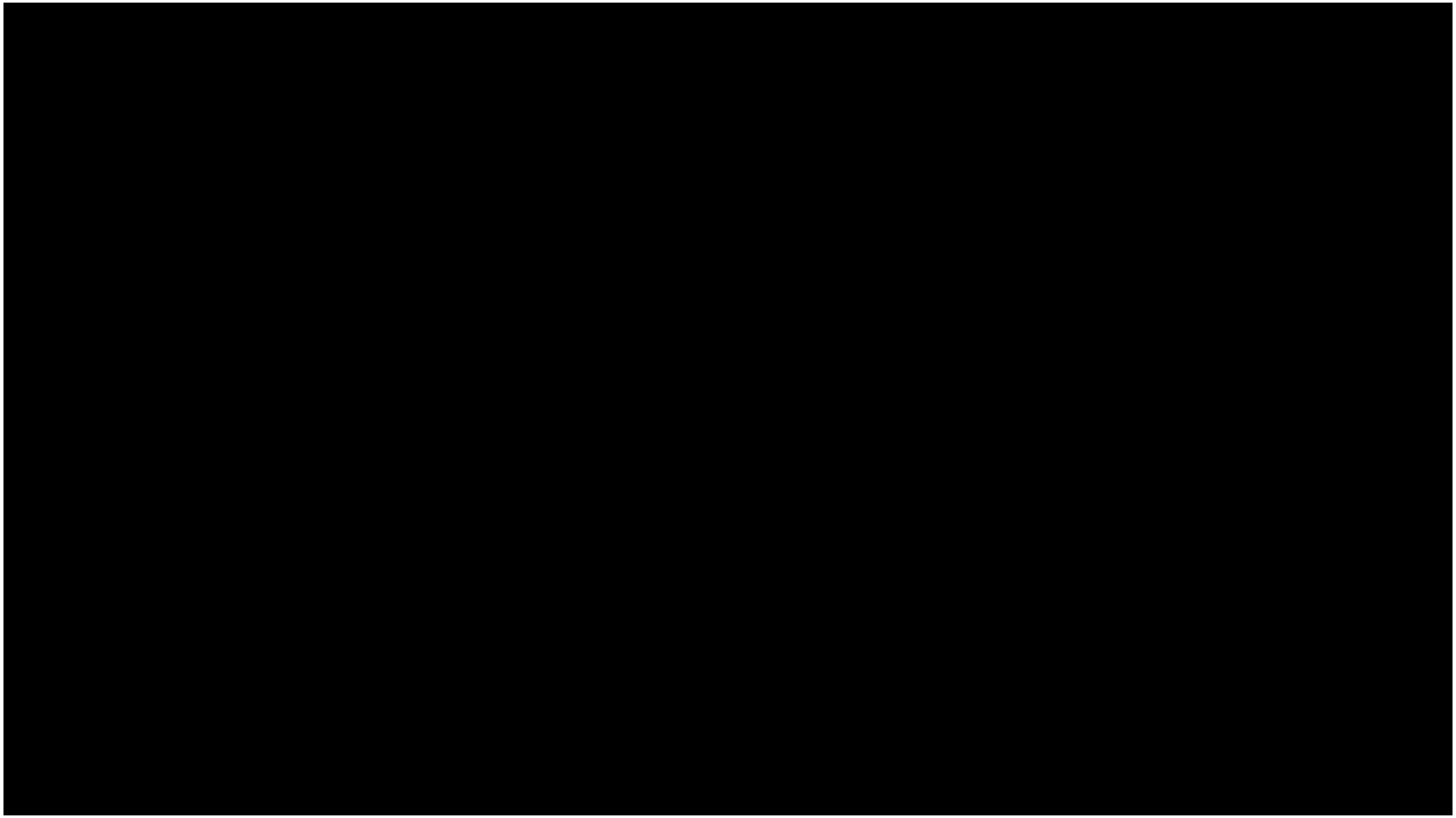
How to convert sound wave into time signals of voltage directly?

- To use piezoelectric transducer.





Example of Implementation …

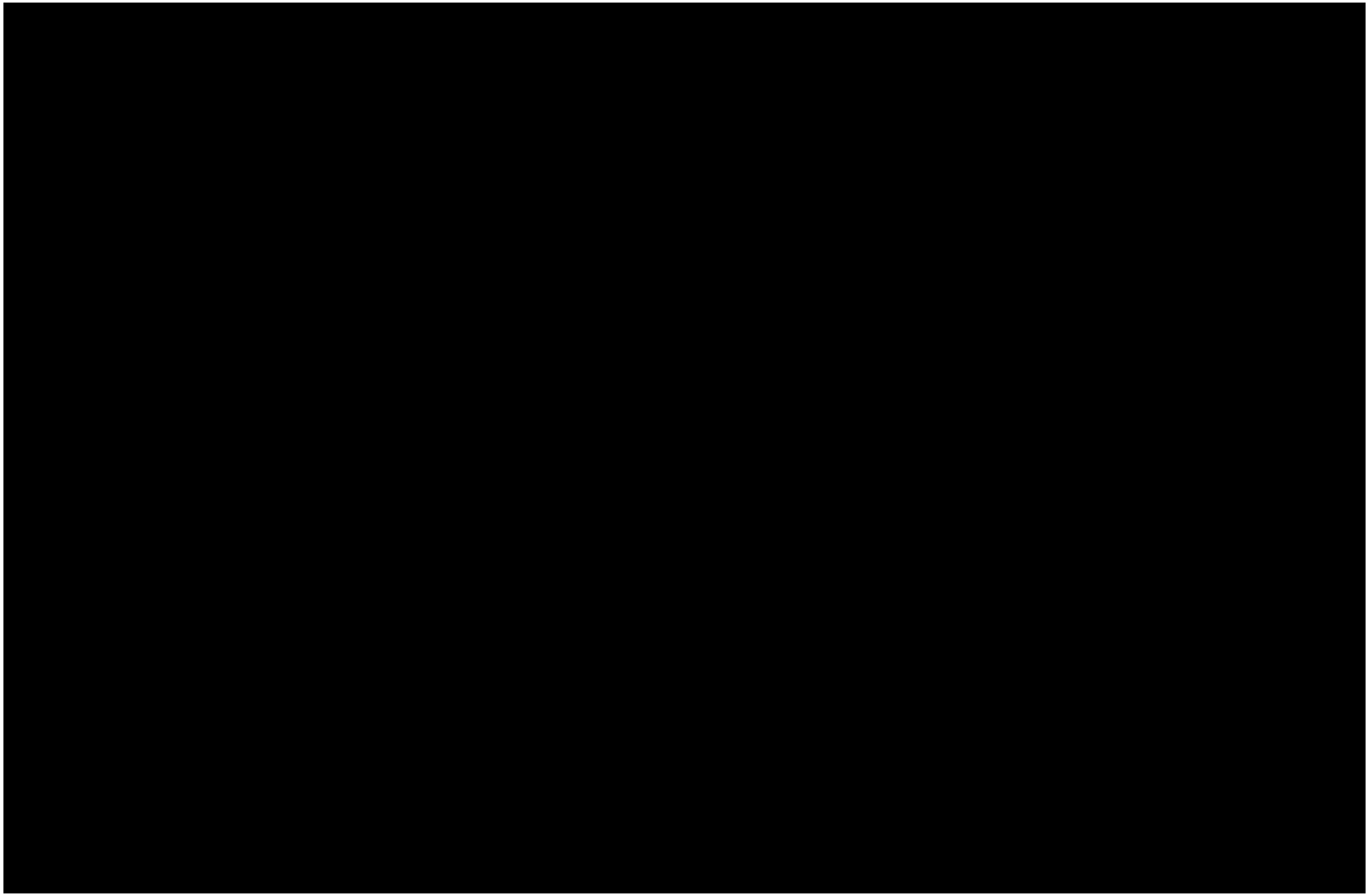


More Example of Implementation …

A Practice of Voice Acquisition with MATLAB …

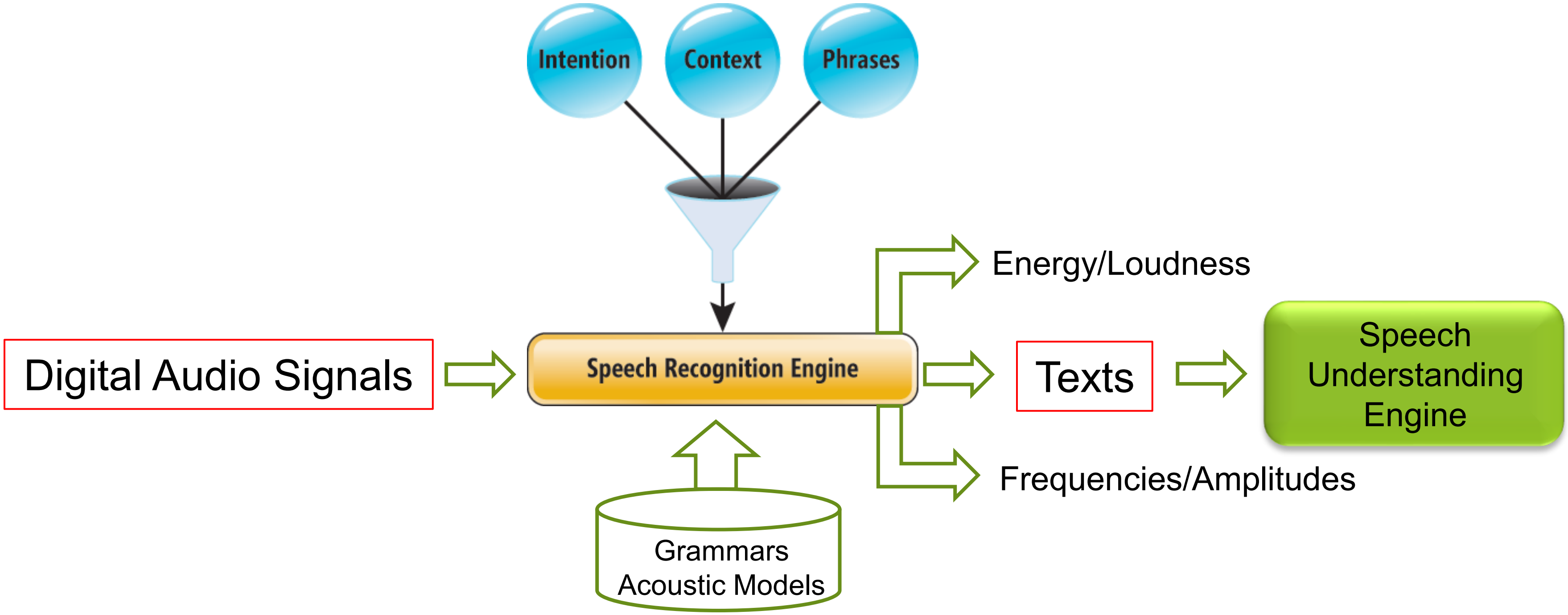
```
Fs = 3000; Ts = 1/Fs; Channels = 1; Bits = 16;
myrecorder = audiorecorder(Fs, Bits, Channels);
duration = 8 ; % 8 seconds
disp('Start recording ...');
recordblocking(myrecorder, duration);
recordedsound = getaudiodata(myrecorder);
sound(recordedsound, Fs, Bits);
t=0:Ts:(length(recordedsound)-1)*Ts;
plot(t, recordedsound, 'Linewidth', 1.5);
xlabel('Time (sec)'); ylabel('Amplitude');
title('Time Signals of Recorded Sound or Voice');
```

Result …

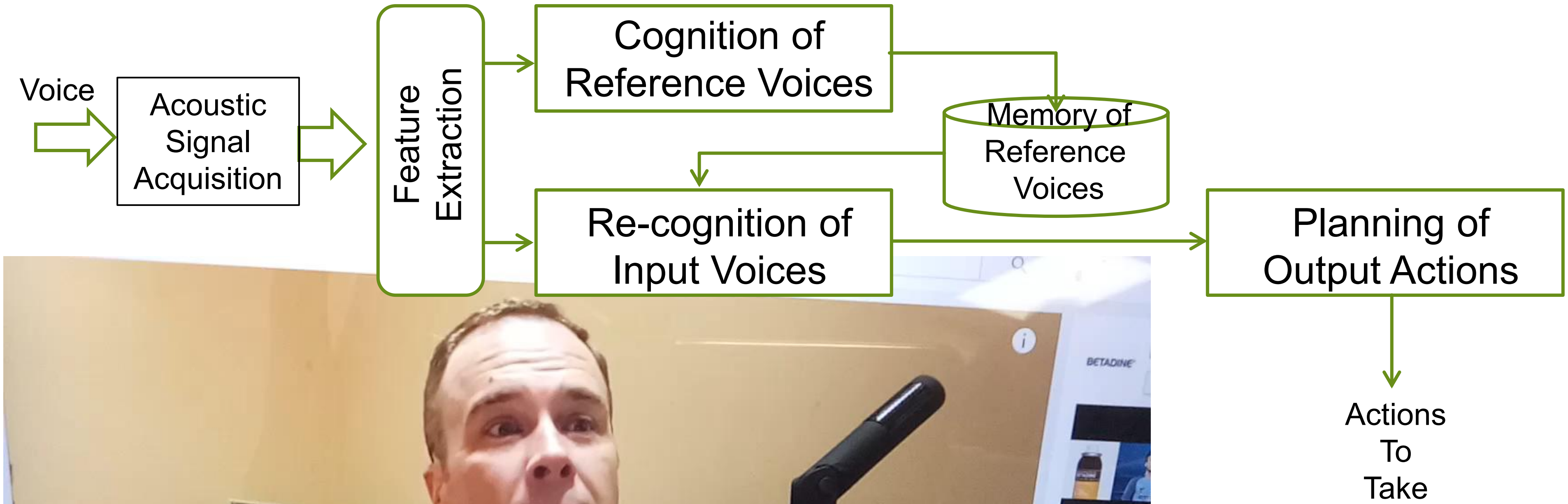


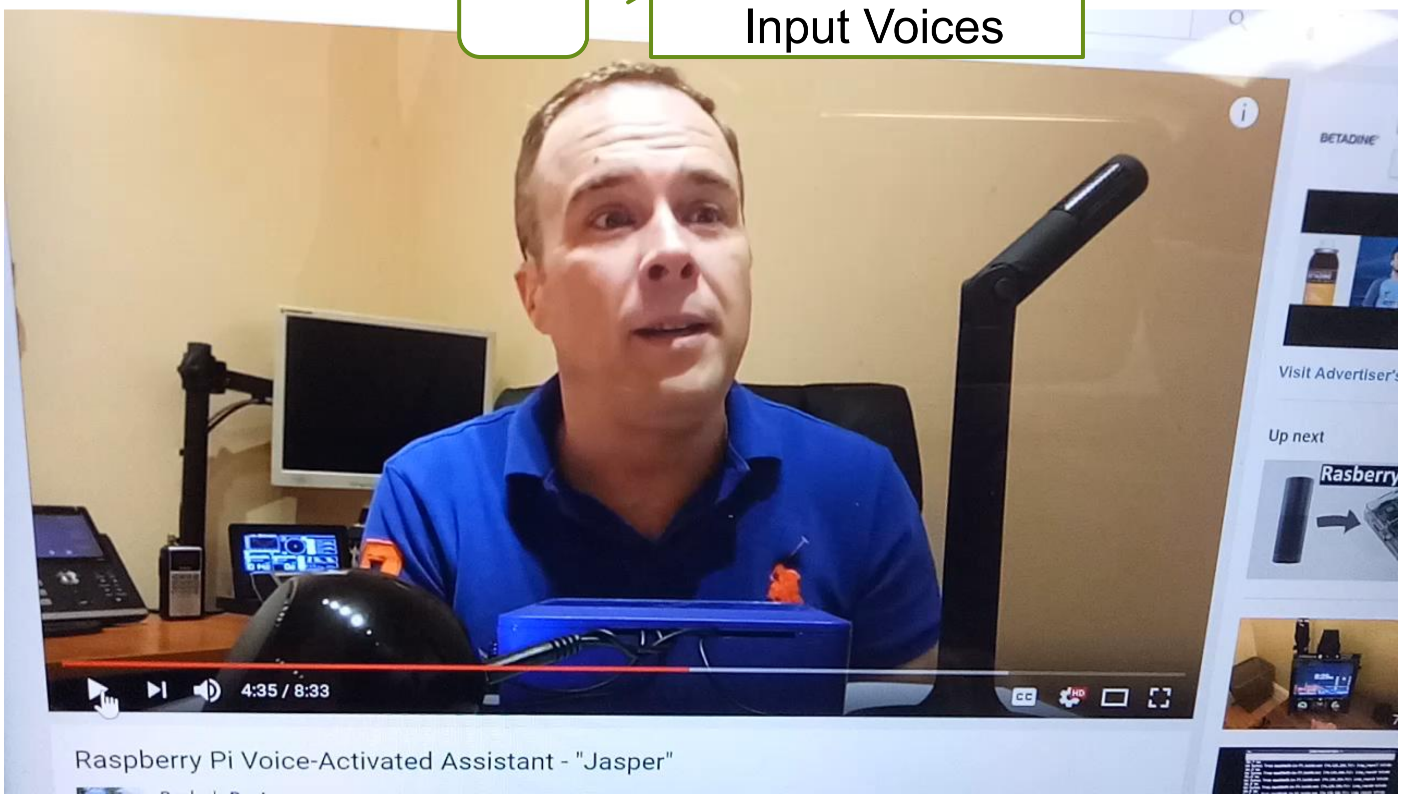
Processing Pipeline of Acoustic Signals

- It involves: feature extraction, learning/training, recognition, and understanding.

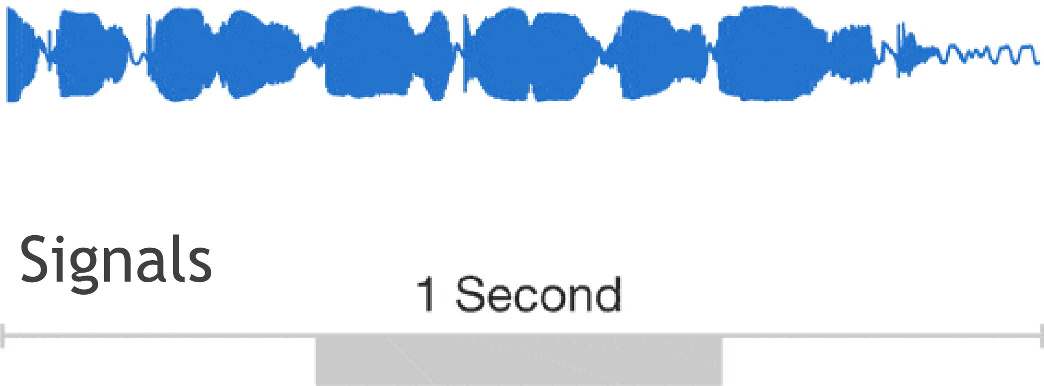


Voice-Enabled AI Systems …

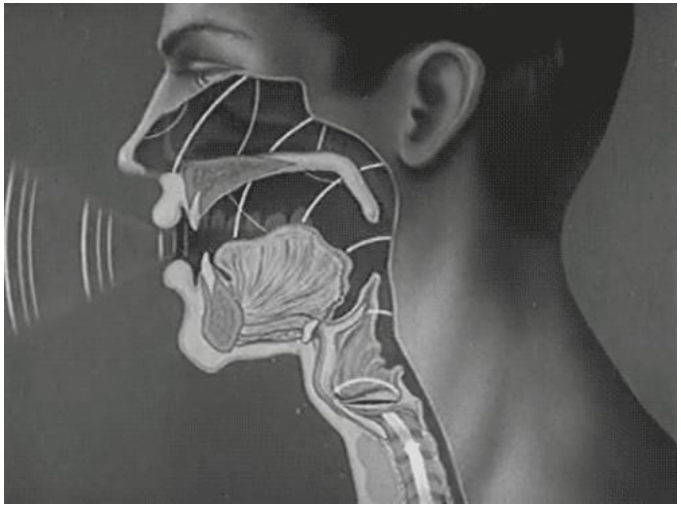




Summary



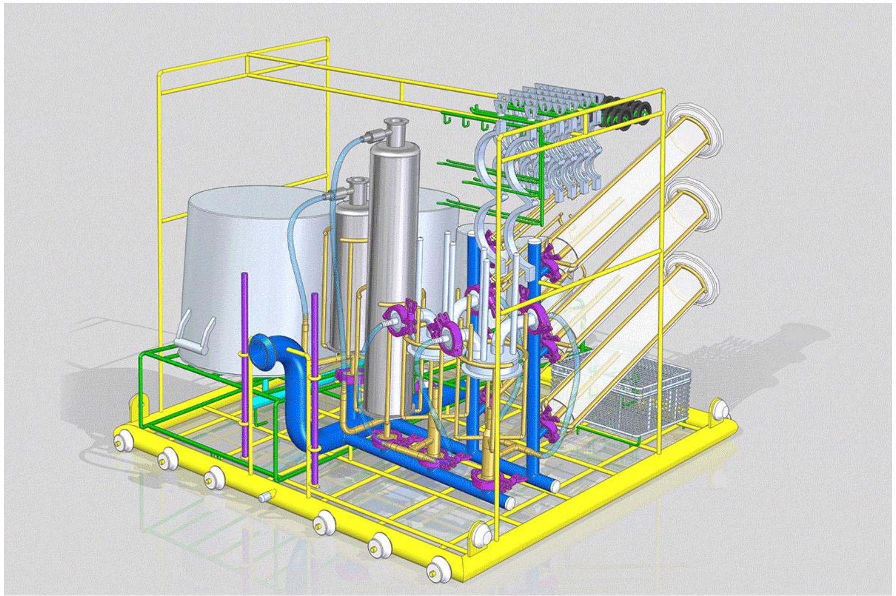
- Understanding of Acoustic Signals
- Computation of Acoustic Signals
- Measurement of Acoustic Signals



Processing of Acoustic Signals

Outline of Module 5

- Lecture 1:
  - Measurement of Fluid Level
- Lecture 2:
  - Measurement of Flow Rate
- Lecture 3:
  - Measurement of Sound/Voice
- Lecture 4:
  - Measurement of Photometry
- Lecture 5:
  - Measurement of Geometry



NANYANG TECHNOLOGICAL UNIVERSITY

School of Mechanical & Aerospace Engineering

Design, Machine, Control, Intelligence

Module 5 Lecture 4

MA4822

Measurement of Photometry

Xie Ming, PhD (France)

mmxie@ntu.edu.sg

http://personal.ntu.edu.sg/mmxie

Outline

- Understanding of Visual Signals
- Computation of Visual Signals
- Measurement of Photometry
- Practices with MATLAB

Should seeing be believing?

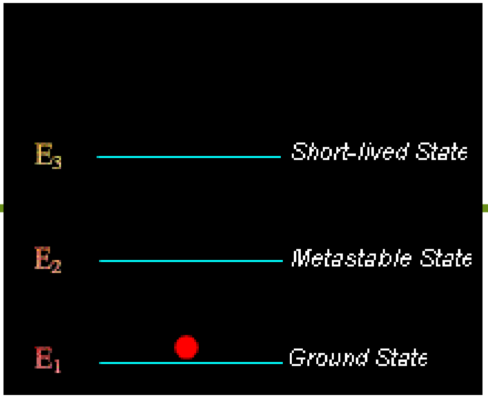
Outline

- Understanding of Visual Signals
- Computation of Visual Signals
- Measurement of Photometry
- Practices with MATLAB

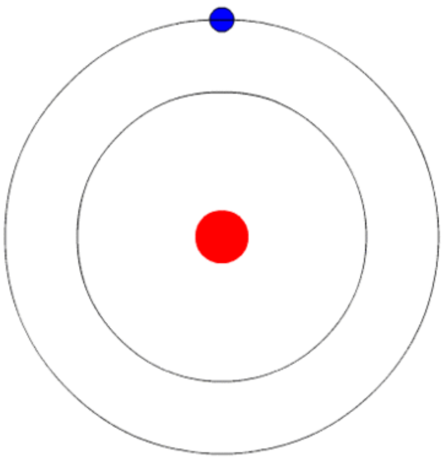
Should seeing be believing?

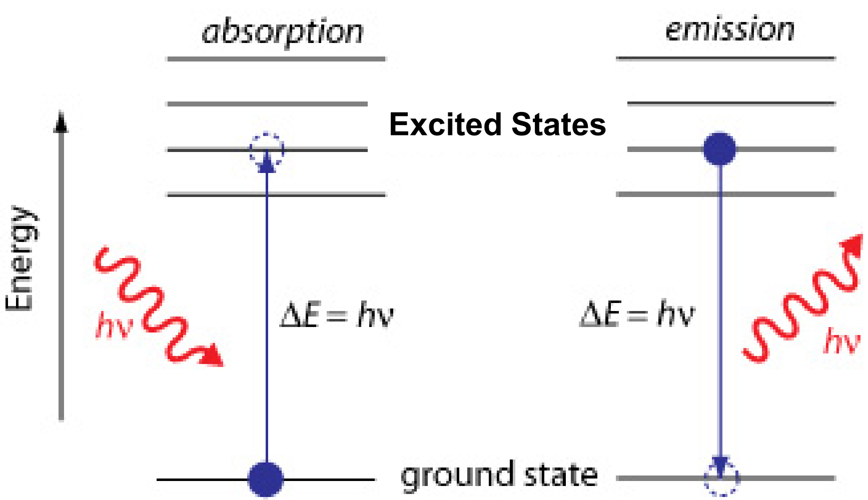
Emission of Photons

- An atom or molecule can transit between the ground state and excited states.

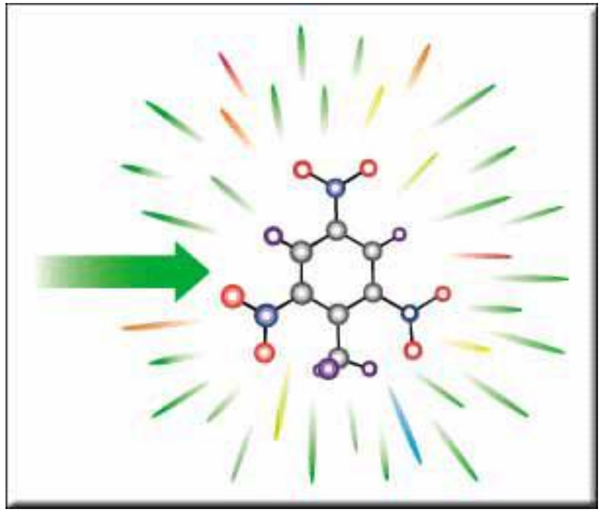


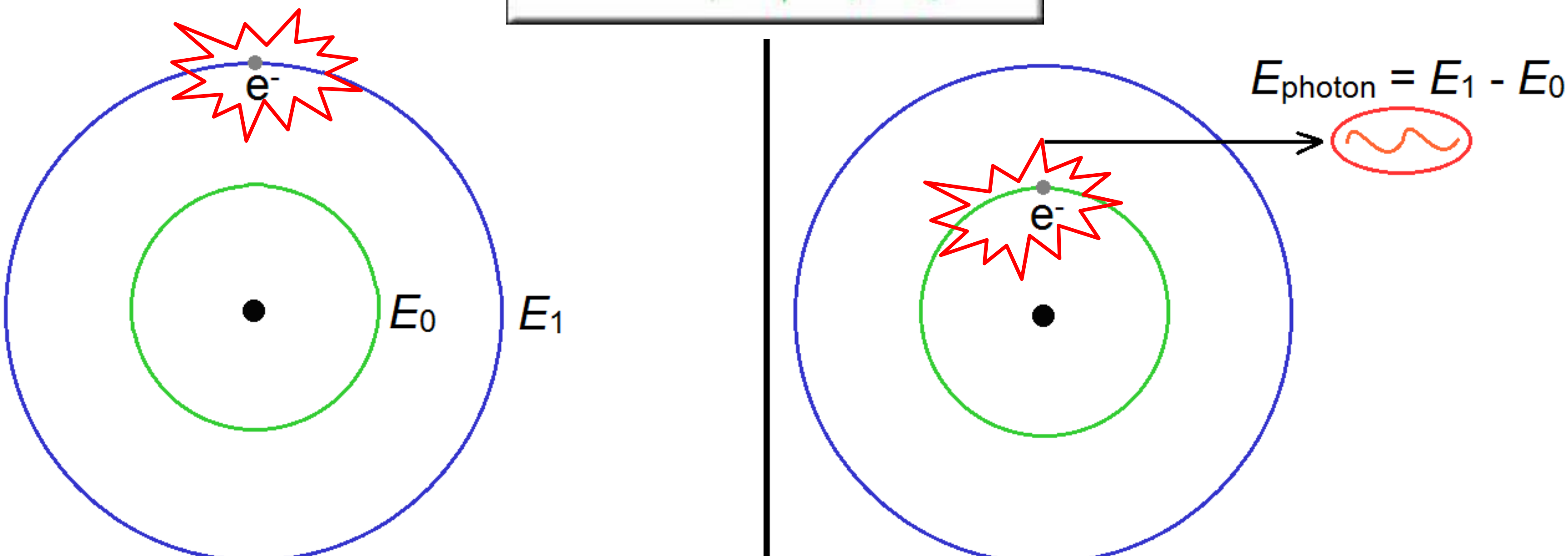
- When an atom or molecule transits from an excited state to the ground state, a photon is emitted.





Example



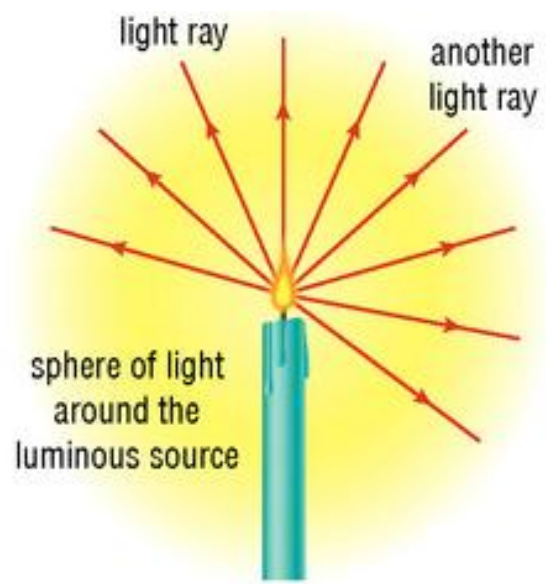


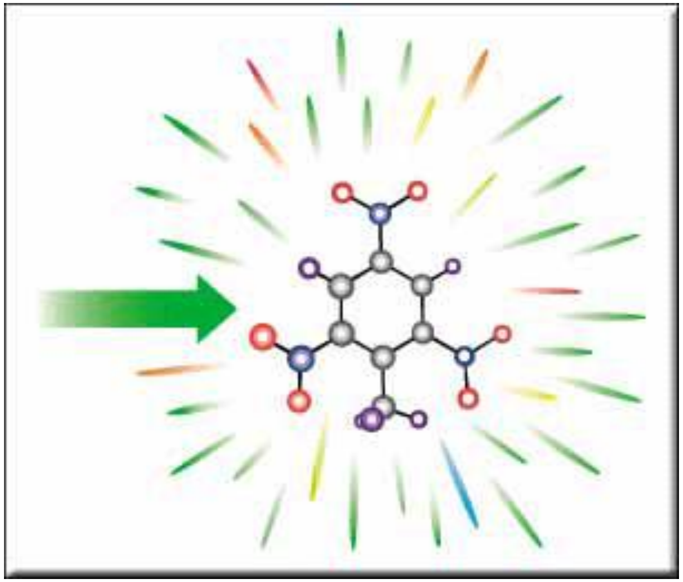
before emission of photon

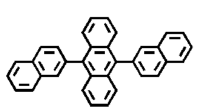
after emission

Sources of Light

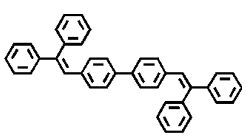
- Any object, which emits continuously photons, is a light source.



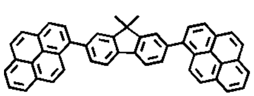




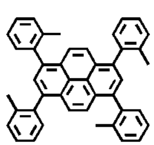
diarylanthracene



di(styryl)arylene

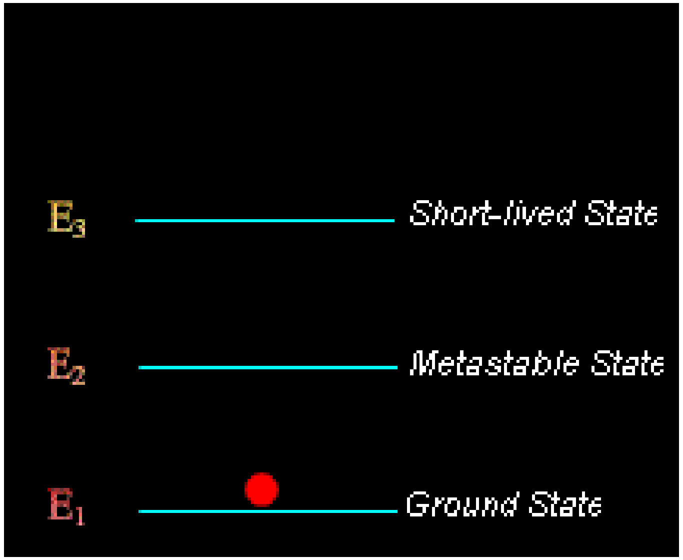


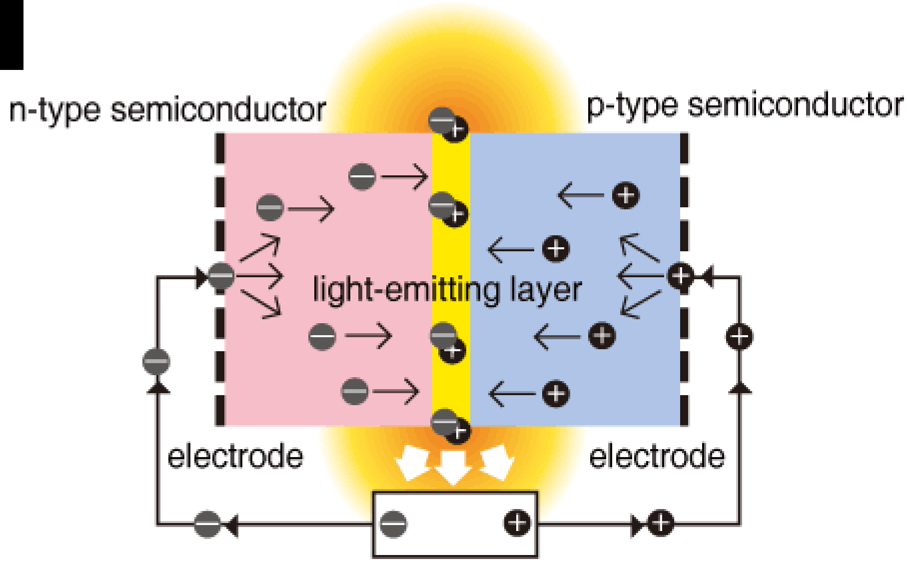
fluorene



pyrene

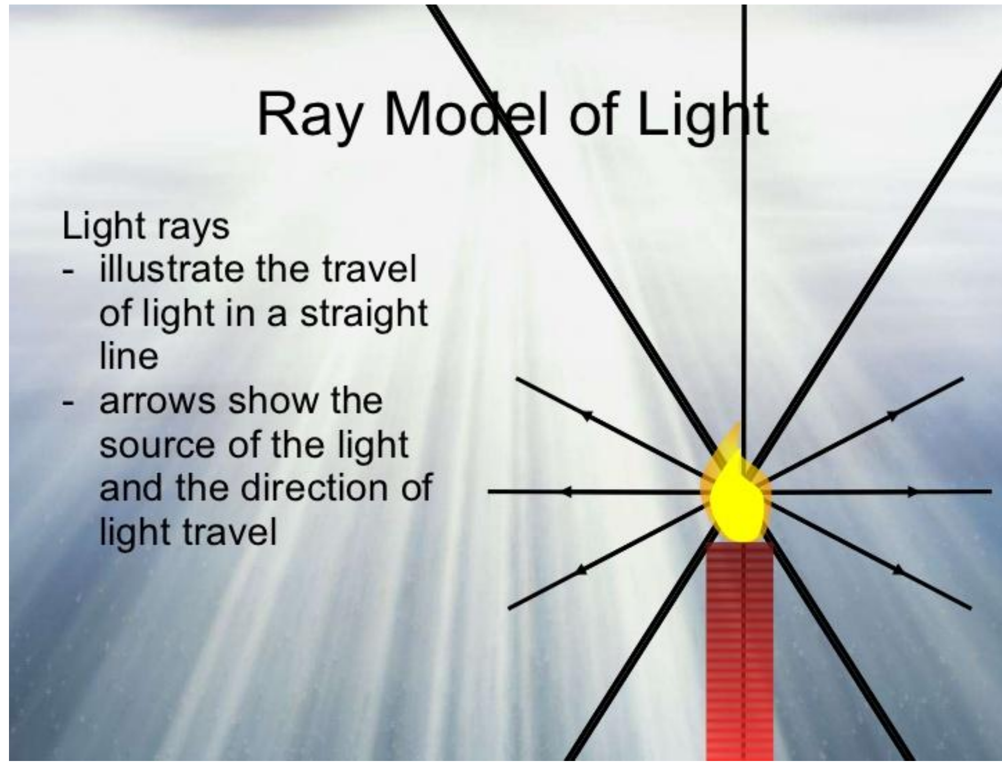
Example of Light Source …

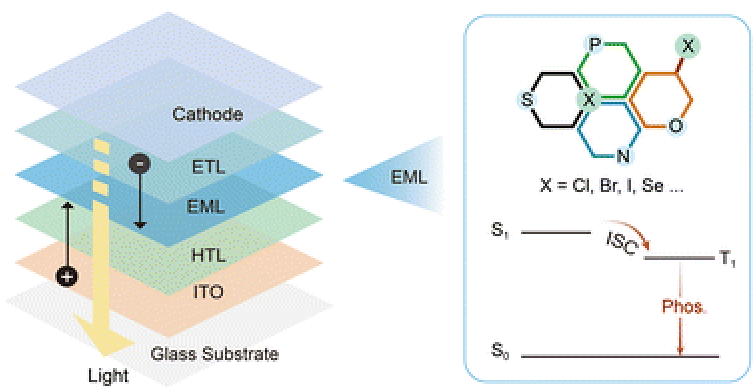




Understanding Lights (1)

- Lights travel in a straight line from a source.
- The photons along a travelled line are called a light ray.

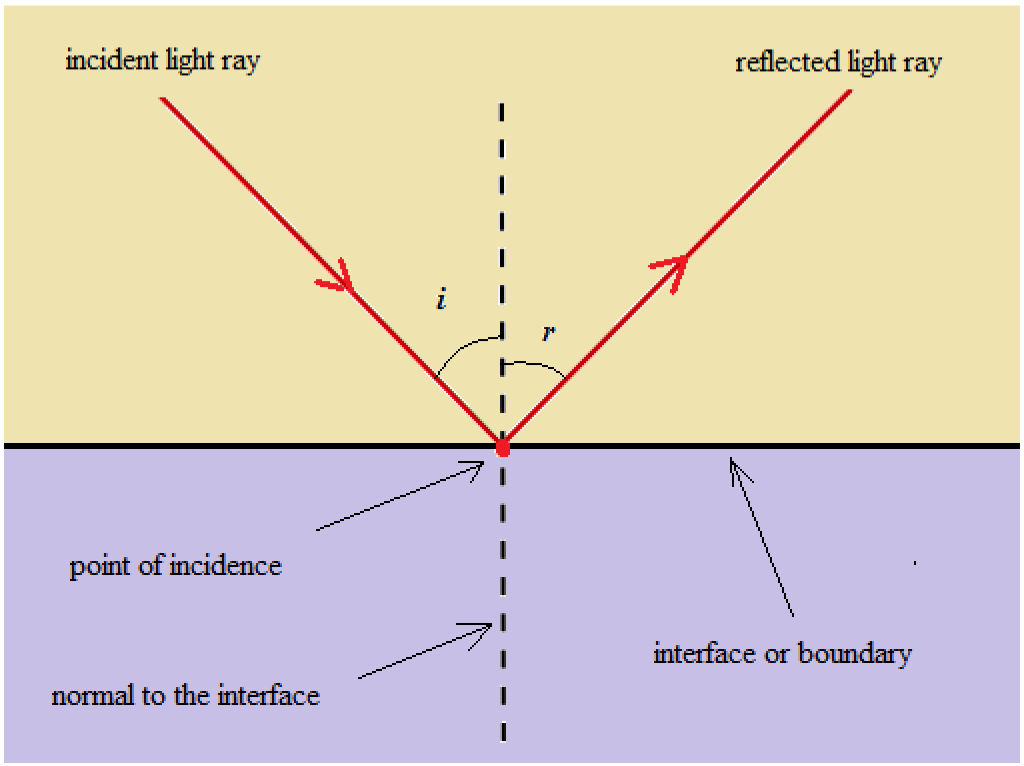


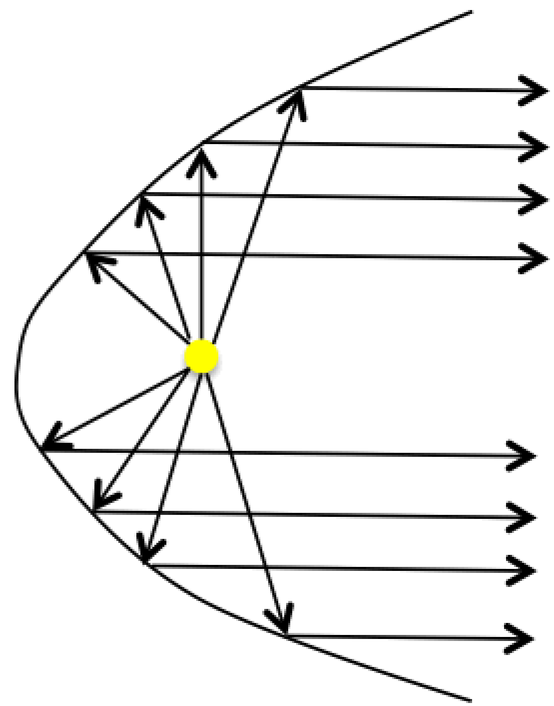


Phosphorescent Materials

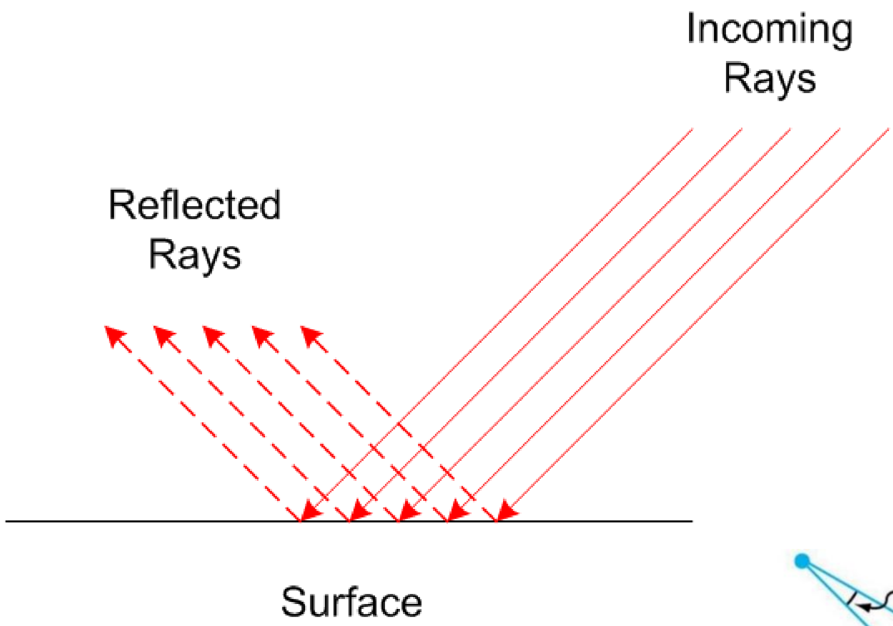
Understanding Lights (2)

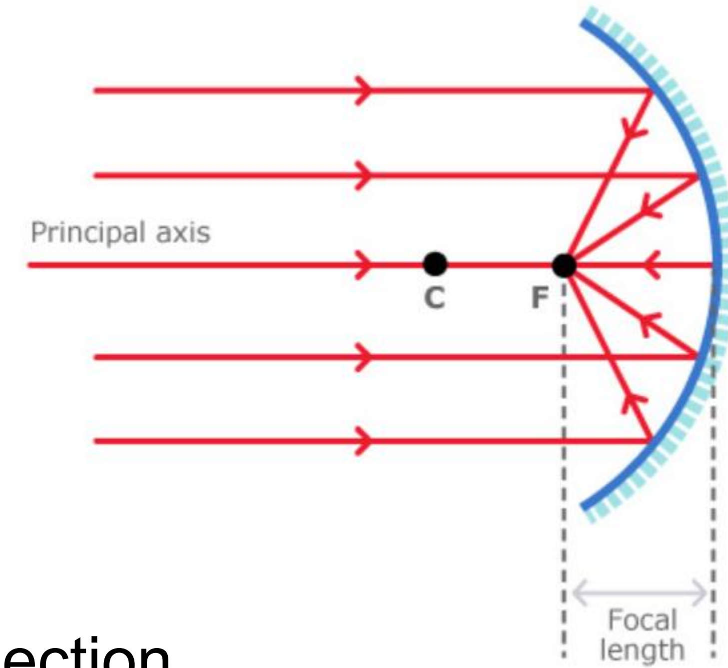
- Light rays can be reflected so as to change the directions of travel.



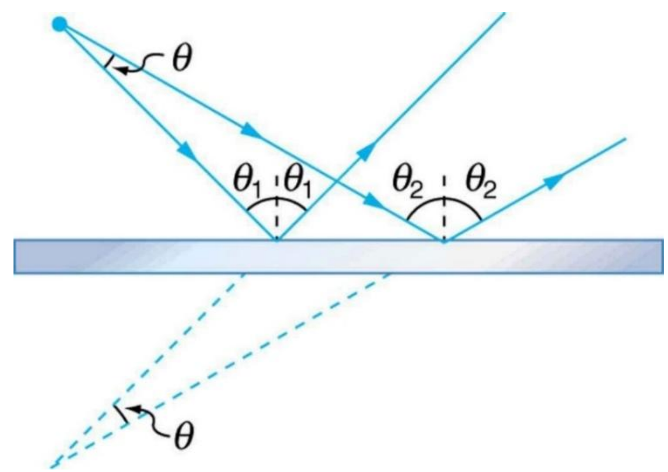


Example





Reflection



Understanding Lights (3)

- Light rays can travel from one media into another media.
- Such change of media will cause light rays to change direction of travel. Such phenomenon is called refraction.

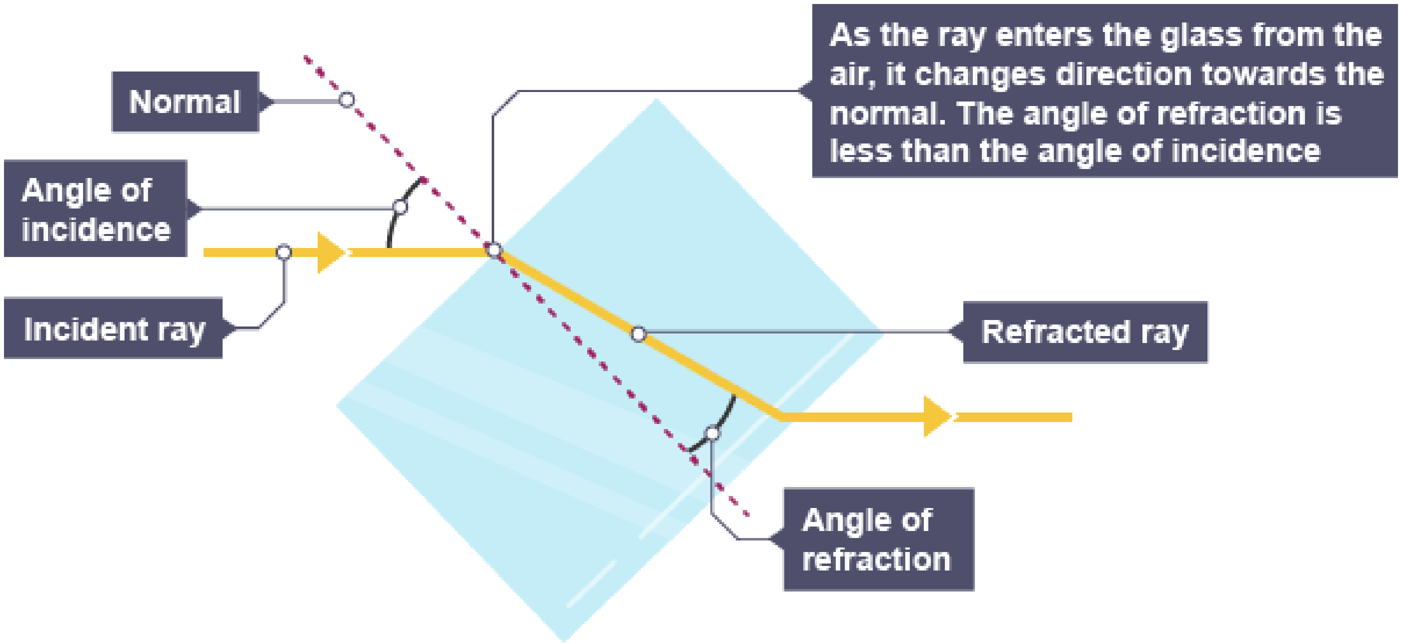
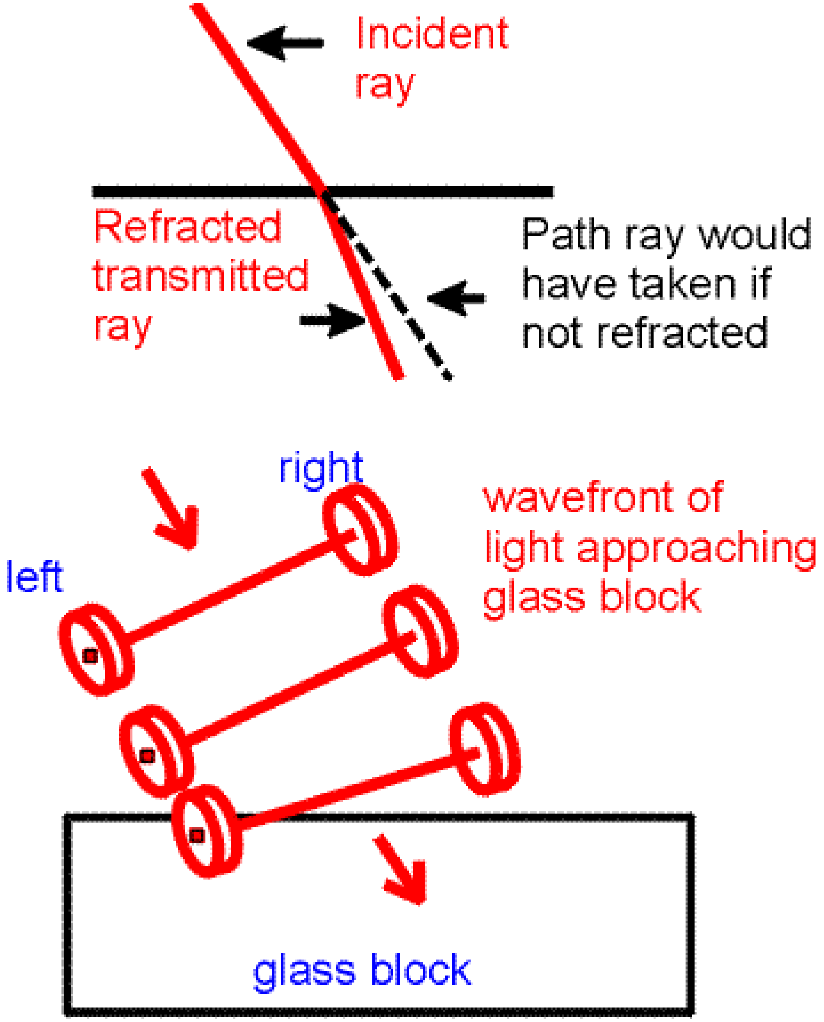
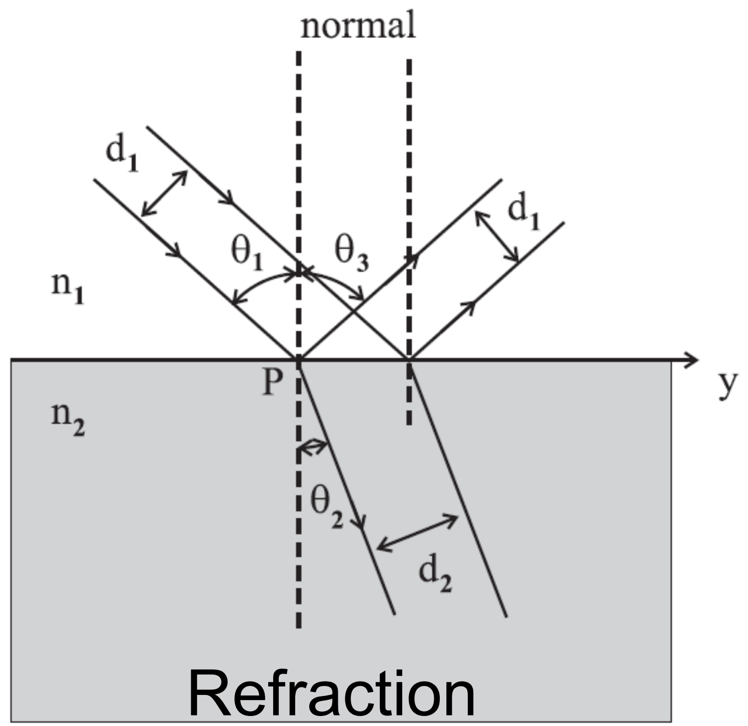
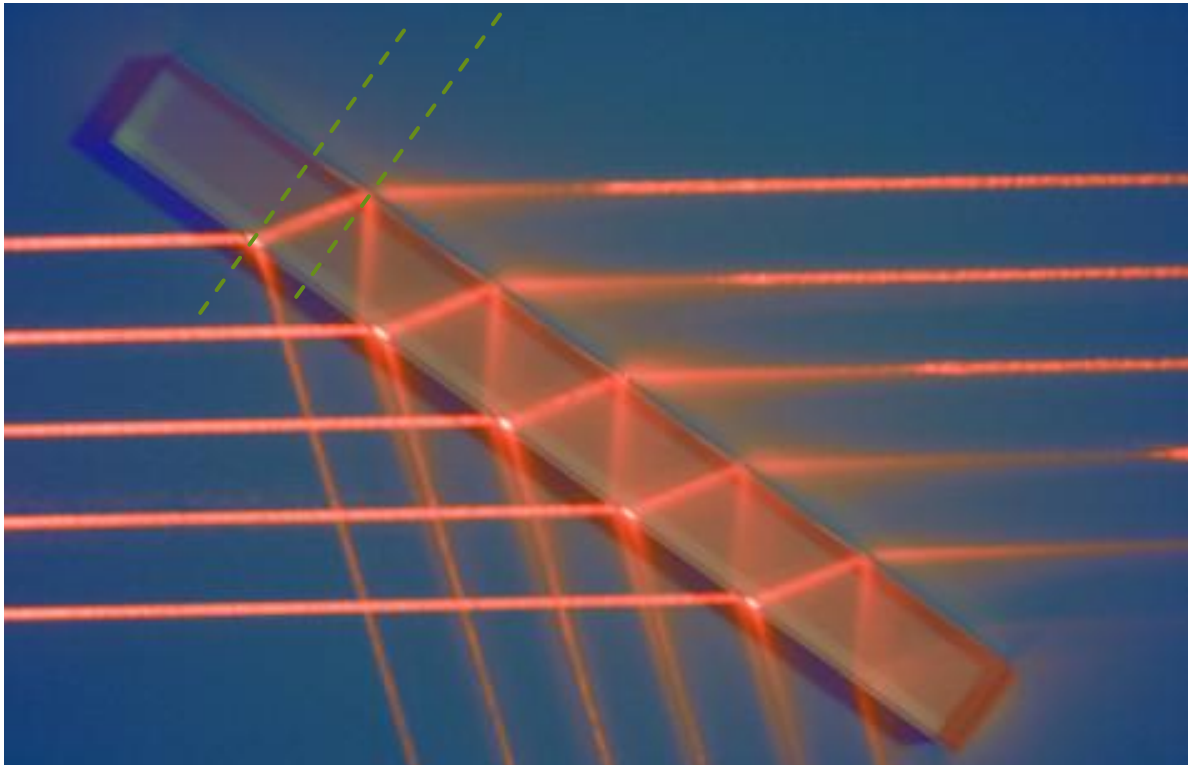


Illustration …



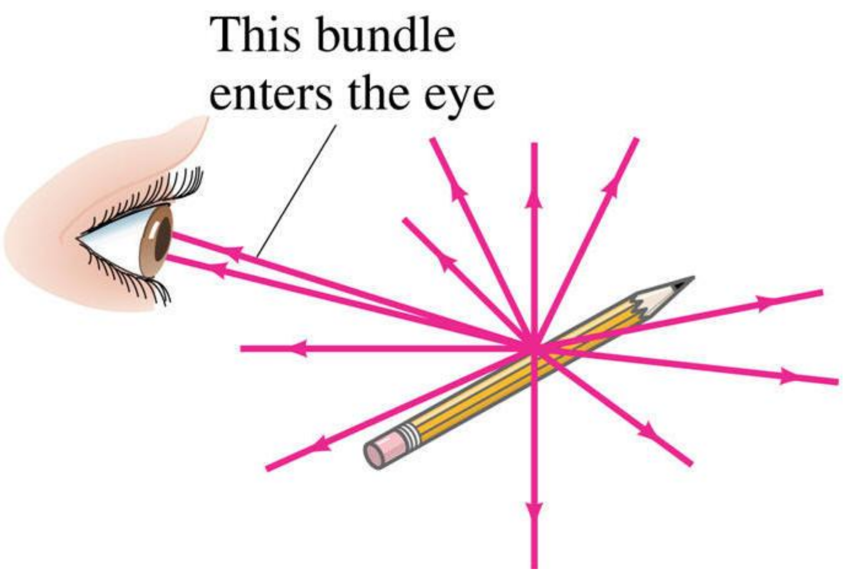


Example

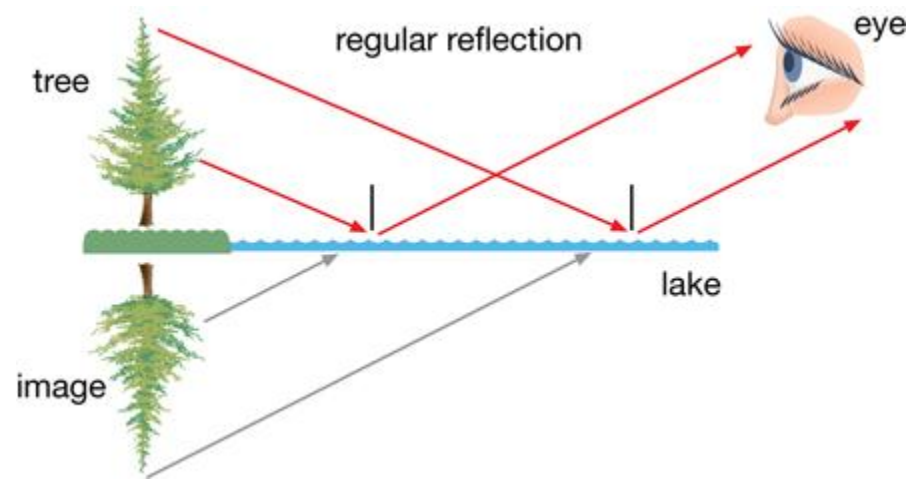


Understanding Lights (4)

- Light rays can end the journey by entering light receivers such as eyes or cameras.



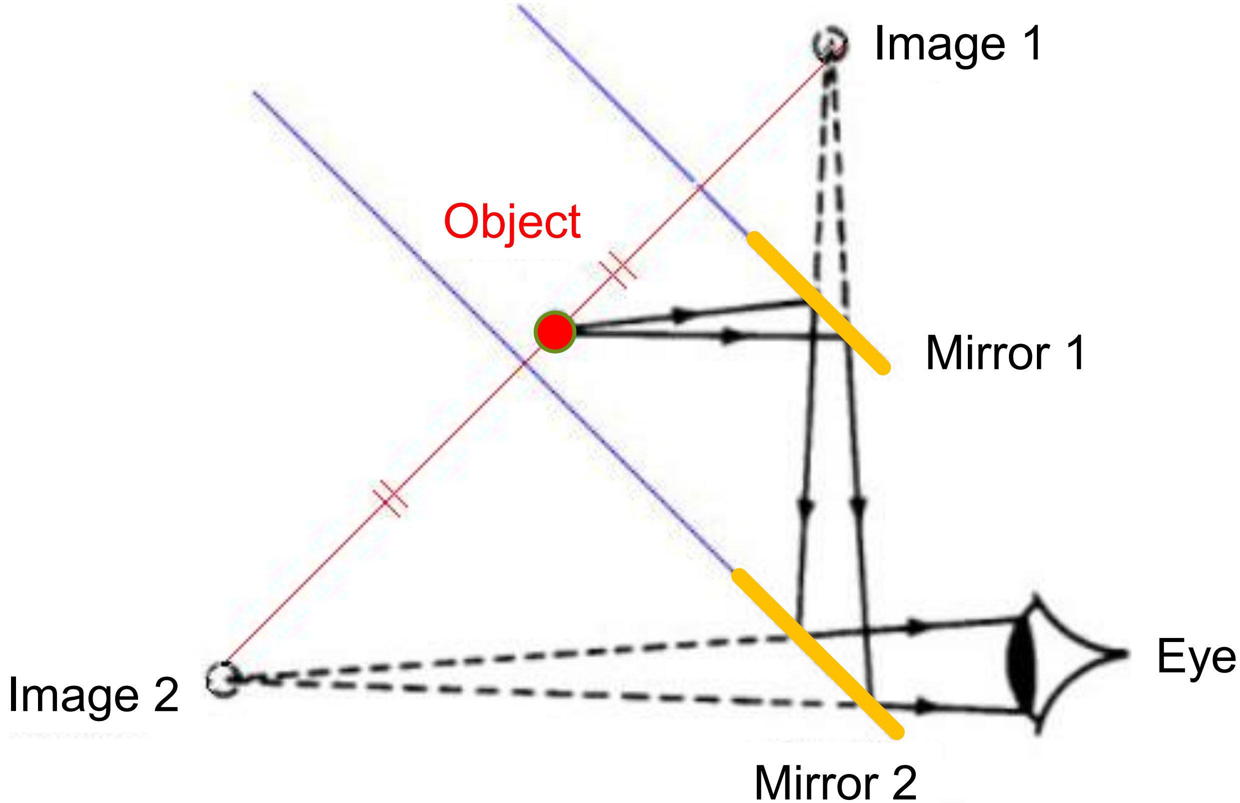
Direct Light Rays



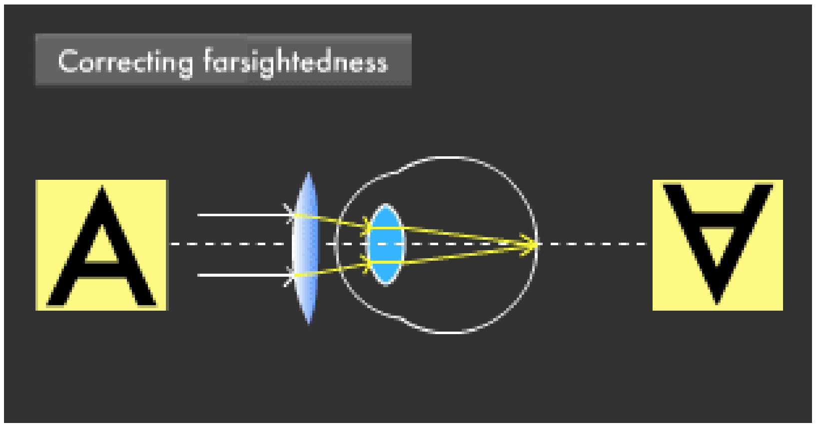
Reflected Light Rays

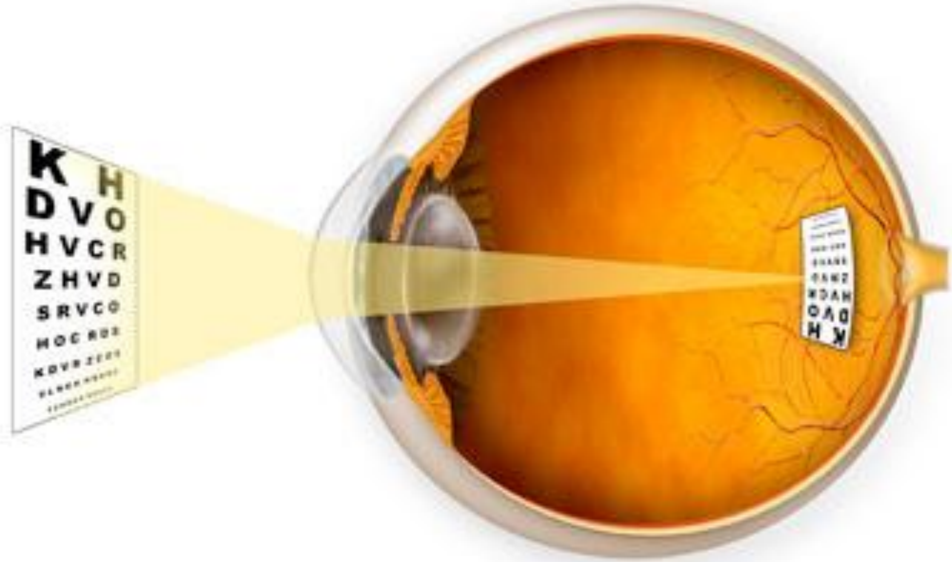
Example of Seeing Object at Image 2

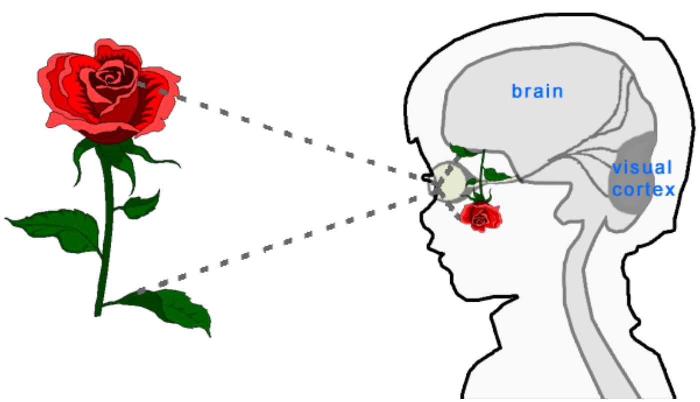
Lights could be interpreted by observers

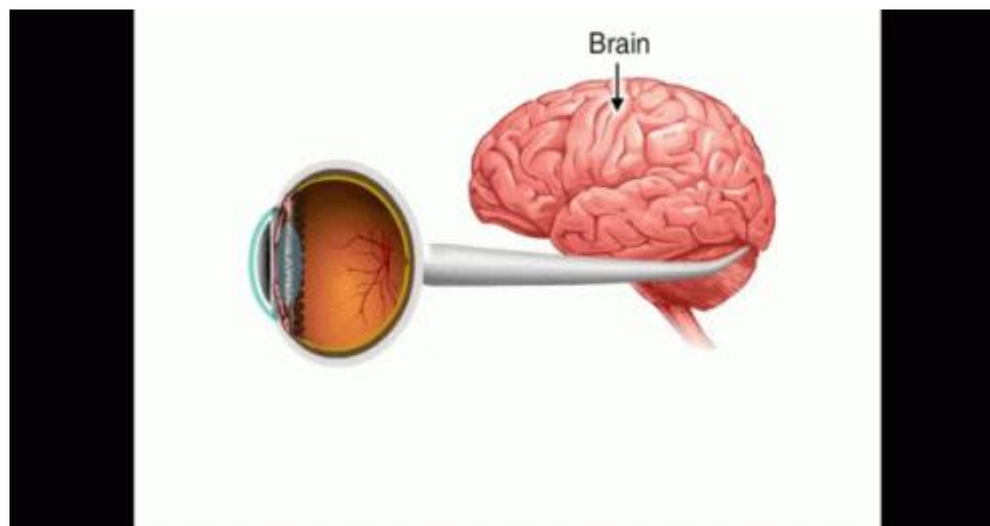


Example of Image Formation inside Human Eye



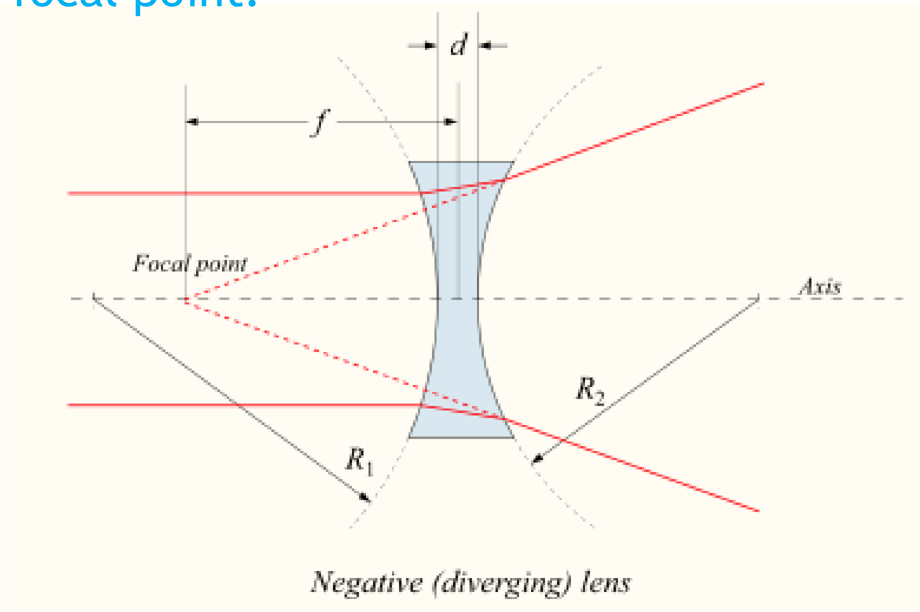


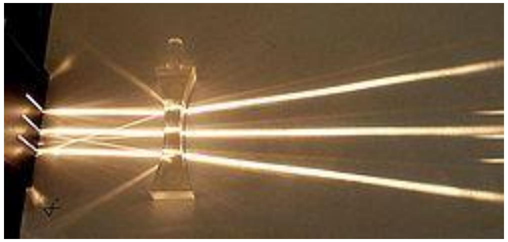




Understanding Lights (5)

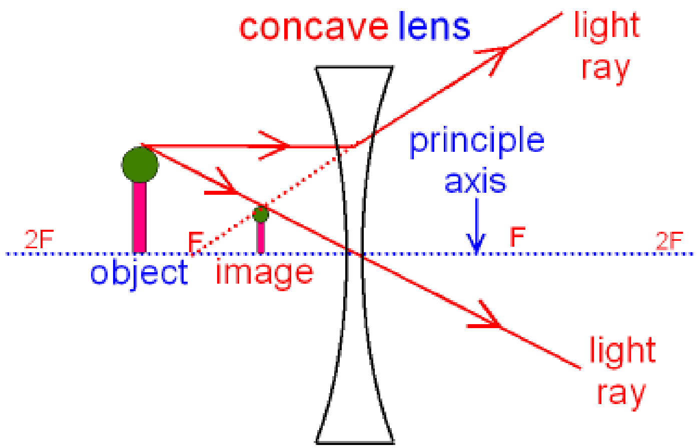
- A transparent device, with two spherical surfaces sharing a common axis, is called a lens.
- If the spherical surfaces are concave, the incoming light rays to such lens will be diverged.
- When light passes through the centre of lens, it will not change direction.
- When incoming light is parallel to optical axis, outgoing light aligns with focal point.

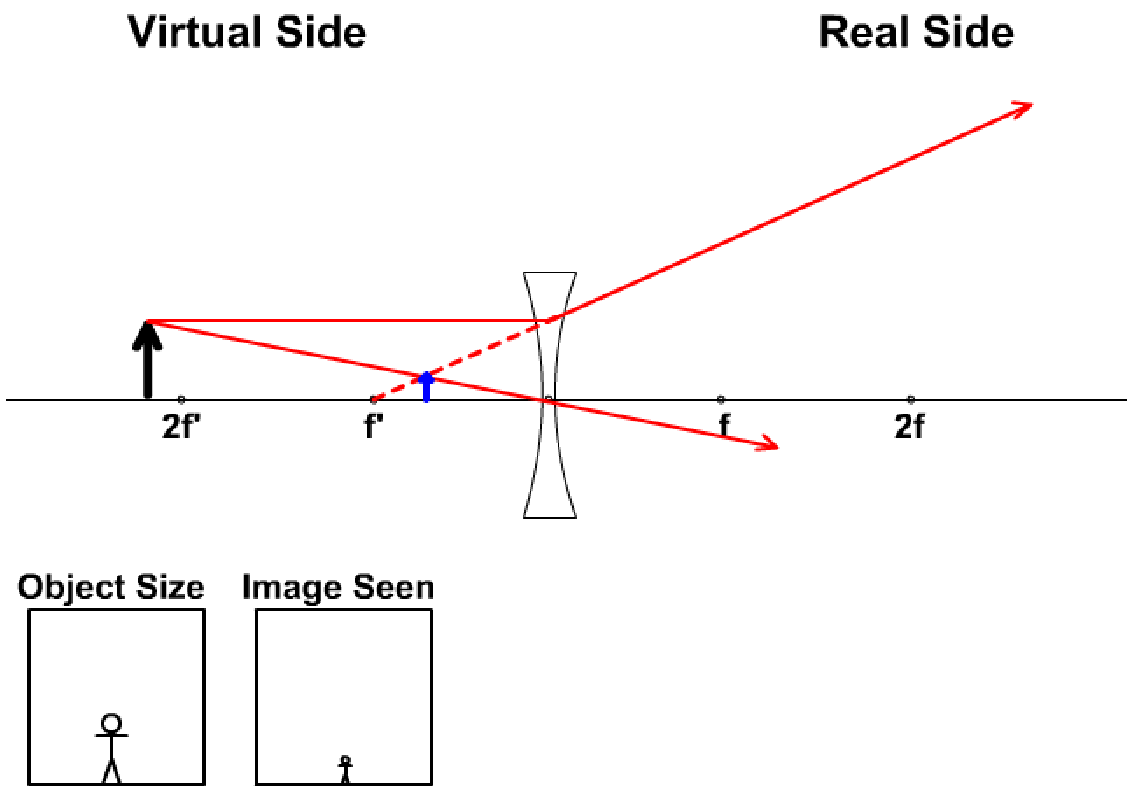




Example of Using Concave Lens

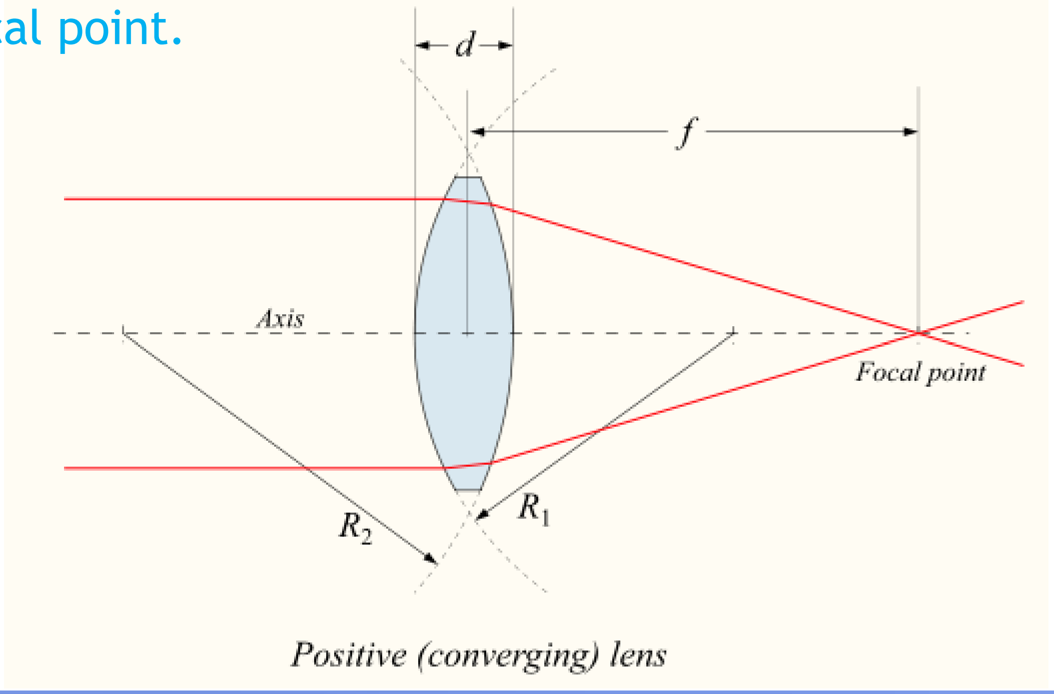
- When light passes through the centre of lens, it will not change direction.
- When incoming light is parallel to optical axis, outgoing light aligns with focal point.

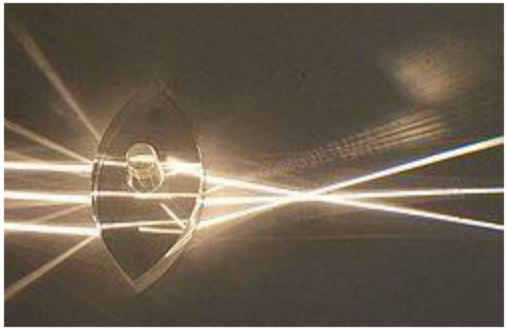




Understanding Lights (6)

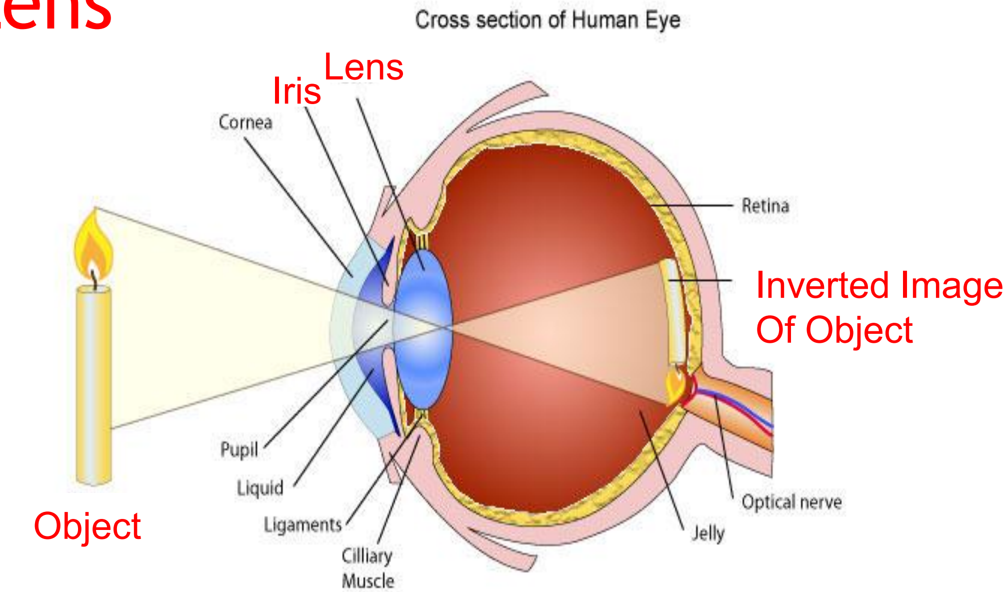
- A transparent device, with two spherical surfaces sharing a common axis, is called a lens.
- If the spherical surfaces are convex, the incoming light rays to such lens will be focused.
- When light passes through the centre of lens, it will not change direction.
- When incoming light is parallel to optical axis, outgoing light passes through focal point.



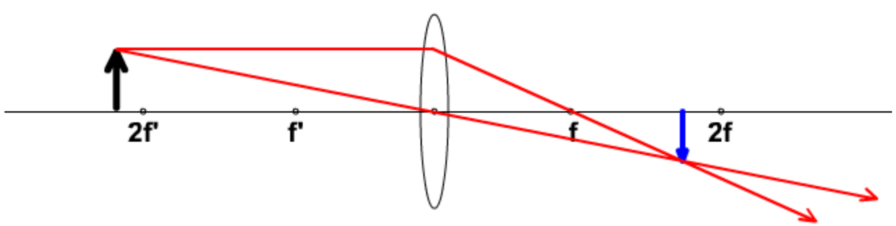


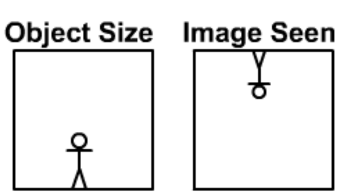
Example of Using Convex Lens

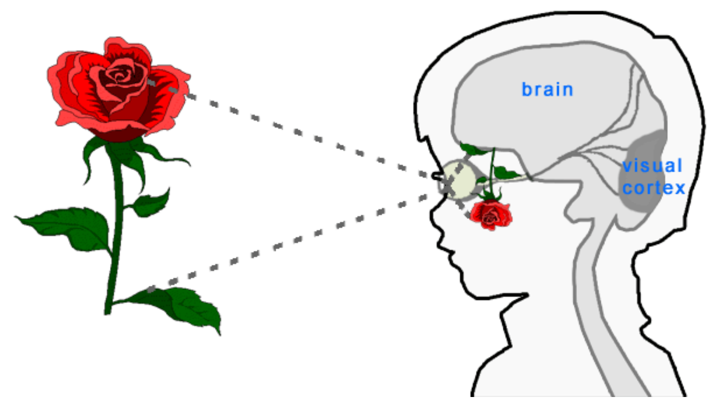
- When light passes through the centre of lens, it will not change direction.
- When incoming light is parallel to optical axis, outgoing light passes through focal point.



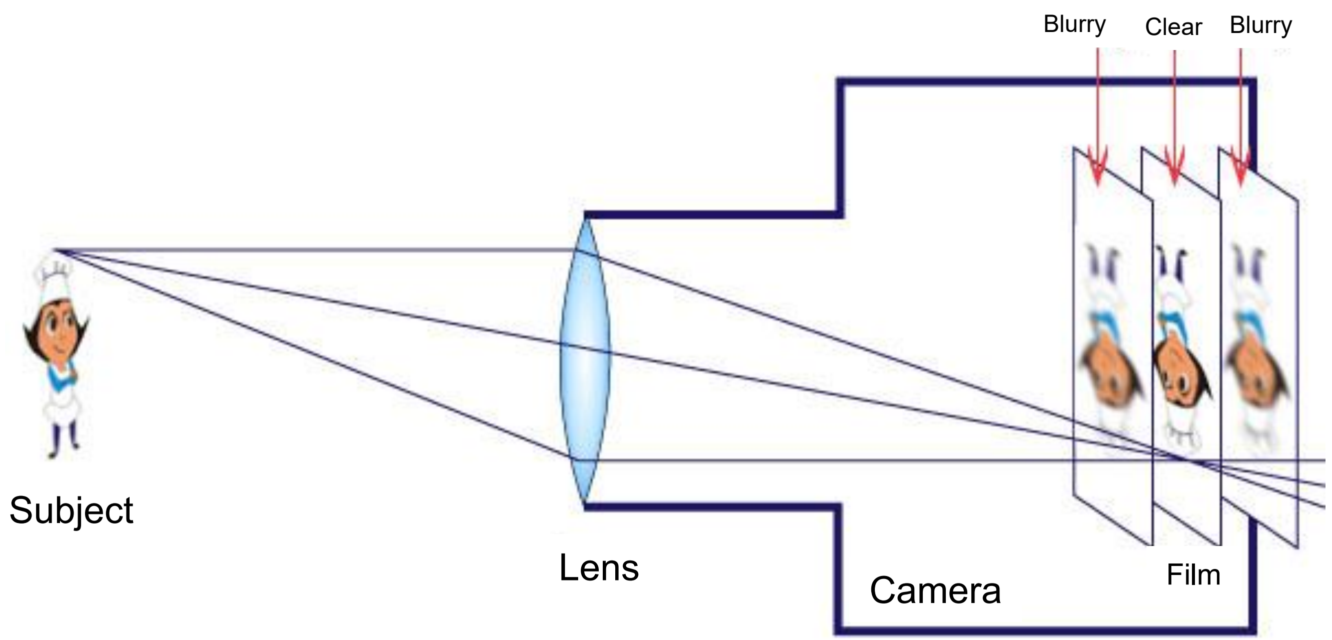
Virtual Side **Real Side**





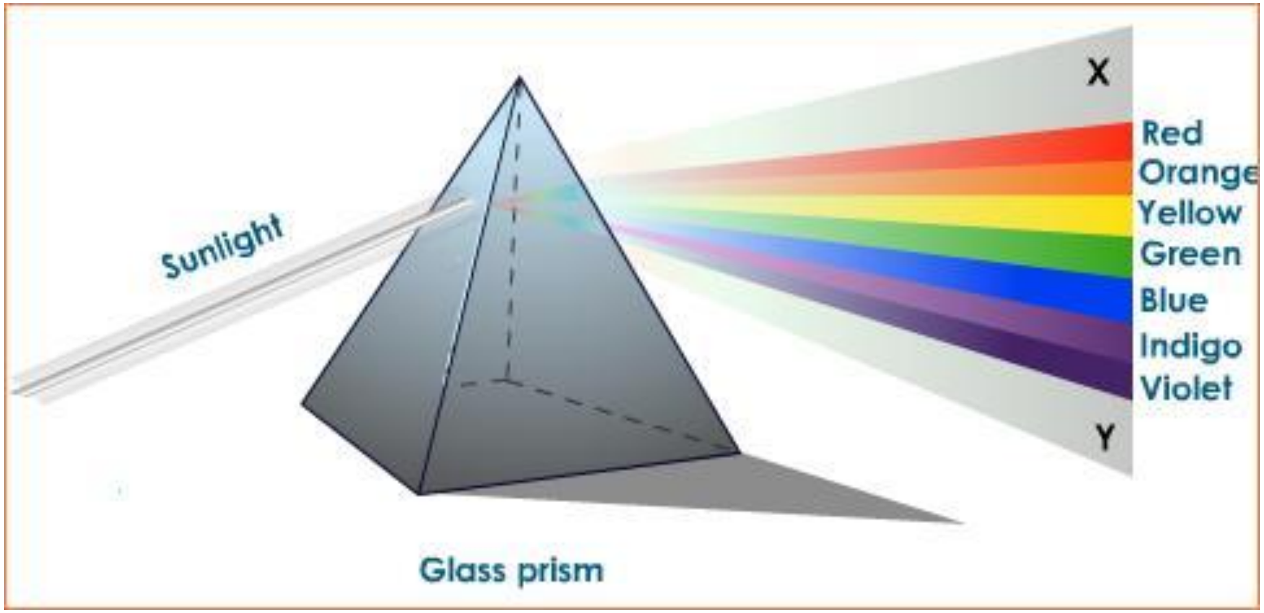


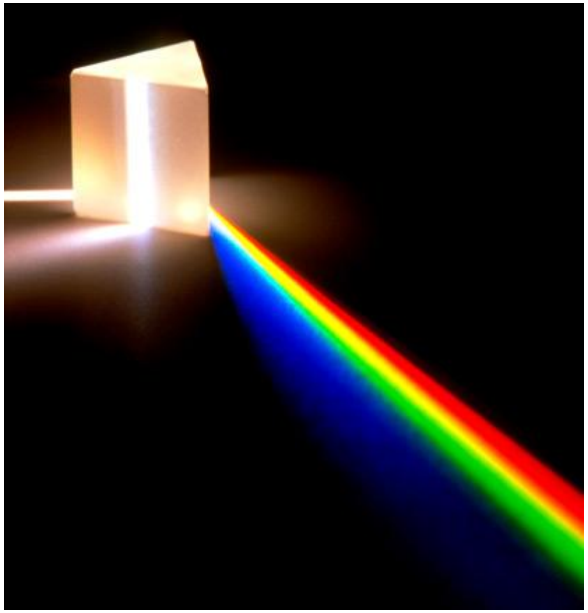
Example of Converting Lights into Optical Images …



Understanding Lights (7)

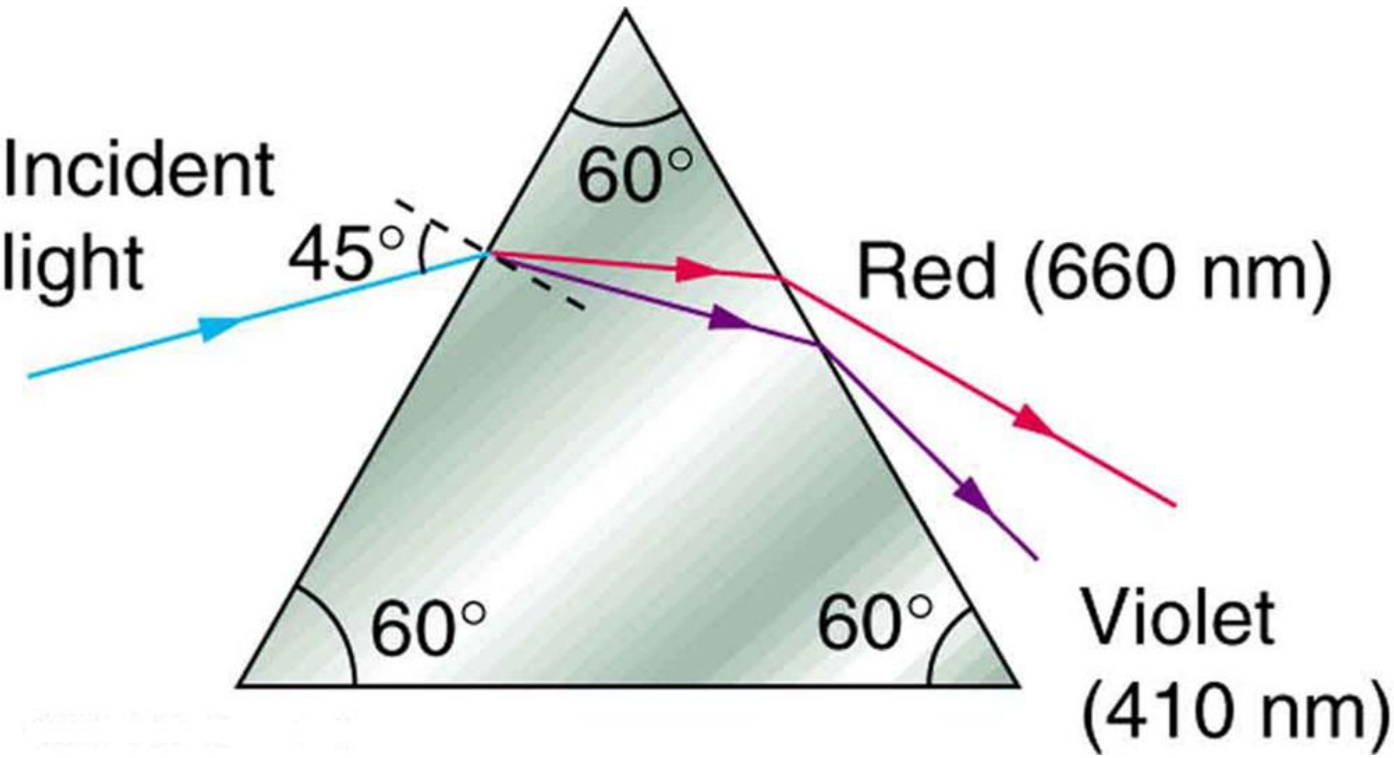
- A light ray is composed of photon waves of different wave lengths or frequencies, which create the sensation of colourful light rays.





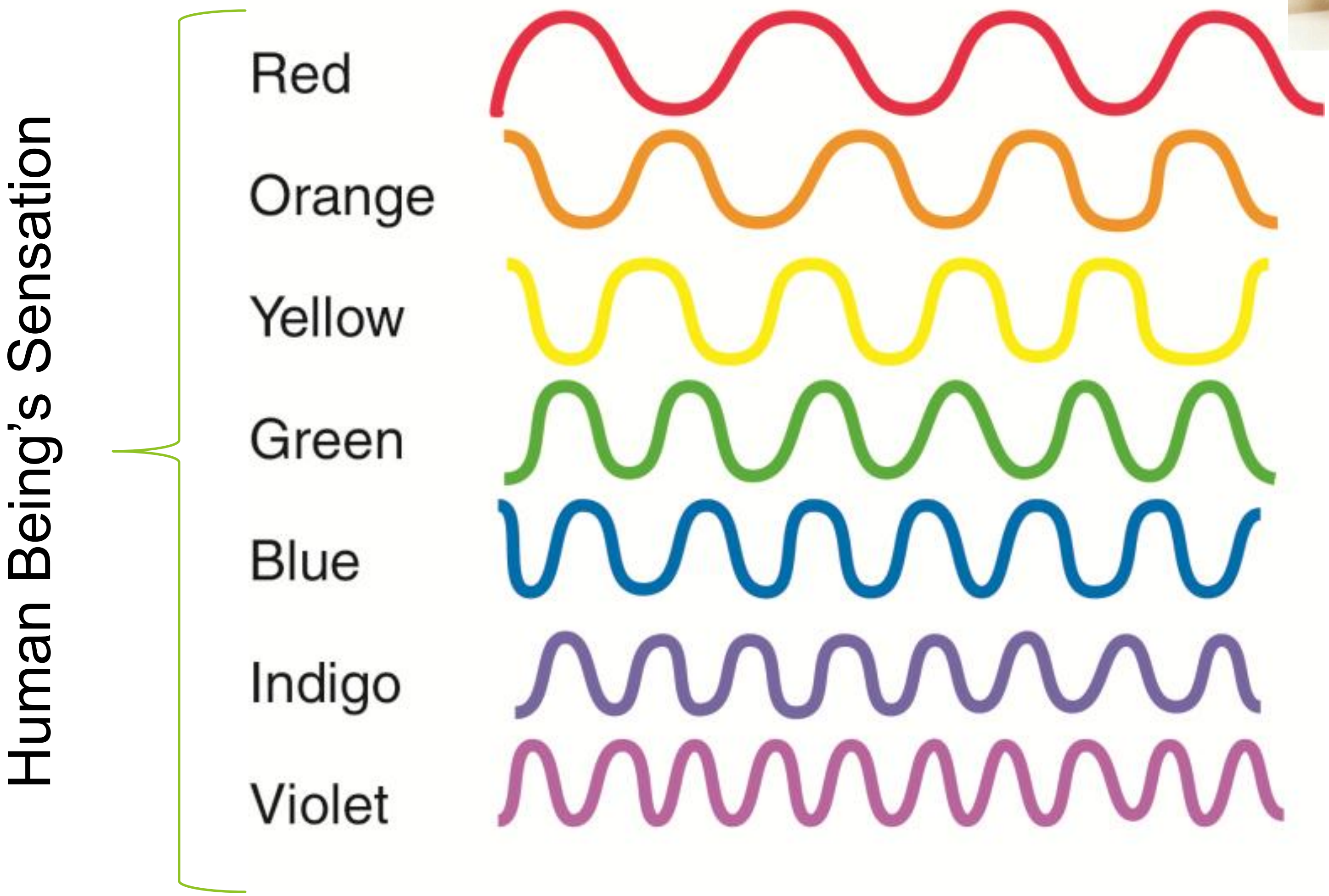
Buddha's Discovery: Colorless is colorful while colorful is colorless!

Example

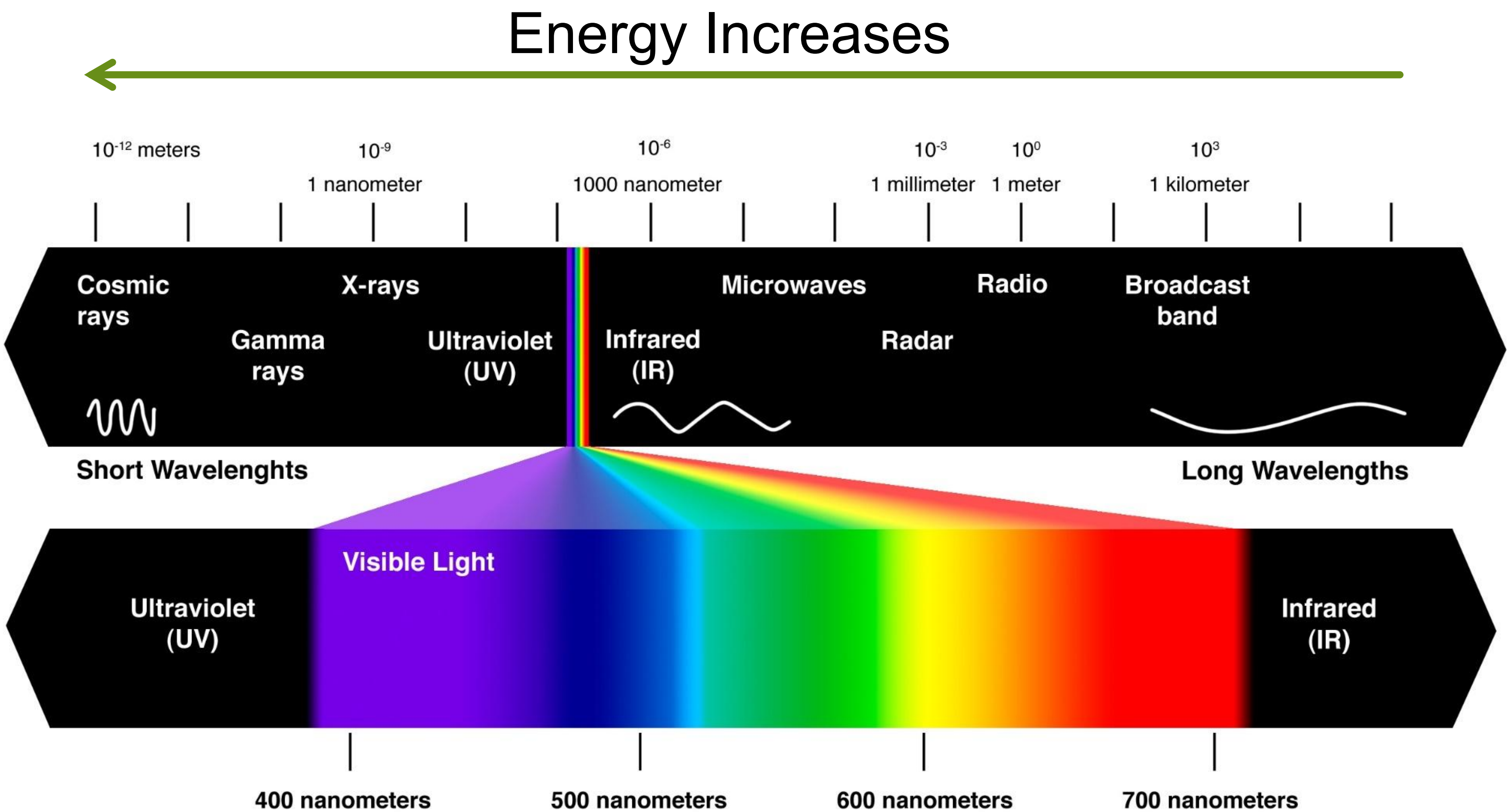


What should be the Doppler Effect on lights?

Example


Human Being's Sensation
Red
Orange
Yellow
Green
Blue
Indigo
Violet

Example

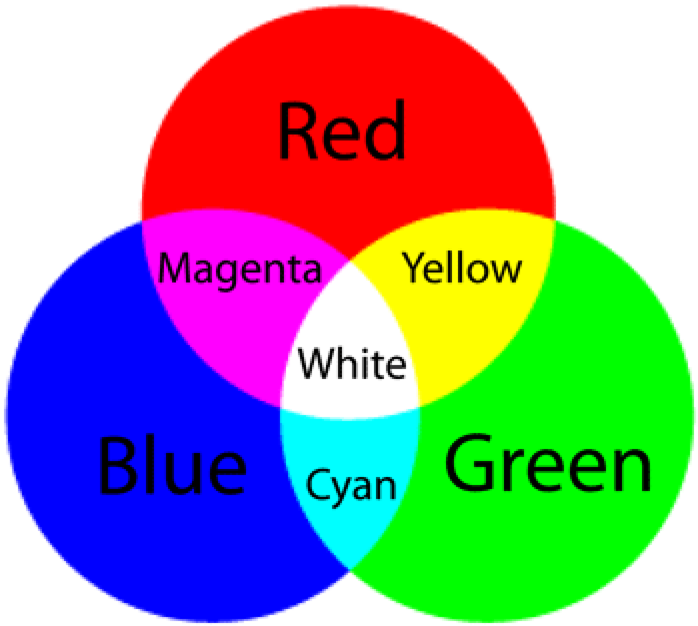


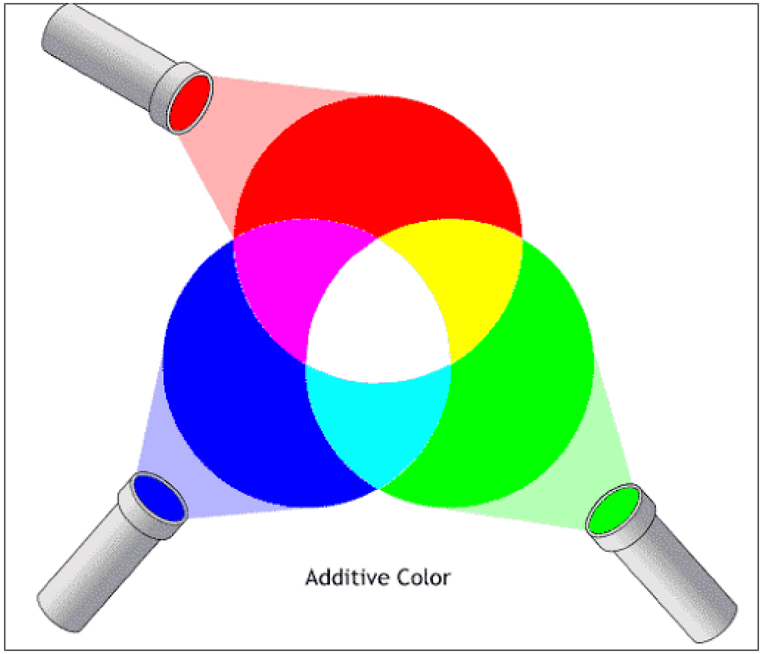
Wisdom of Buddha: Colorless is colorful while colorful is colorless!

Comparison of Night Vision Systems

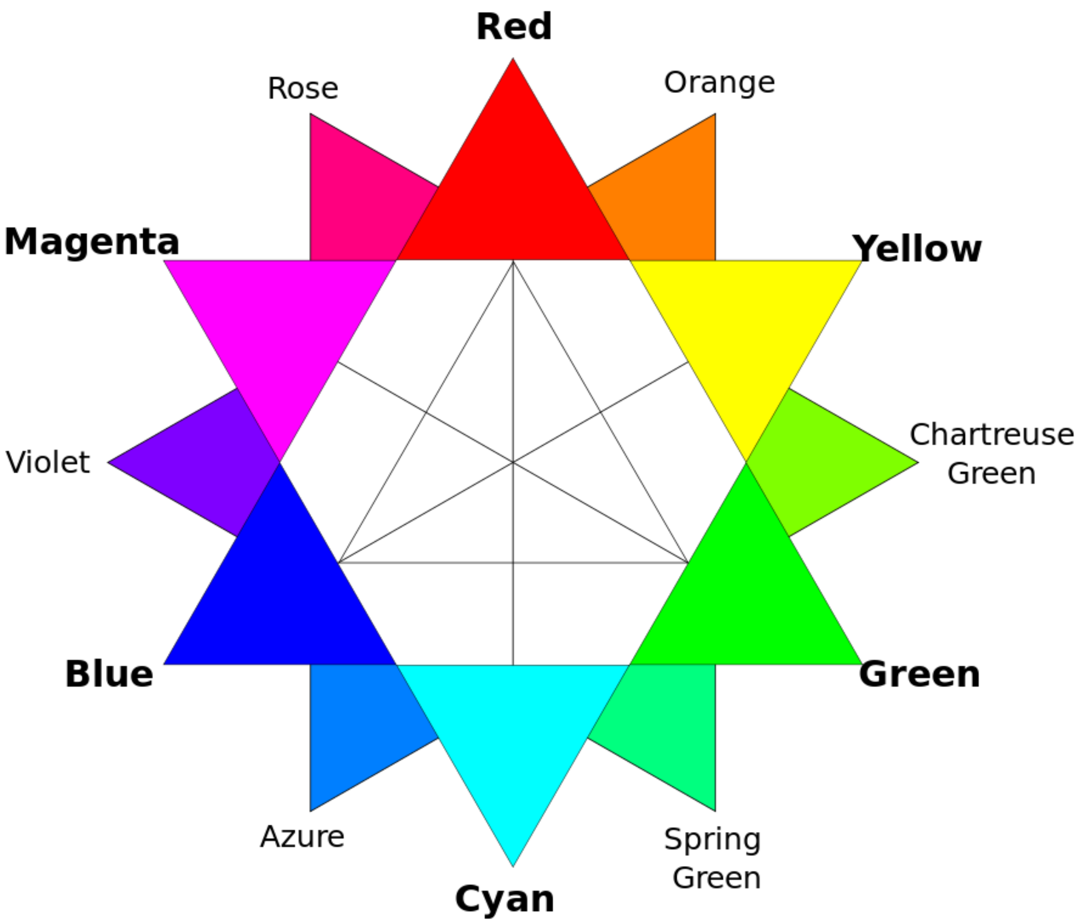
Understanding Lights (8)

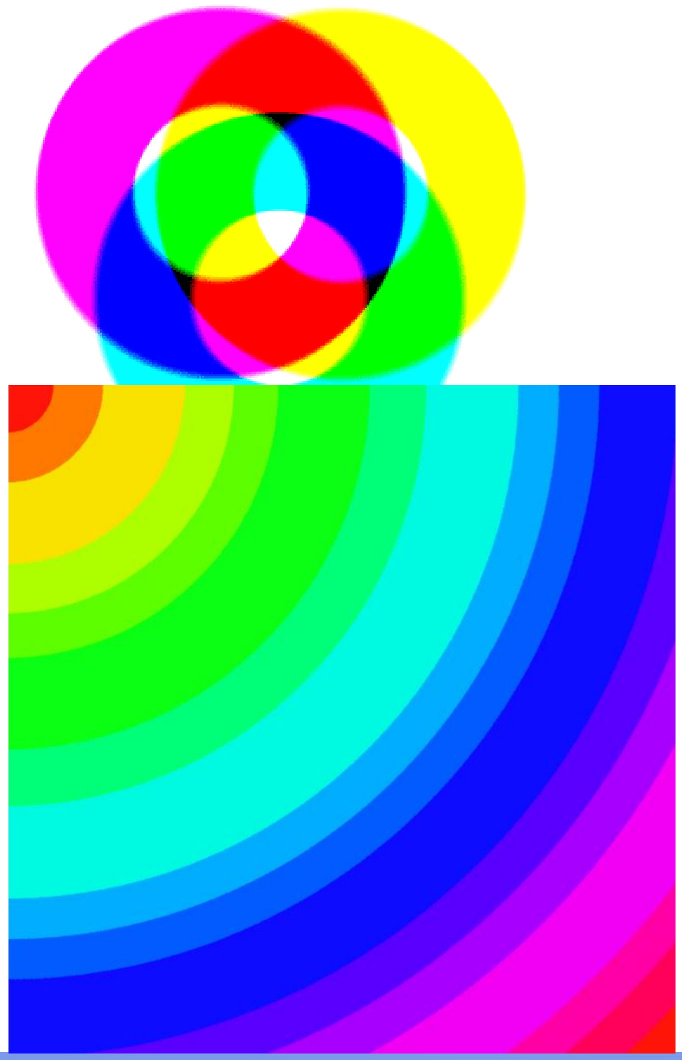
- Red, Green and Blue are three primary additive colours. The mixture of the primary additive colours can produce other colours.





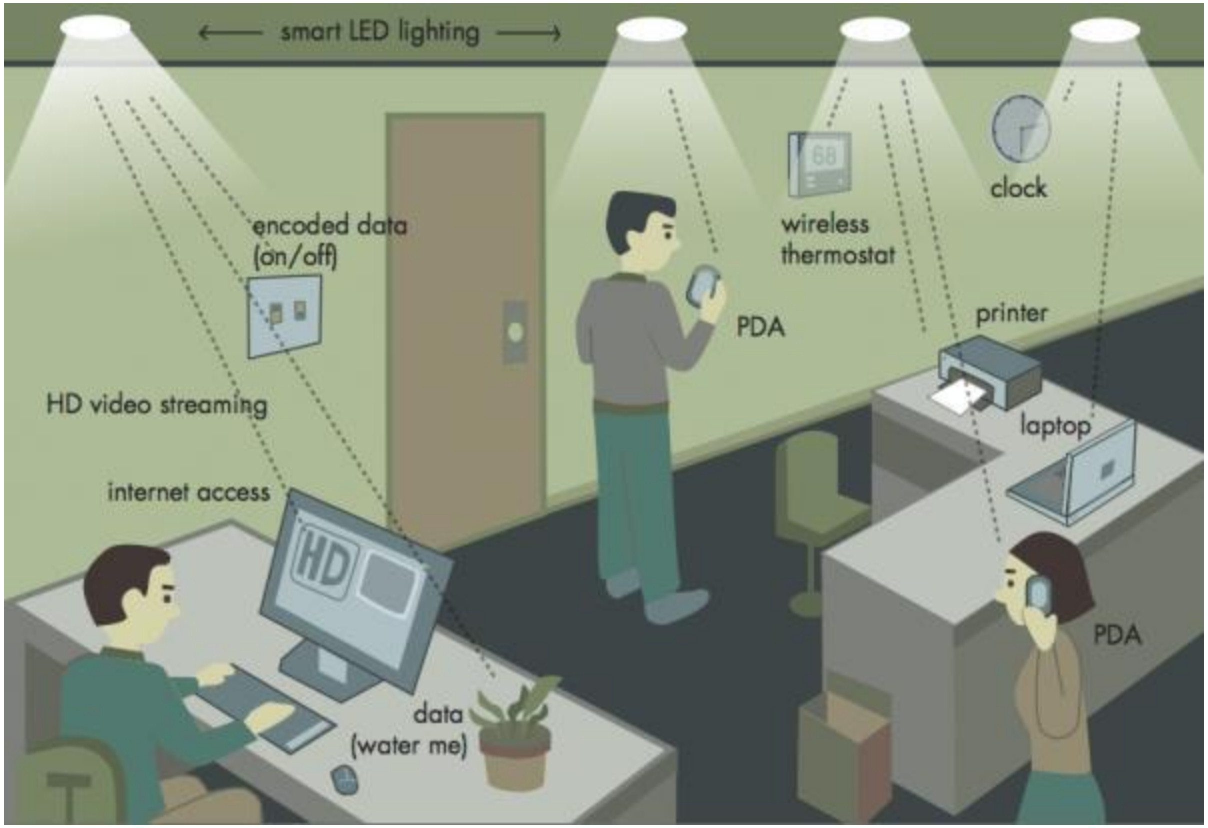
Example of Synthesizing Colours



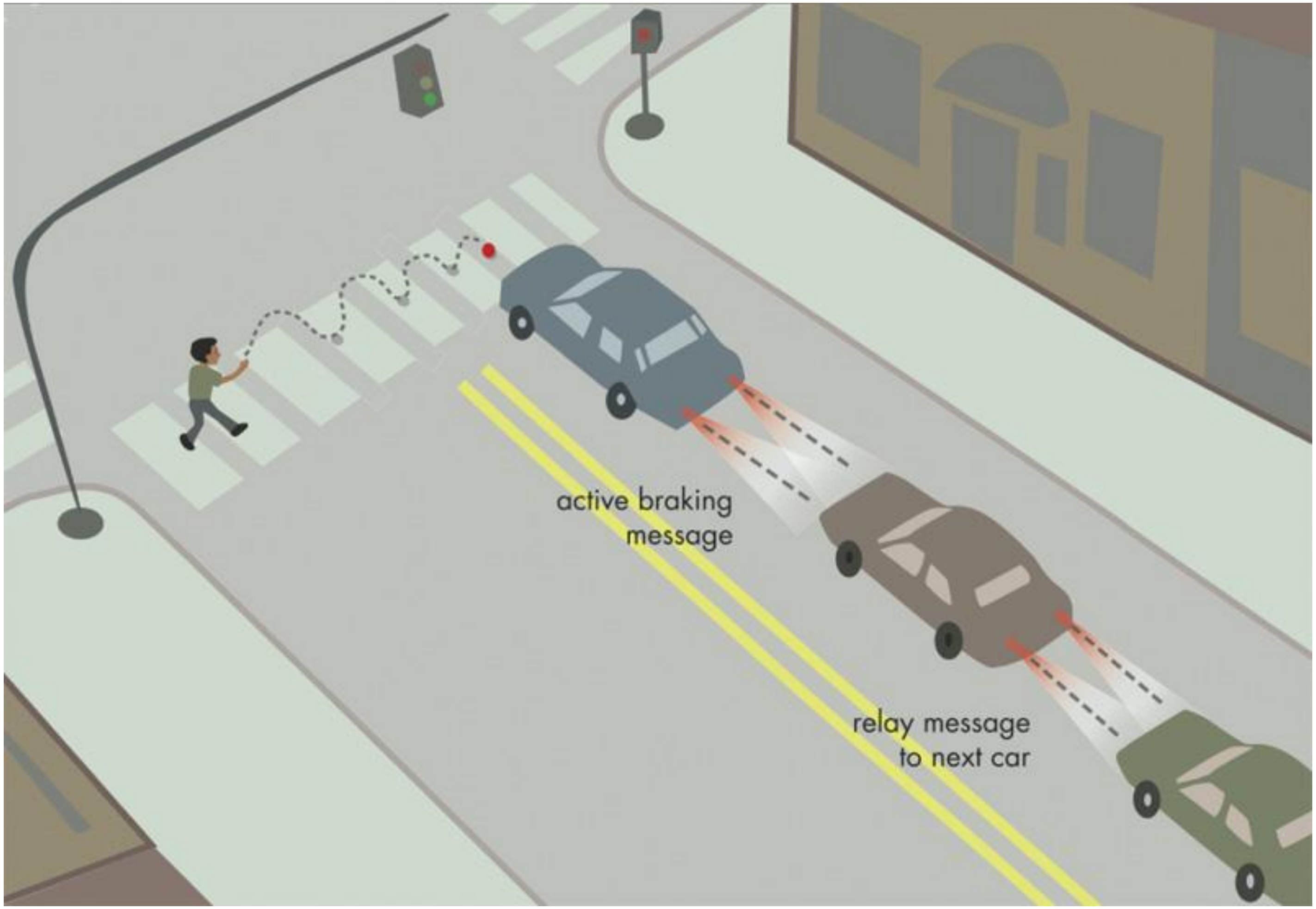


Understanding Lights (9)

- Light rays are electro-magnetic waves which can serve as signal carriers for data communications.



Example of Using Lights to Do Communications …



Outline

- Understanding of Visual Signals
- Computation of Visual Signals
- Measurement of Photometry
- Practices with MATLAB

Should seeing be believing?

What could be computed from visual signals?

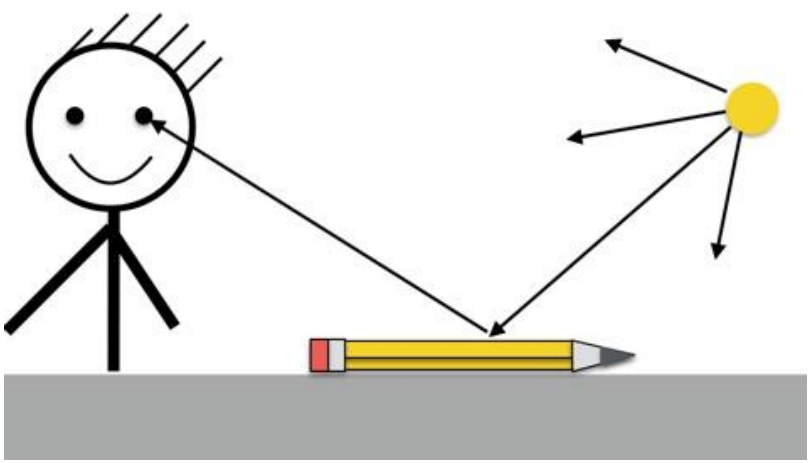
<u>Geometry</u>

- Path (Motion)
- Direction (Appearance)

<u>Photometry</u>

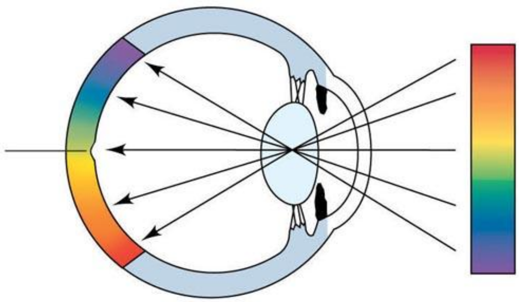
- Luminance (or Intensity)
- Chrominance (or Colour)

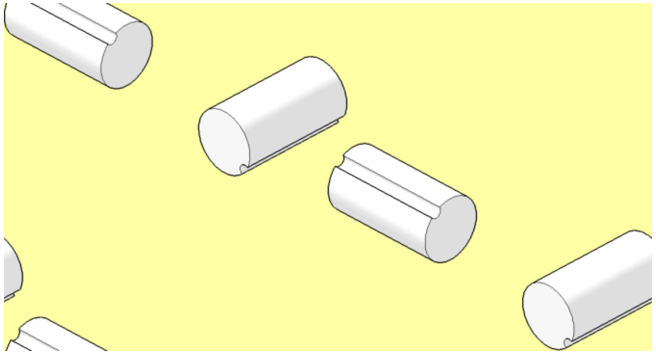
Colour Space

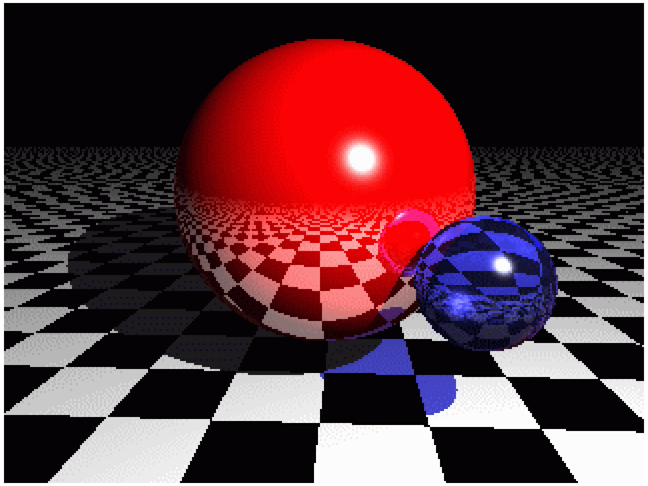


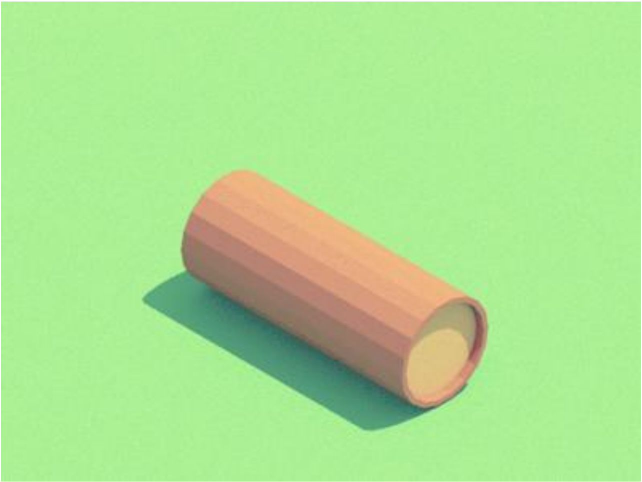
What is Path of Visual Signals?

- Paths refer to the spatial locations that light sources pass through.



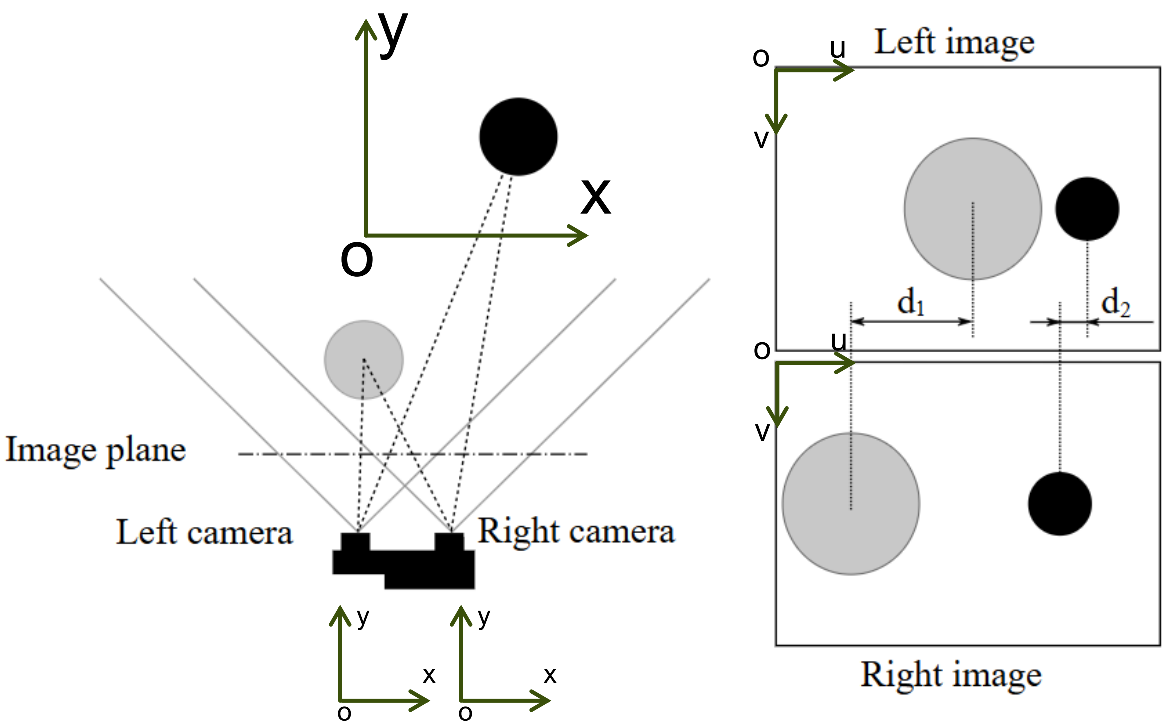






What is Direction of Visual Signals?

- Directions refer to the angles of light rays with respect to reference coordinate systems.

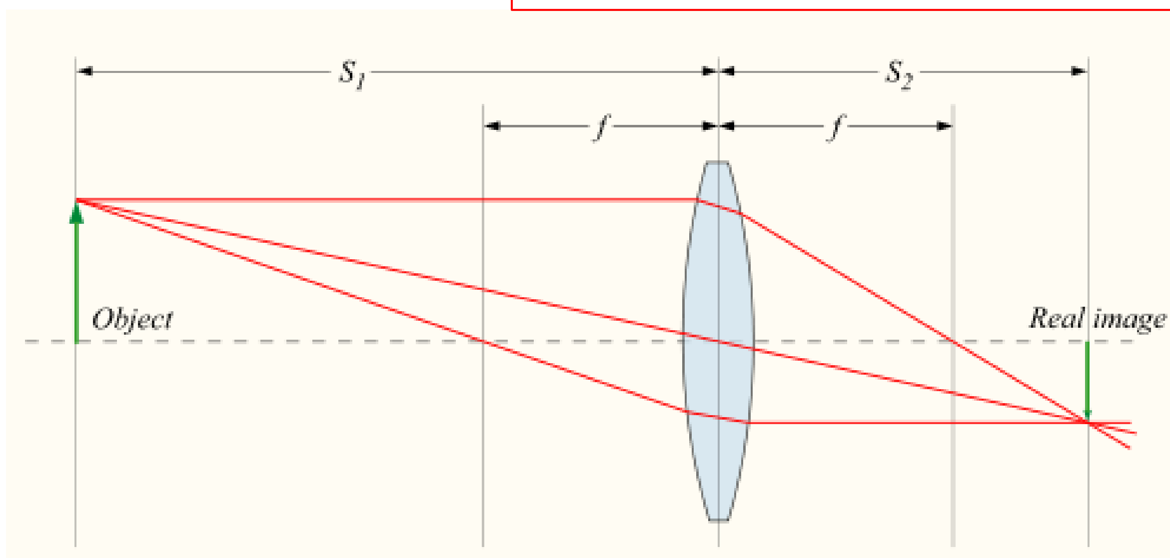


Geometric Equation of Thin Lens (1)

$$\frac{1}{S_1}+\frac{1}{S_2}=\frac{1}{f}$$

f:	Focal Length
S1:	Distance to Object
S2:	Distance to Image

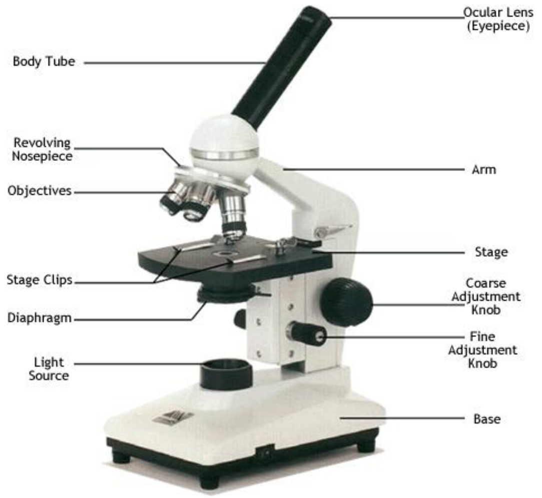
Normal Scope



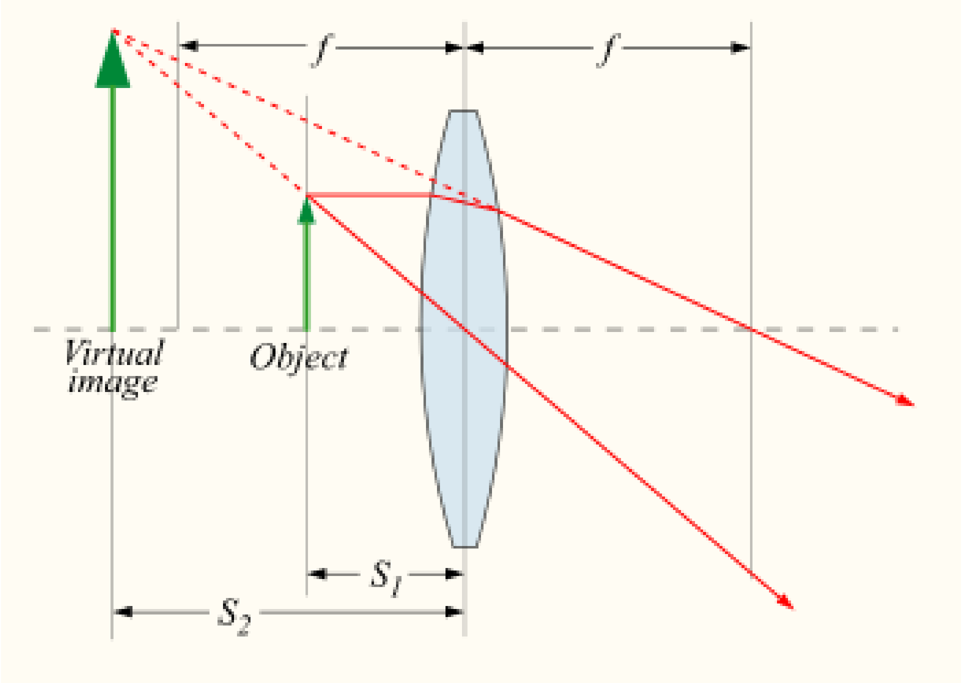
Geometric Equation of Thin Lens (2)

$$\frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f}$$

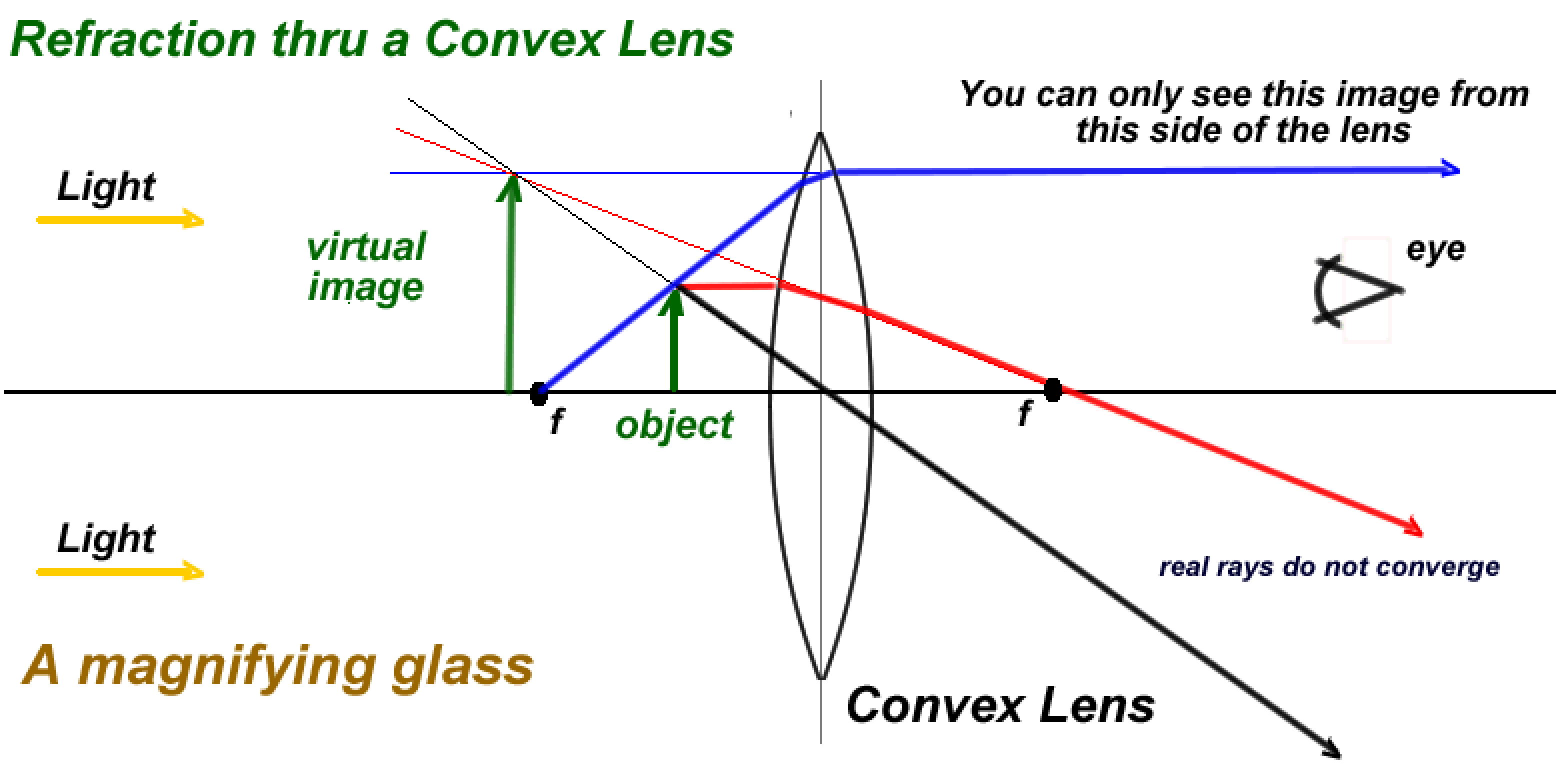
f:	Focal Length
S1:	Distance to Object
S2:	Distance to Image



Microscope

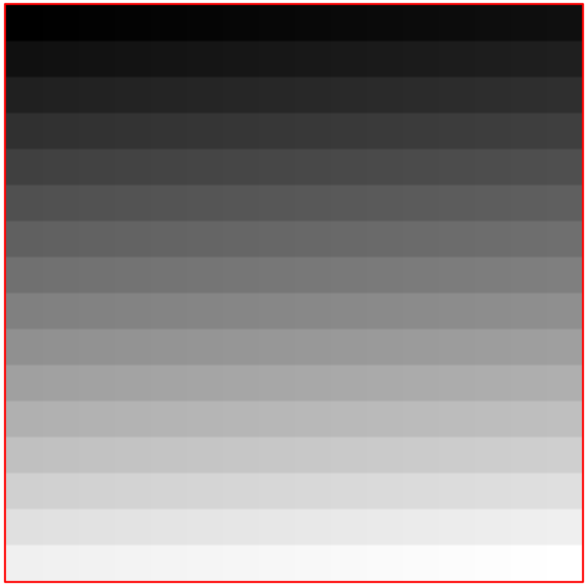


Principle of Designing Microscope …



What is Luminance of Visual Signals?

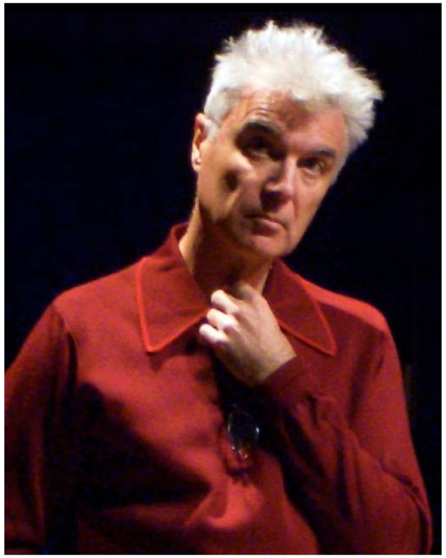
- Luminance refers to a single value which represents the energy levels of light rays.

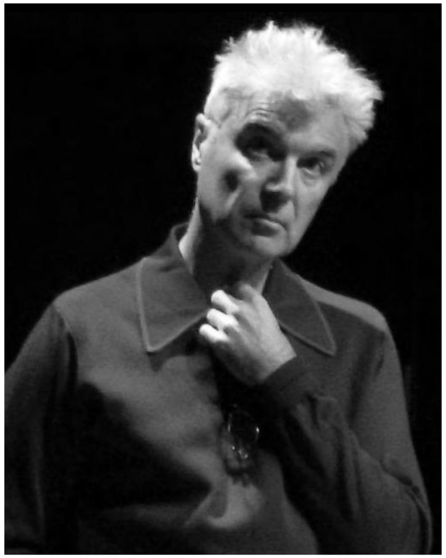


Grey Scale Levels

What is Chrominance of Visual Signals?

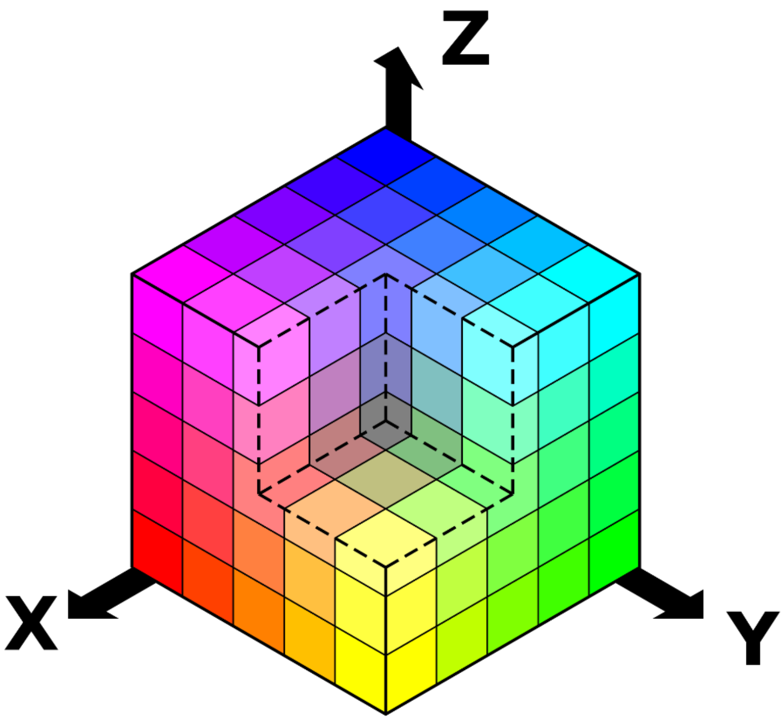
- Chrominance refers to a set of two values which represent the colour information of light rays.


With Colours

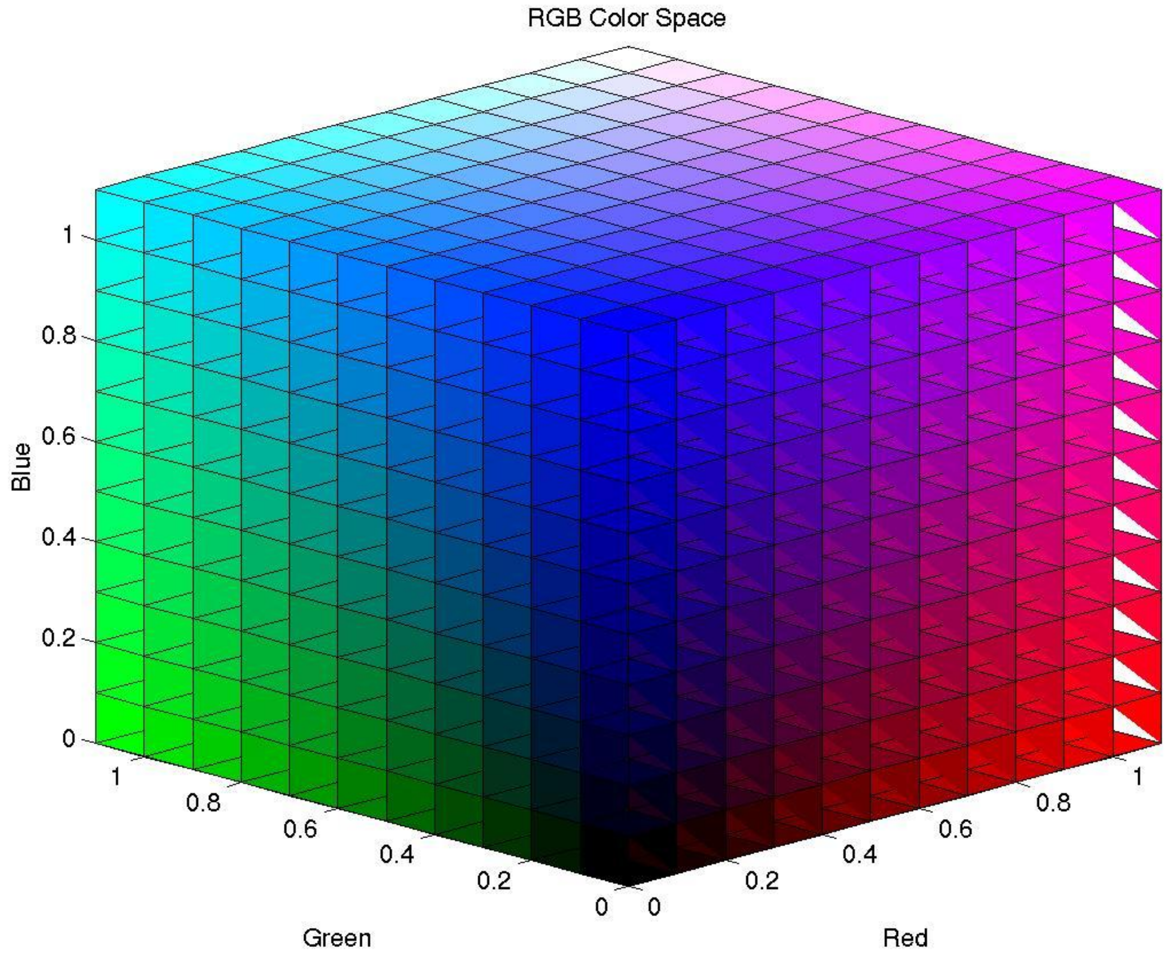

Without Colours

Colour Spaces of Visual Signals

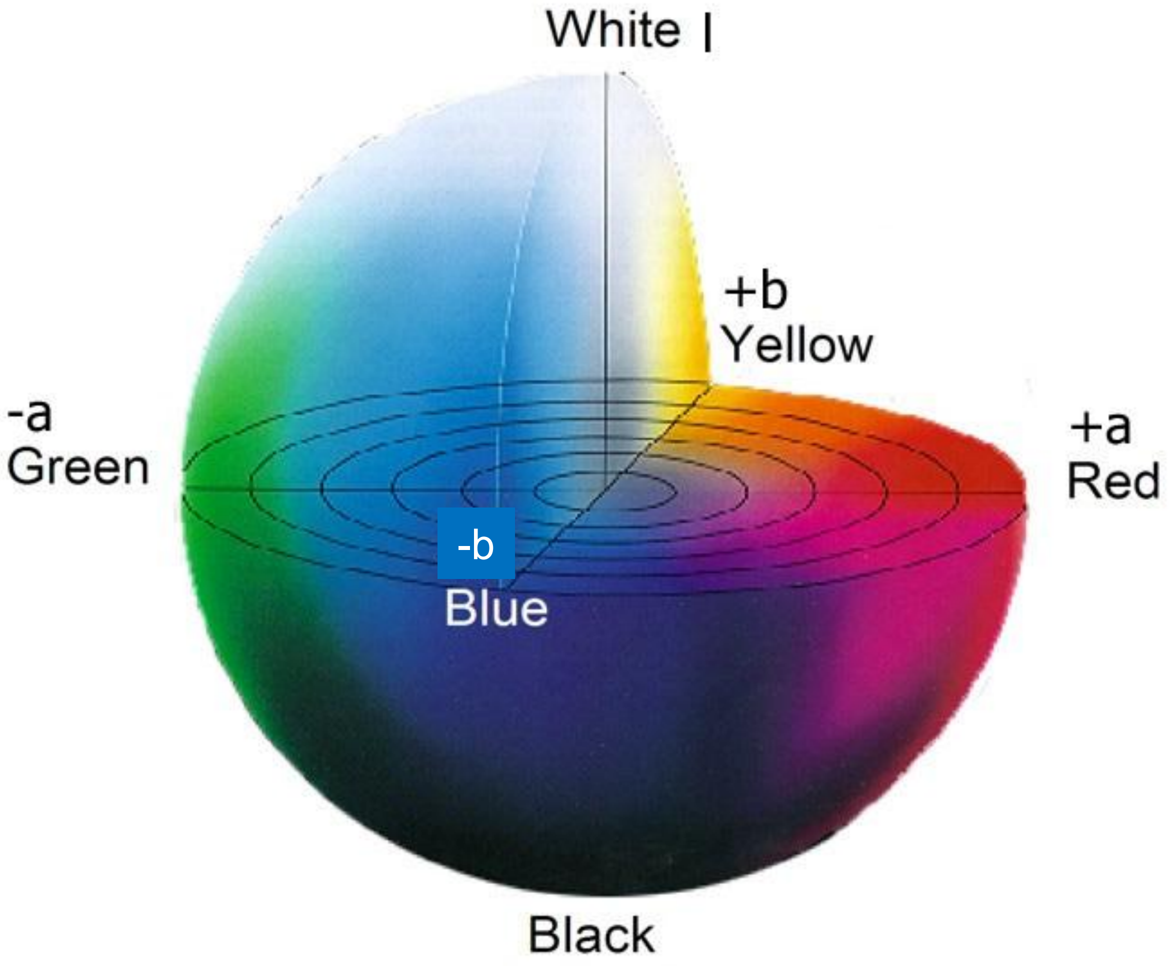
- The values of luminance and chrominance form three-dimensional colour spaces.



Example of RGB Colour Space

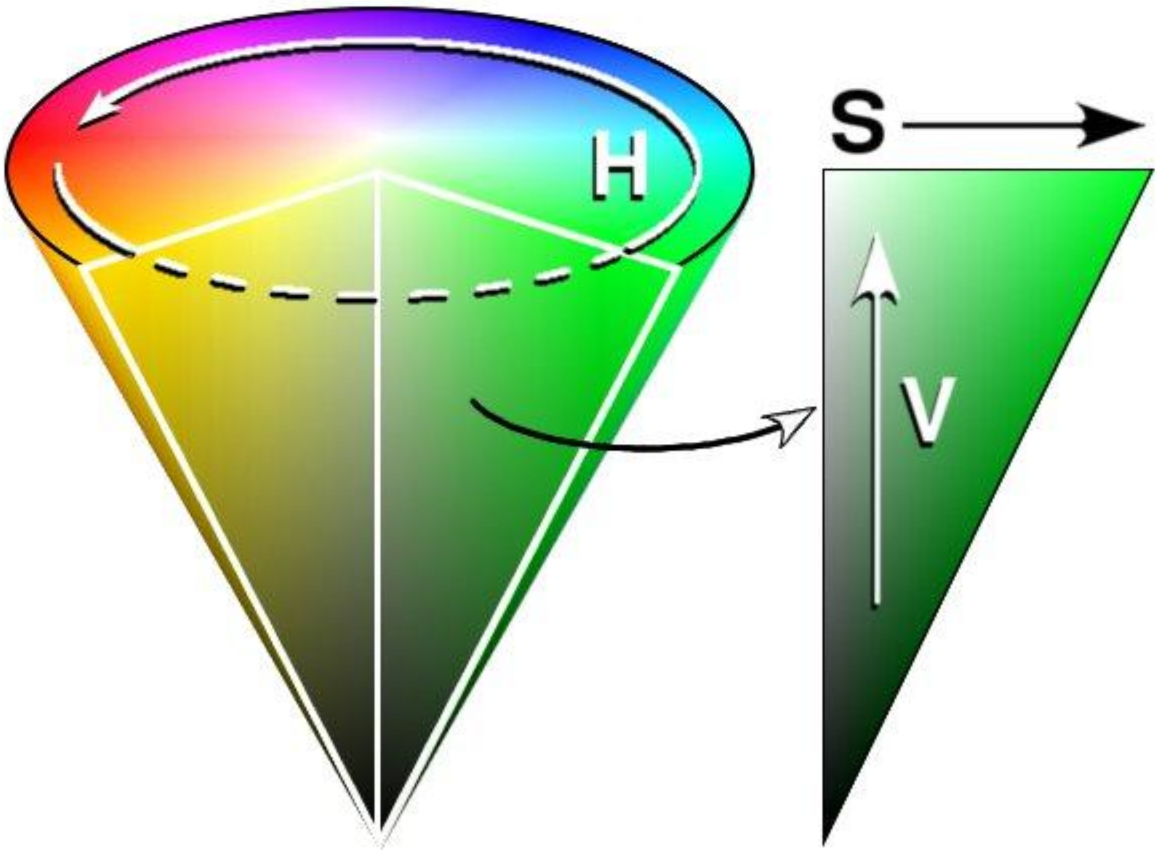


Example of L*a*b Colour Space



Example of HSV Colour Space

- Hue (colour angle), Saturation (colour amplitude), Visual Brightness



How to Convert RGB Colour Space to L*a*b Colour Space?

Solution:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.607 & 0.174 & 0.200 \\ 0.299 & 0.587 & 0.114 \\ 0.000 & 0.066 & 1.116 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{cases} L = 25.0 \bullet (100.0 \bullet Y / Y_{max})^{1/3} - 16.0 \\ a = 500.0 \bullet [(X / X_{max})^{1/3} - (Y / Y_{max})^{1/3}] \\ b = 200.0 \bullet [(Y / Y_{max})^{1/3} - (Z / Z_{max})^{1/3}] \end{cases}$$

RGB Working Space	Reference White	RGB to XYZ [M]
Adobe RGB (1998)	D65	0.5767309 0.1855540 0.1881852 0.2973769 0.6273491 0.0752741 0.0270343 0.0706872 0.9911085
AppleRGB	D65	0.4497288 0.3162486 0.1844926 0.2446525 0.6720283 0.0833192 0.0251848 0.1411824 0.9224628
Best RGB	D50	0.6326696 0.2045558 0.1269946 0.2284569 0.7373523 0.0341908 0.0000000 0.0095142 0.8156958
Beta RGB	D50	0.6712537 0.1745834 0.1183829 0.3032726 0.6637861 0.0329413 0.0000000 0.0407010 0.7845090
Bruce RGB	D65	0.4674162 0.2944512 0.1886026 0.2410115 0.6835475 0.0754410 0.0219101 0.0736128 0.9933071
CIE RGB	E	0.4887180 0.3106803 0.2006017 0.1762044 0.8129847 0.0108109 0.0000000 0.0102048 0.9897952

Ekta Space PS5	D50	0.5938914 0.2606286 0.0000000	0.2729801 0.7349465 0.0419969	0.0973485 0.0044249 0.7832131
NTSC RGB	C	0.6068909 0.2989164 0.0000000	0.1735011 0.5865990 0.0660957	0.2003480 0.1144845 1.1162243
PAL/SECAM RGB	D65	0.4306190 0.2220379 0.0201853	0.3415419 0.7066384 0.1295504	0.1783091 0.0713236 0.9390944
ProPhoto RGB	D50	0.7976749 0.2880402 0.0000000	0.1351917 0.7118741 0.0000000	0.0313534 0.0000857 0.8252100
SMPTE-C RGB	D65	0.3935891 0.2124132 0.0187423	0.3652497 0.7010437 0.1119313	0.1916313 0.0865432 0.9581563
sRGB	D65	0.4124564 0.2126729 0.0193339	0.3575761 0.7151522 0.1191920	0.1804375 0.0721750 0.9503041
Wide Gamut RGB	D50	0.7161046 0.2581874 0.0000000	0.1009296 0.7249378 0.0517813	0.1471858 0.0168748 0.7734287

How to Convert RGB Colour Space to HSV Colour Space?

Solution:

$$M = \max\{R/255, G/255, B/255\}$$

$$m = \min\{R/255, G/255, B/255\}$$

$$C = M - m$$

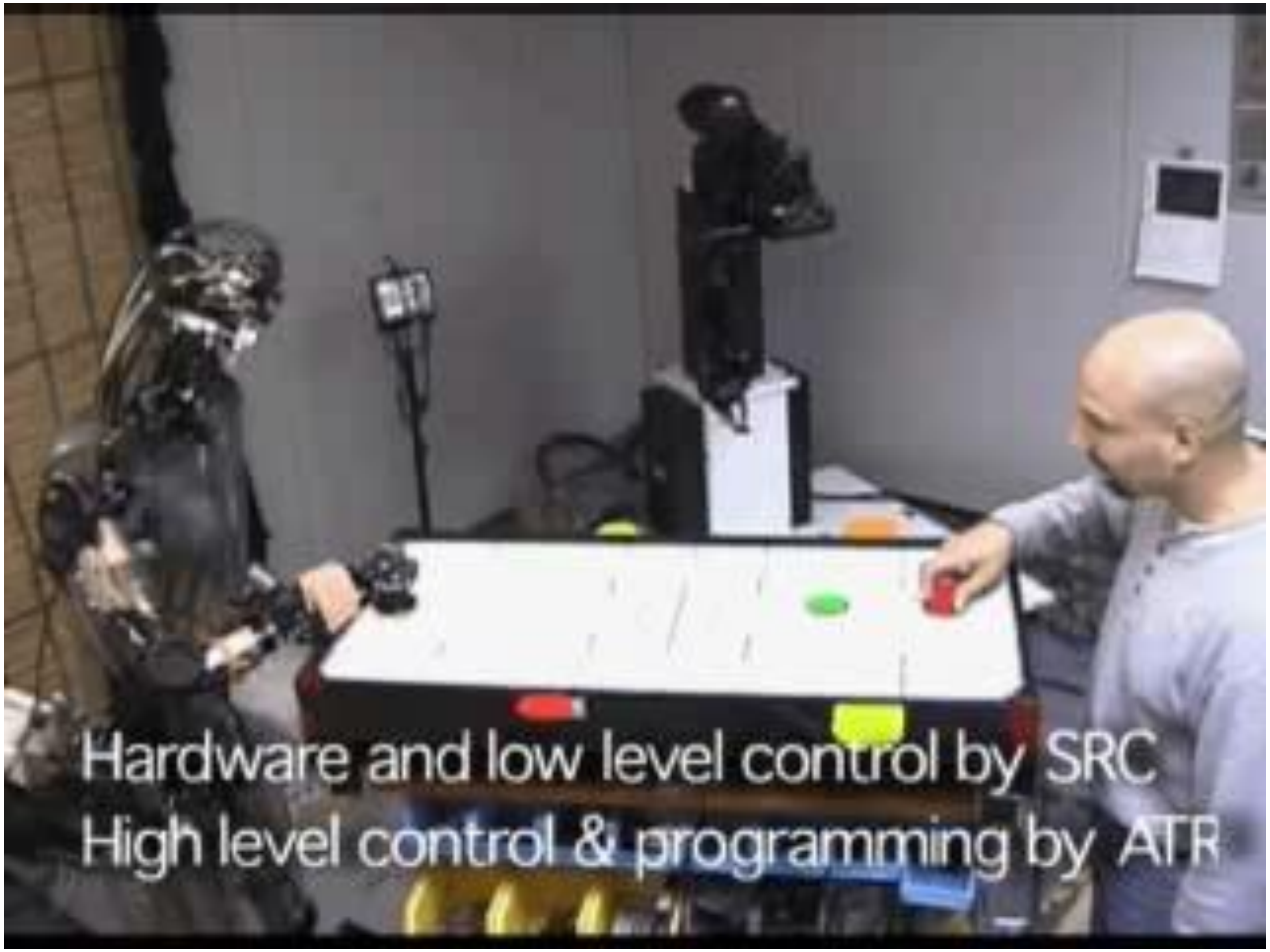
$$S = \frac{M - m}{M} \qquad V = M \qquad H = \begin{cases} \frac{G/255 - B/255}{6C} & \text{if M} = \text{R/255} \\ \frac{B/255 - R/255}{6C} + \frac{1}{3} & \text{if M} = \text{G/255} \\ \frac{R/255 - G/255}{6C} + \frac{2}{3} & \text{if M} = \text{B/255} \end{cases}$$

Outline

- Understanding of Visual Signals
- Computation of Visual Signals
- Measurement of Photometry
- Practices with MATLAB

Should seeing be believing?

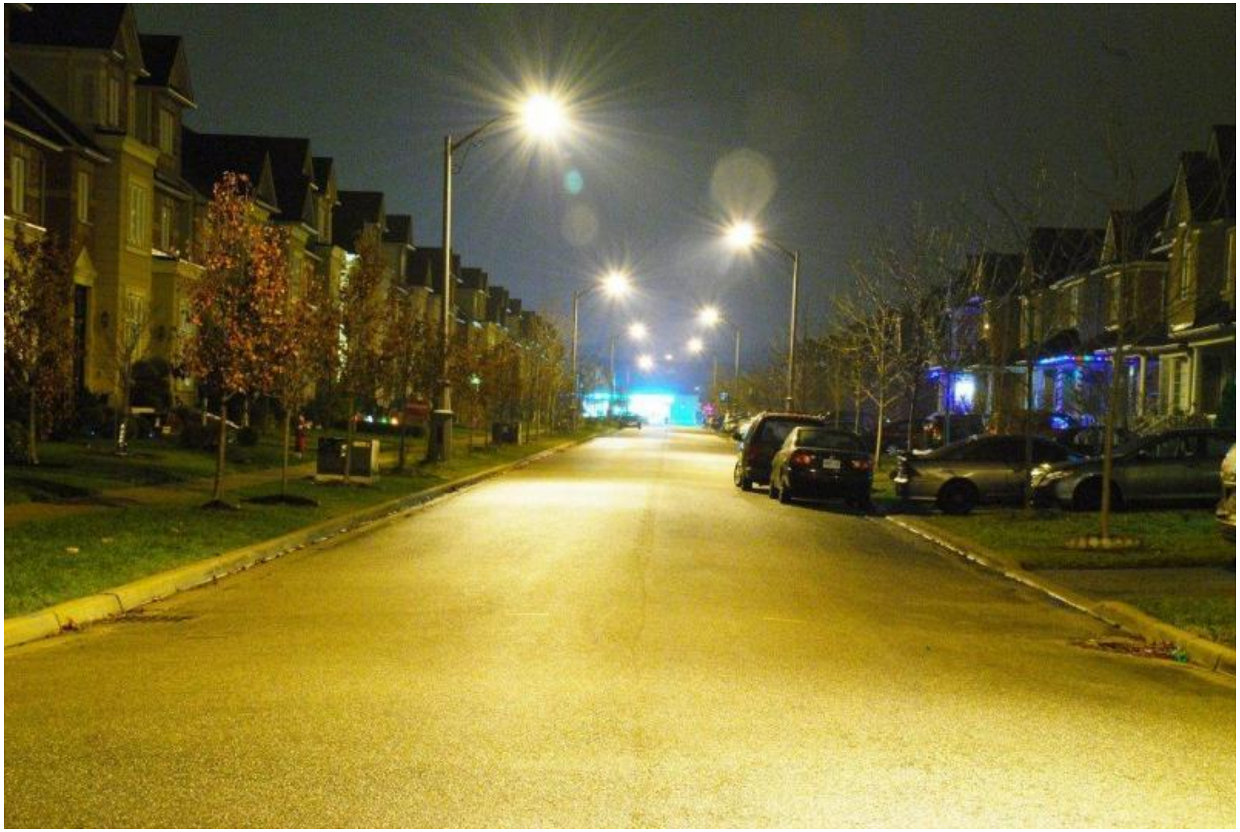
Visual Signals Enable Interaction …



Visual Signals Enable Automation …

Applications (1)

- Illuminations

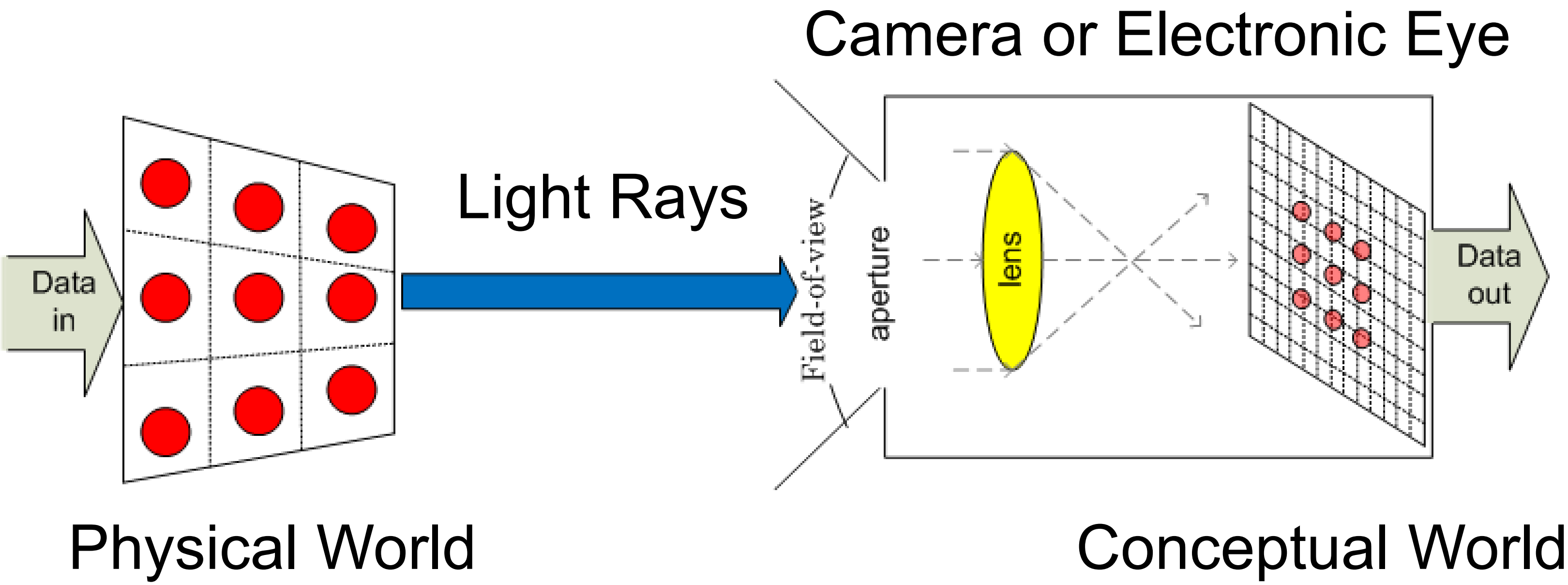


Applications (2)

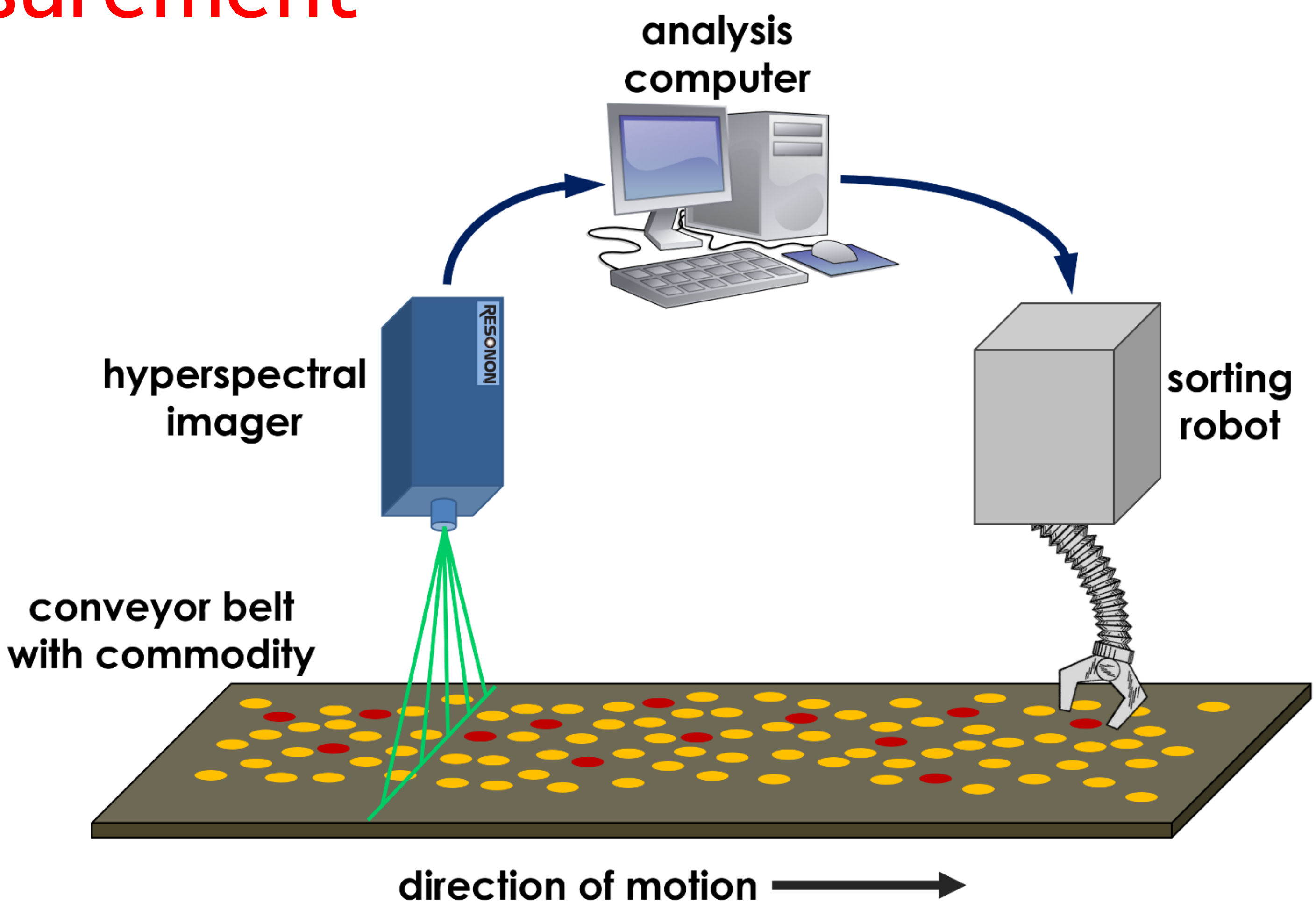
- Communications

Applications (3)

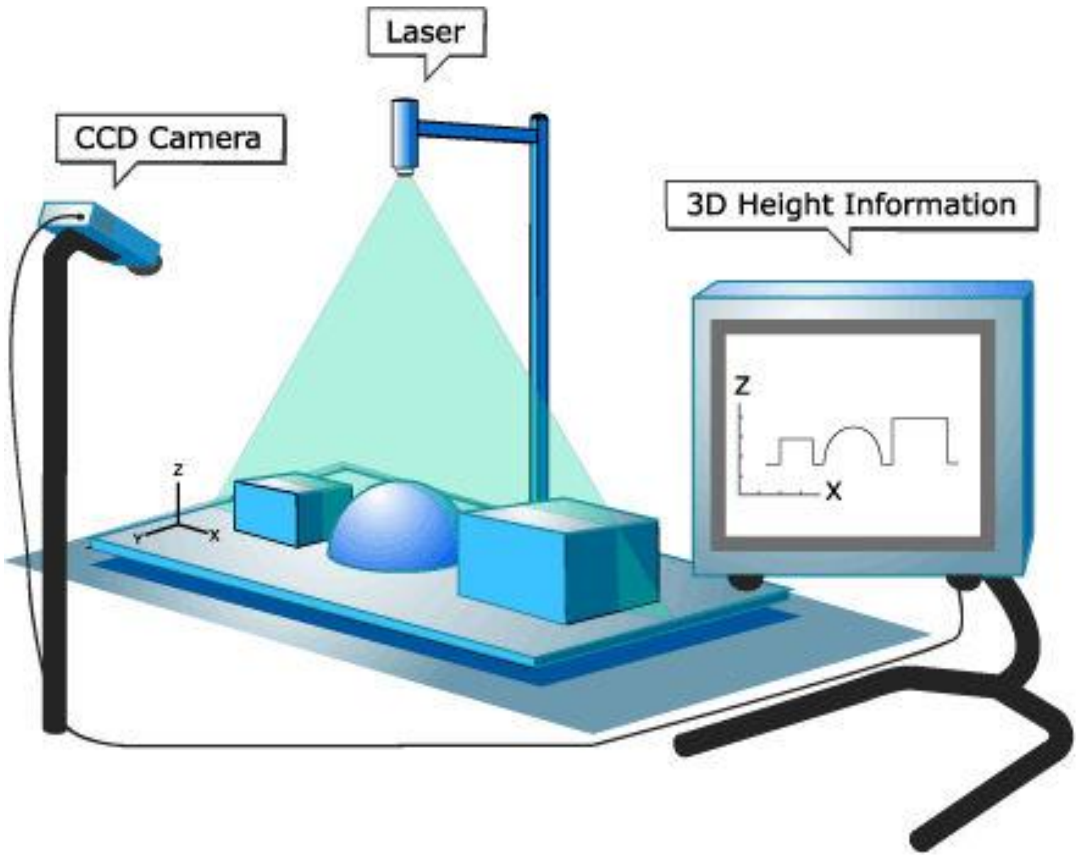
- Vision for Measurement, Inspection, Surveillance, Guidance, Recording, Learning, and Interaction, etc.



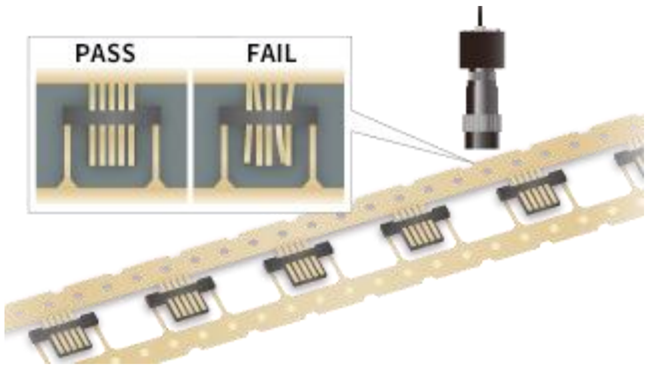
Example of Using Visual Signal to Do Measurement

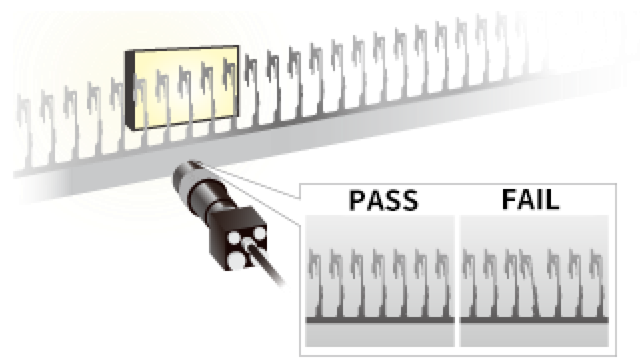


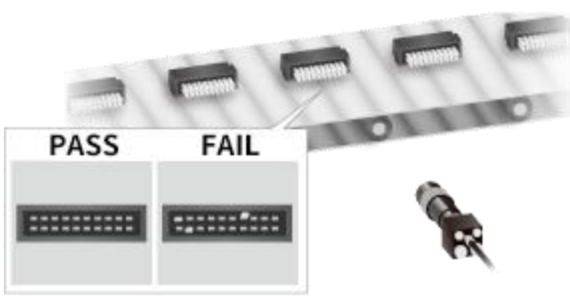
Example of Using Visual Signal to Do Measurement



More Examples of Using Visual Signals to Guide Automation …

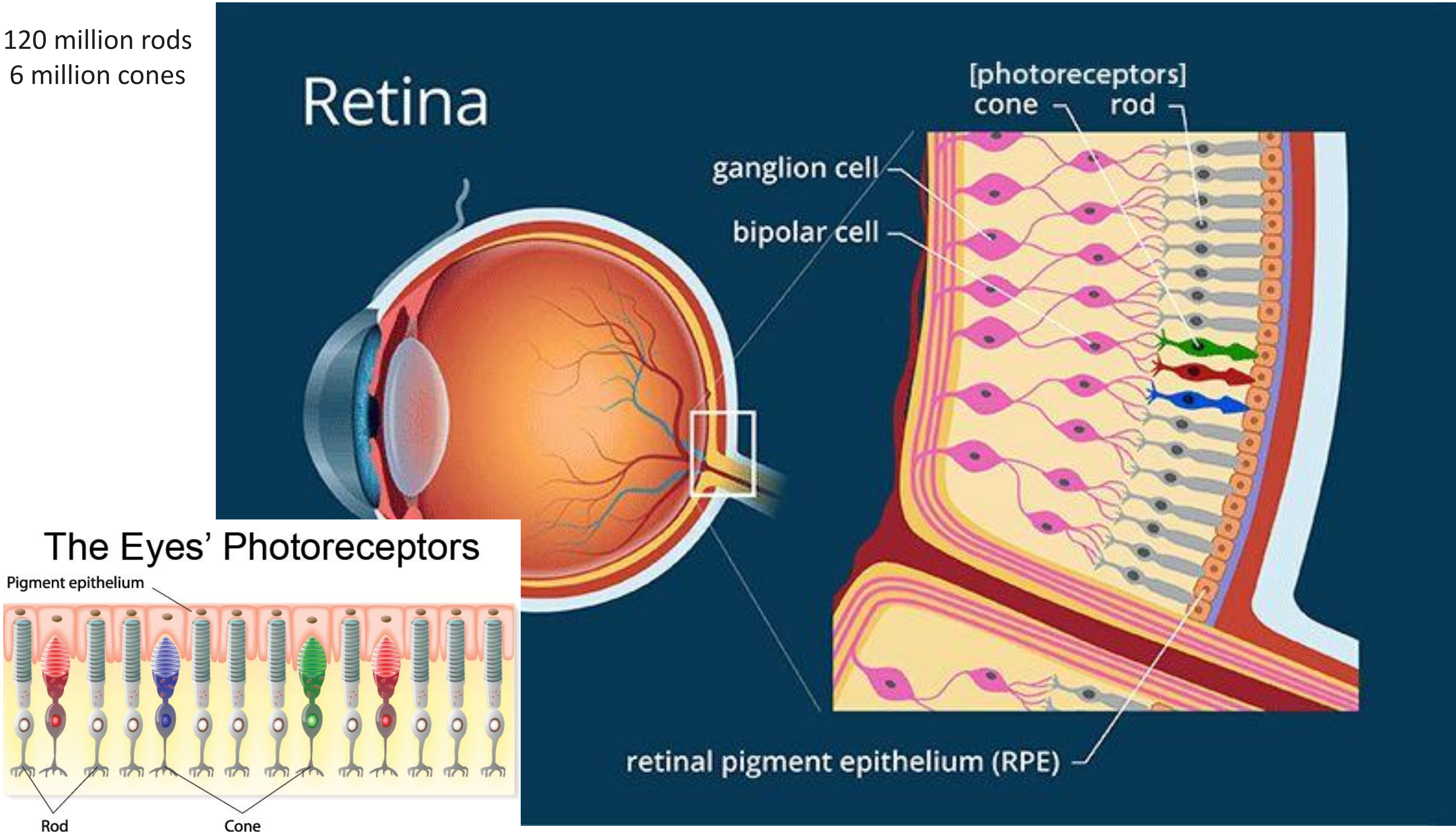




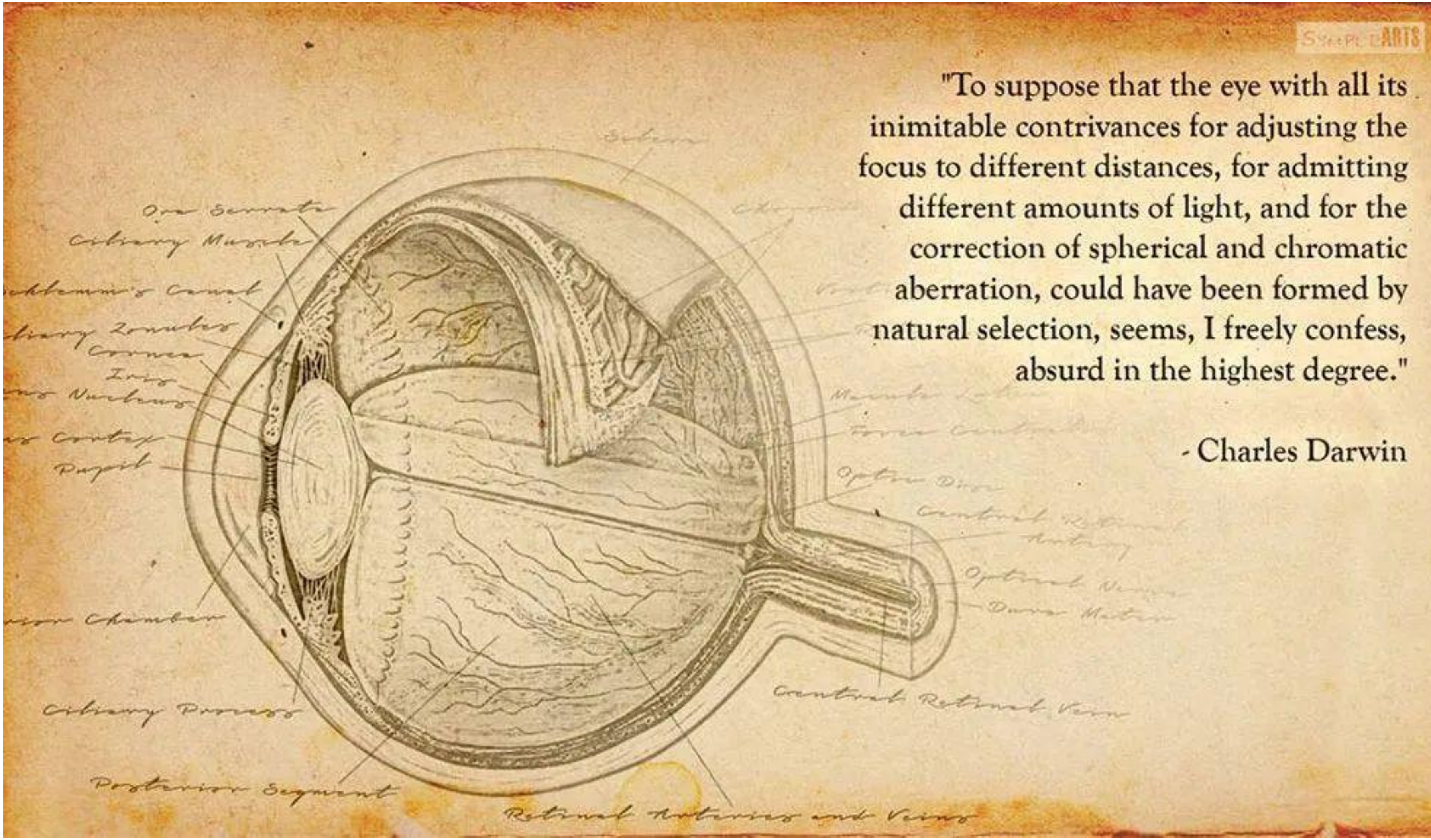


Measurement of Photometry by Human Eyes:

120 million rods
6 million cones

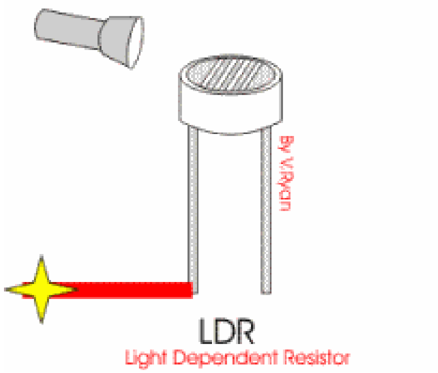


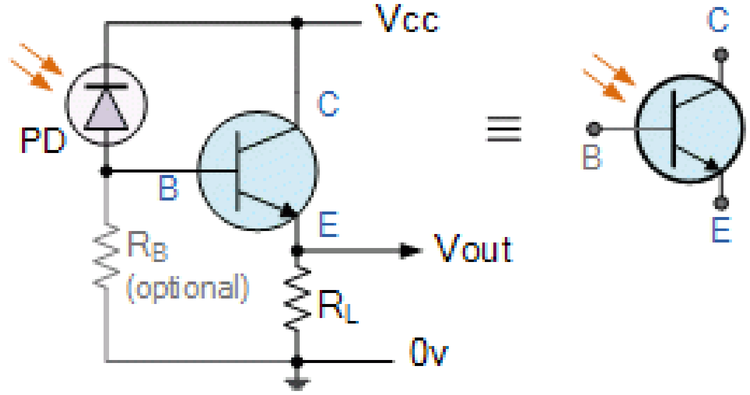
Discussion: Top-Down Design versus Bottom-Up Evolution

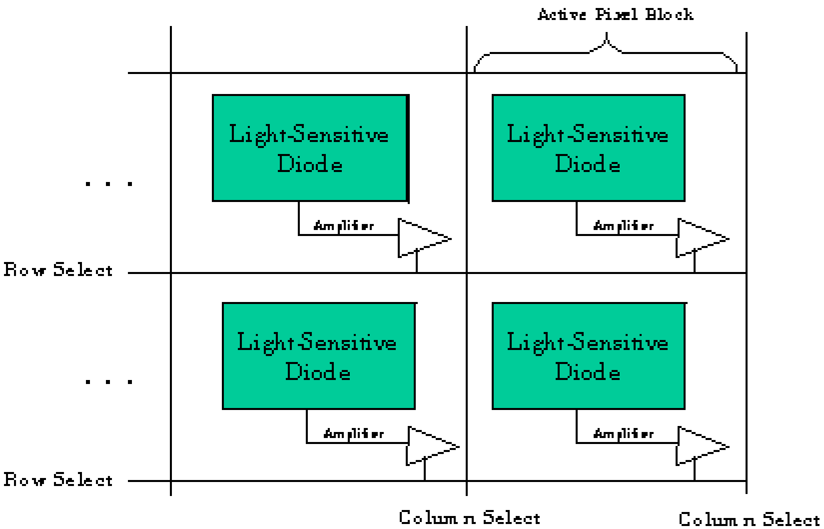


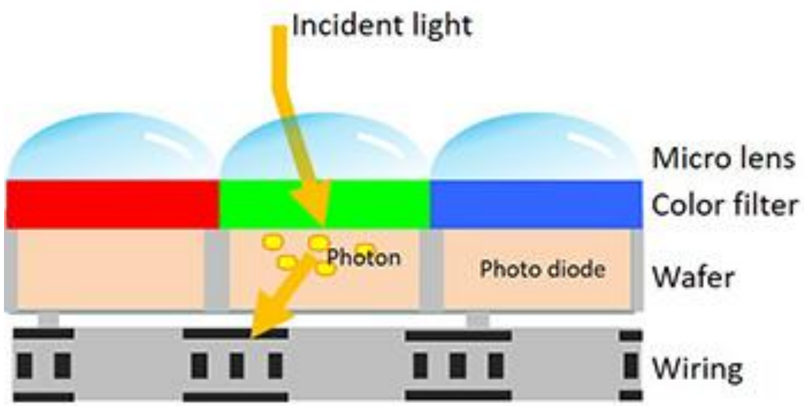
How to measure photometry?

- Use of Photoelectric Device to Sense:
  - Intensities
  - Colors



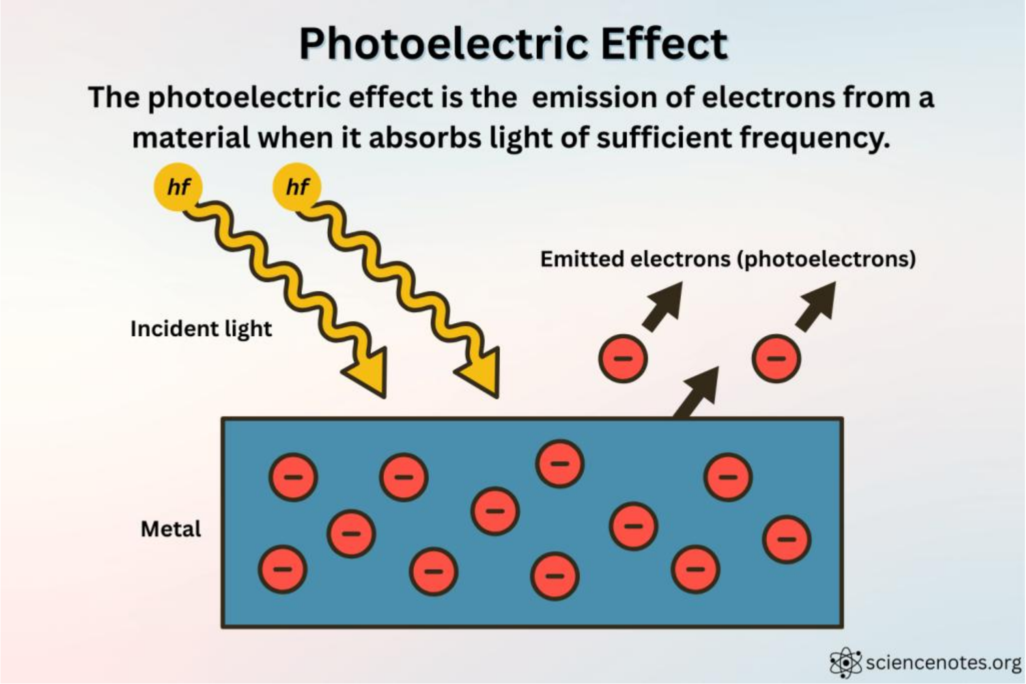


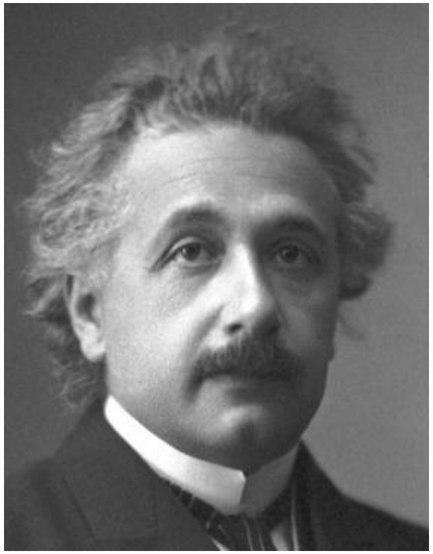




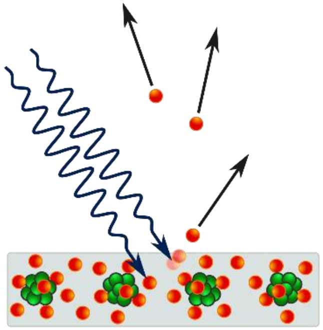
A Person to Remember: Albert Einstein

- He has discovered the photoelectric effect which is the emission of electrons from a material caused by electromagnetic radiation such as ultraviolet light. Electrons emitted in this manner are called photoelectrons.



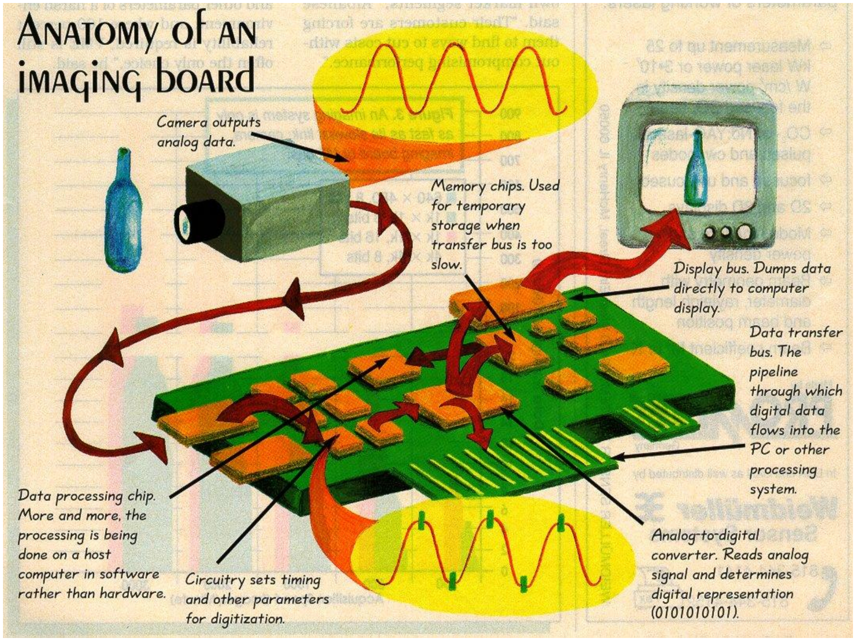


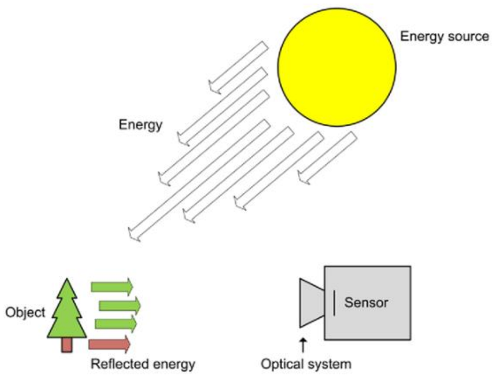
Nobel Prize in Physics 1921

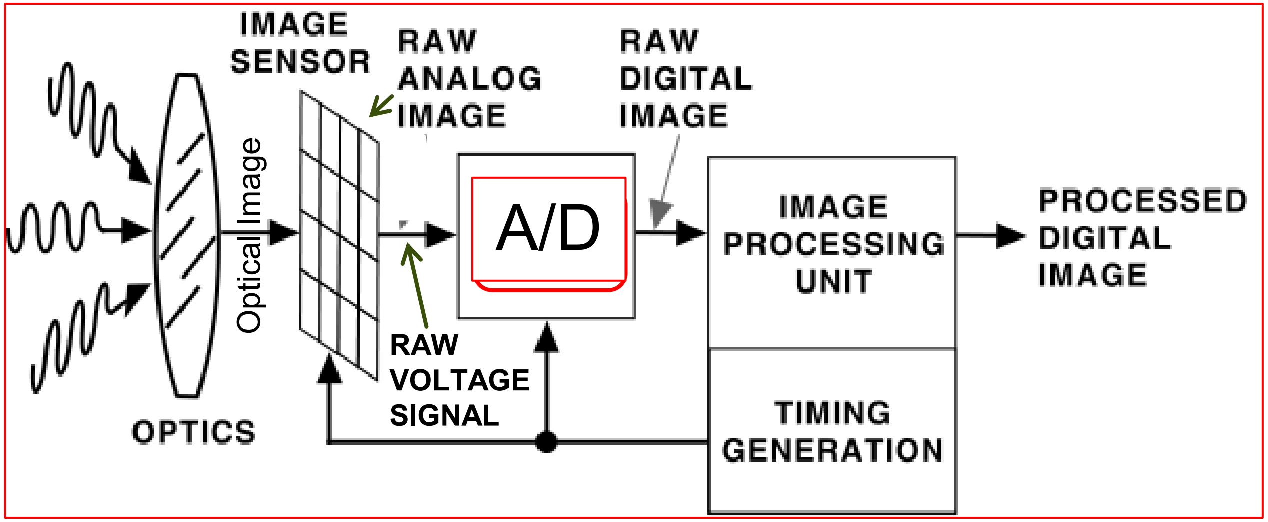


Principle of Measurement

- The principle consists of converting lights into optical images, which are then converted into analogue images. The analogue images could be formatted into time functions of voltages which could be automatically measured by microcontrollers or other advanced electronic hardware.

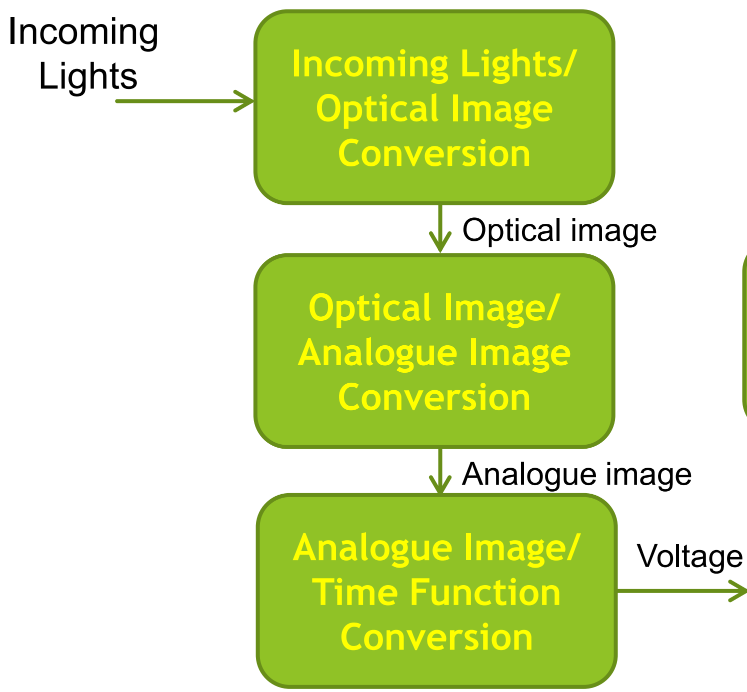


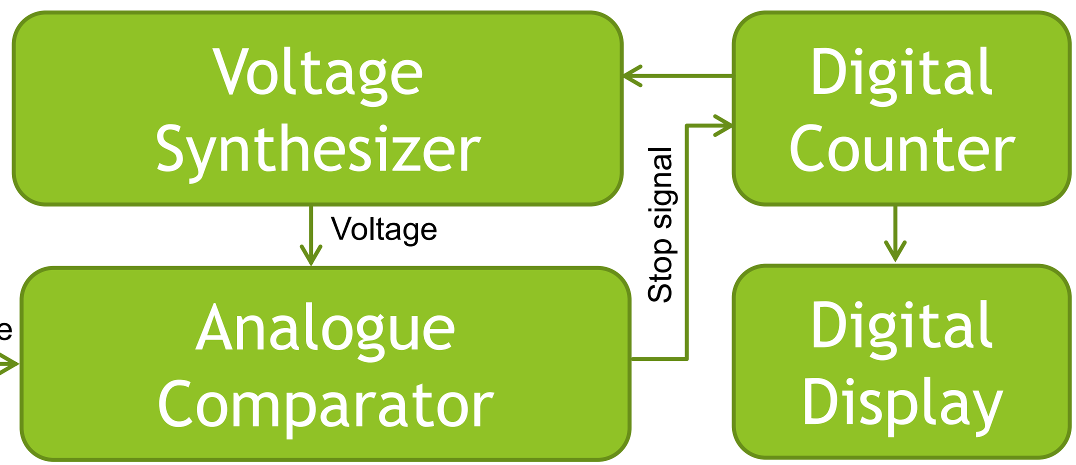




How to implement the principle of doing direct measurement of photometry?

- In general, the implementation incudes the following two extra modules:
  - Conversion of incoming lights into optical images
  - Conversion of optical images into analogue voltage images
  - Conversion of analogue voltage images into time functions of voltage



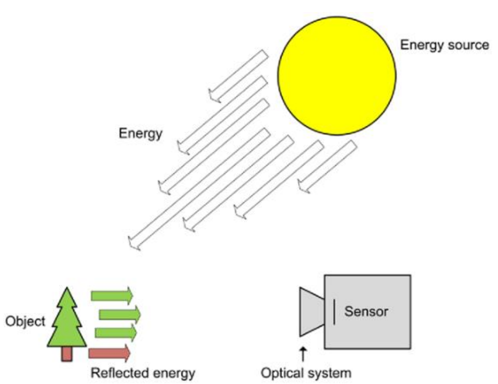


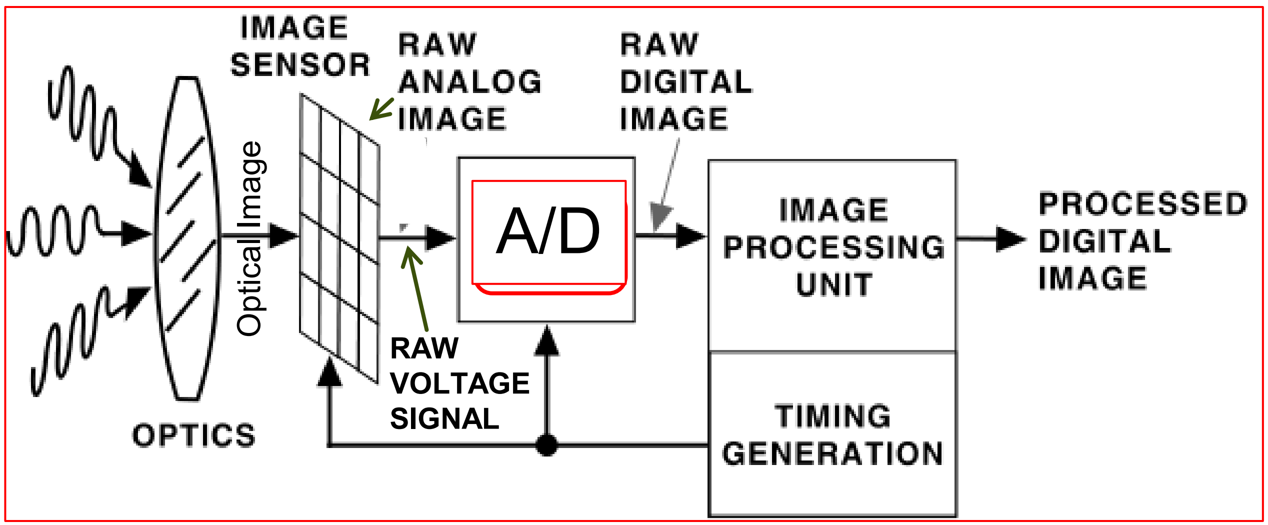
All microcontrollers are programmable digital sensors of voltage!

The Pipeline of Signal Flows

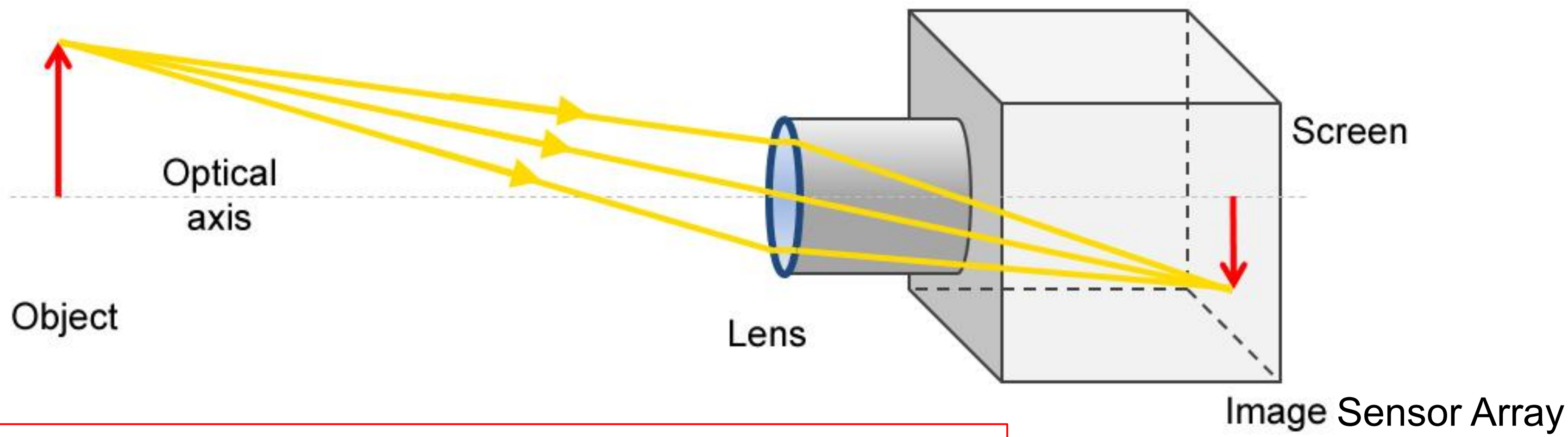
- 1. From Light Rays to Optical Image: MIMO
- 2. From Optical Image to Analogue Image: MIMO
- 3. From Analogue Image to Voltage Signals: MISO
- 4. From Voltage Signals to Digital Image: SIMO
- 5. From Digital Image to Display
- 6. From Digital Image to Image Processing …

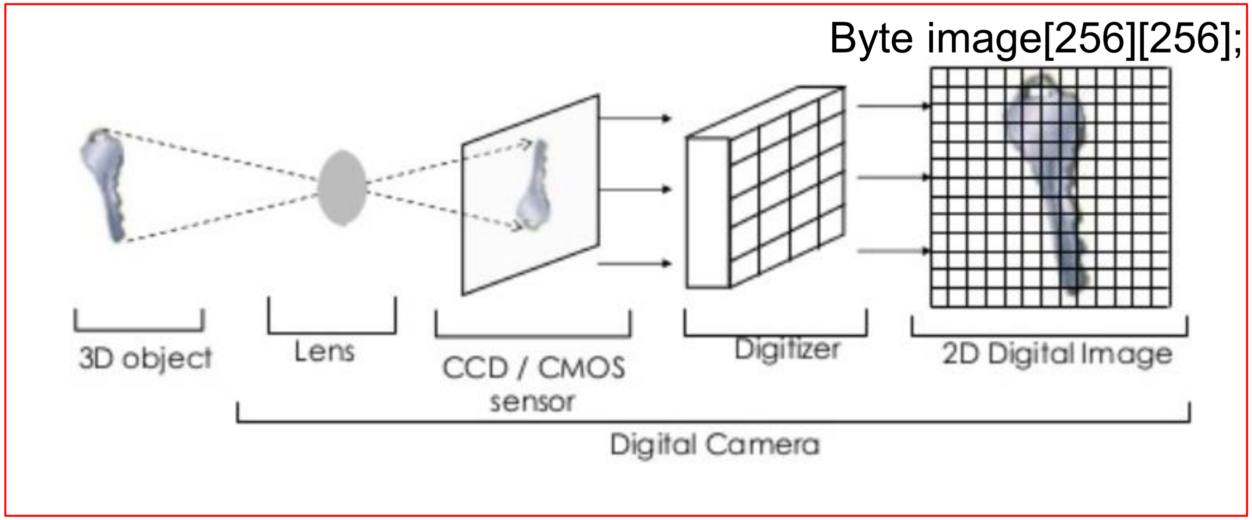
(Items 1–4 together: MIMO)



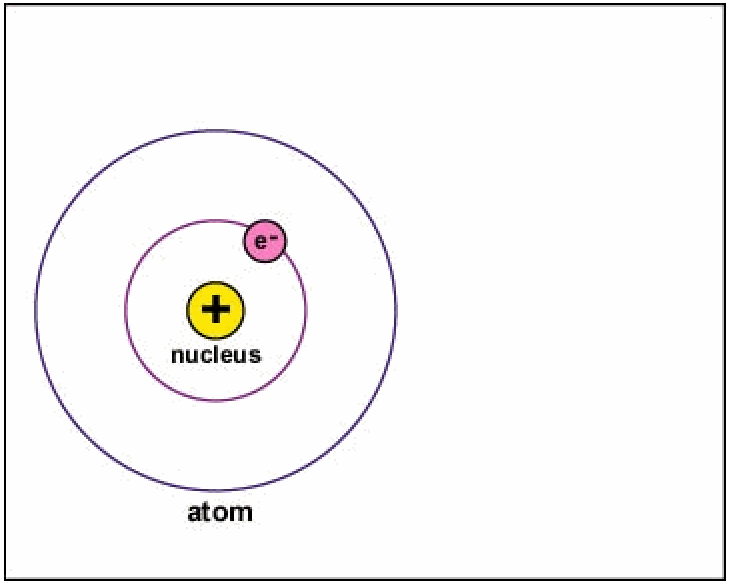


How to convert lights into optical images?

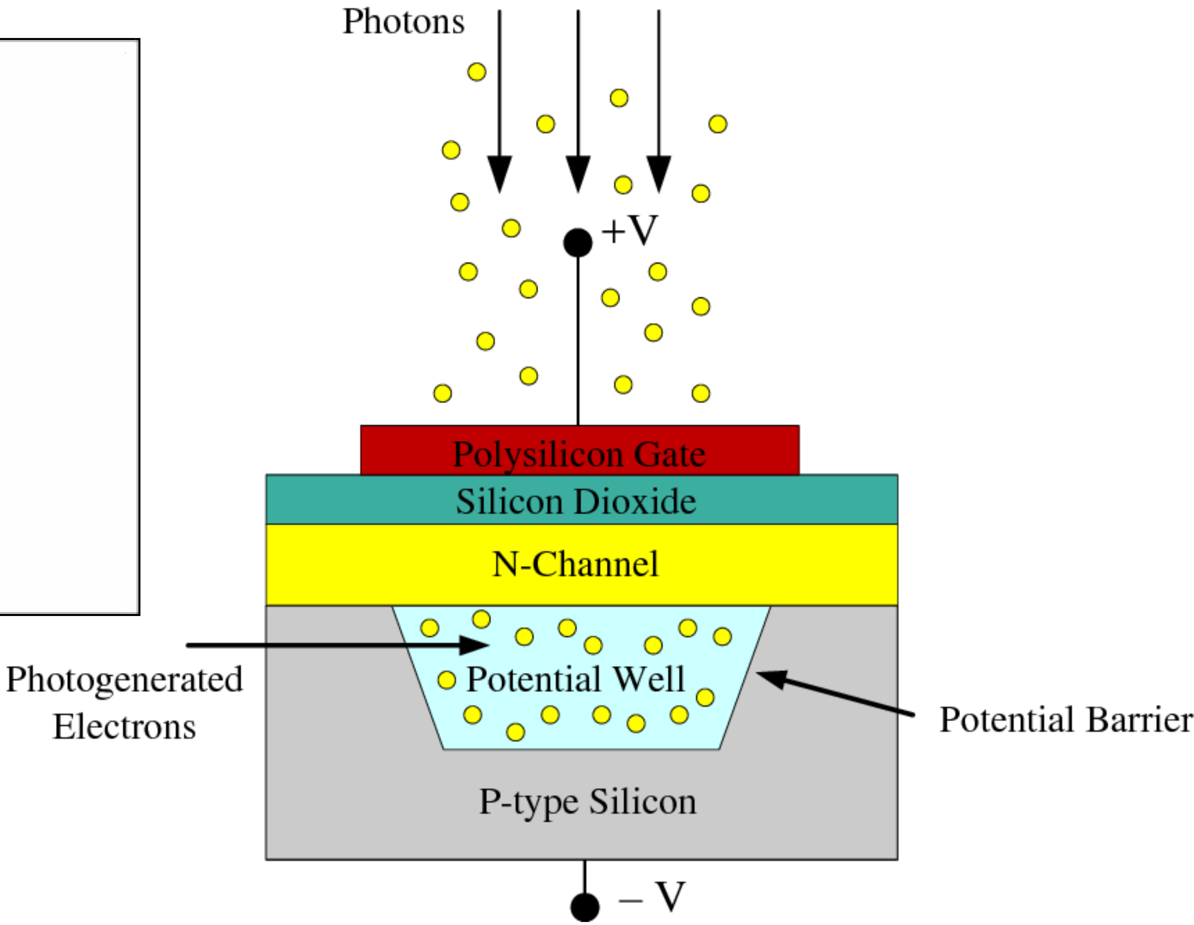




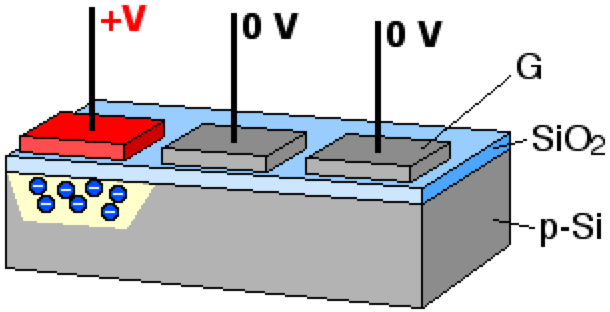
How to convert the light intensity at a single point of optical image into analogue voltage?

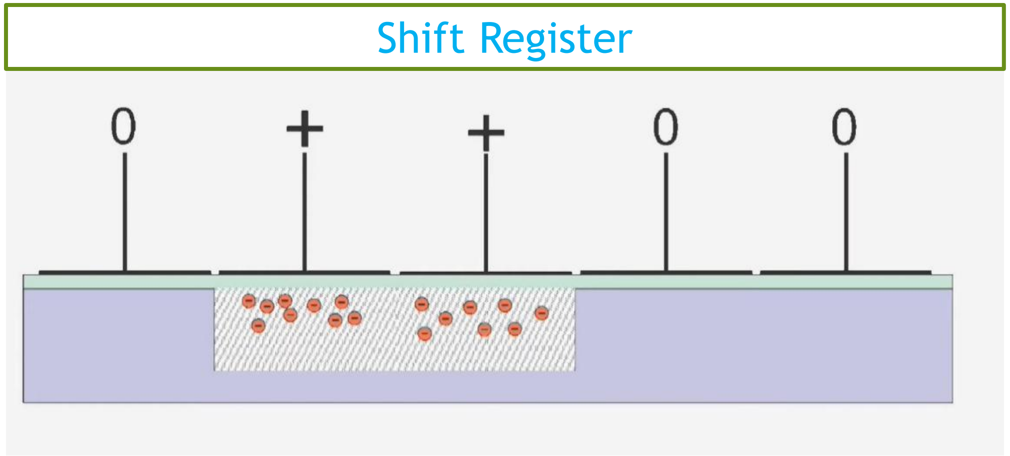


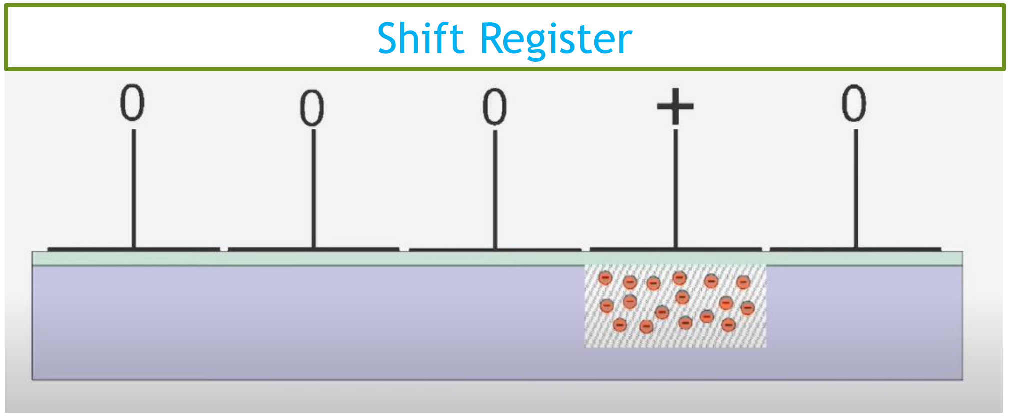
- Photodiode
- MOS Capacitor



Example of Charge Coupled Device (CCD) (including photodiodes)



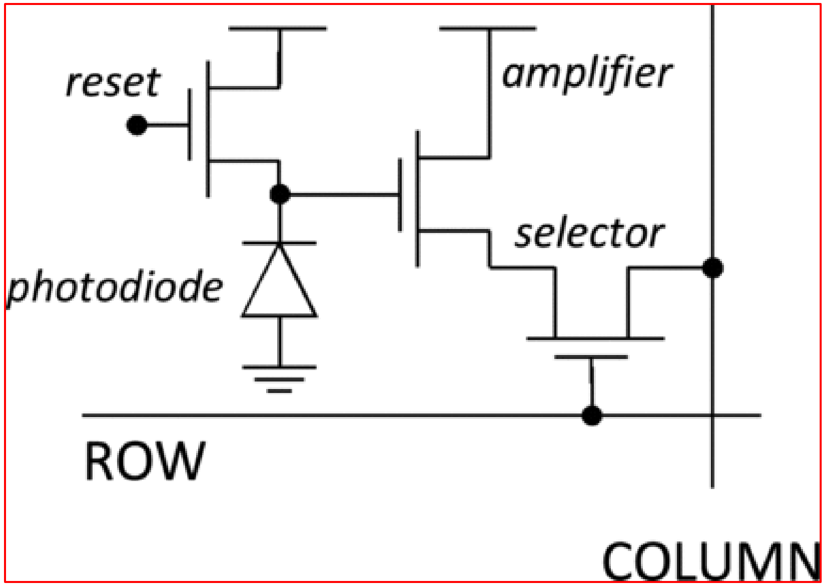




To shift charges

Example of Three-Transistor Device

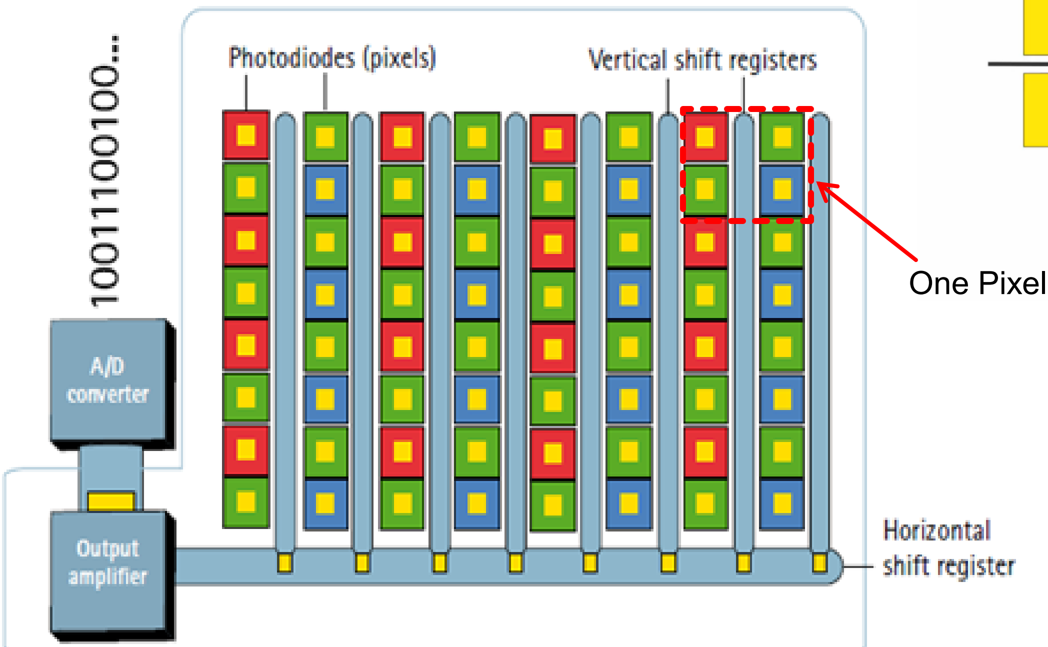
- Complementary Metal Oxide Semiconductor (CMOS) Photodiode

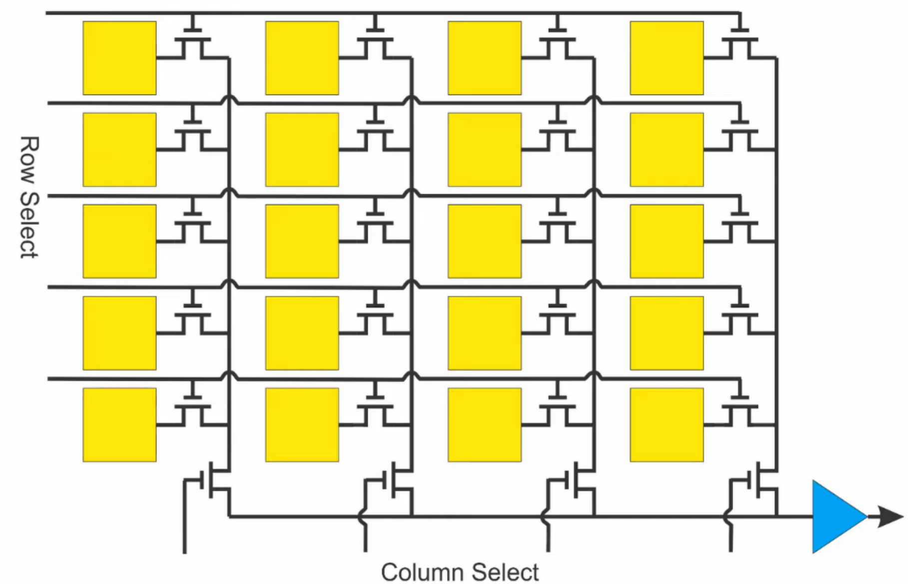


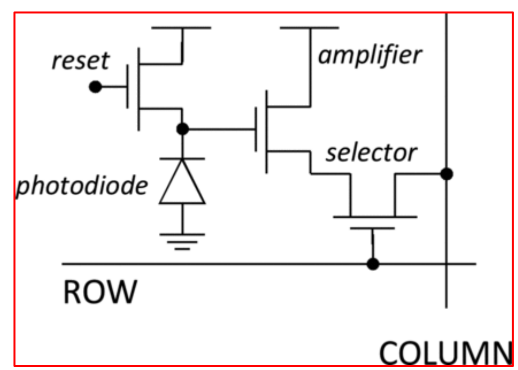
- Row line for selection control
- Column line for reading output

How to convert the light intensity at each point of an optical image into a voltage?

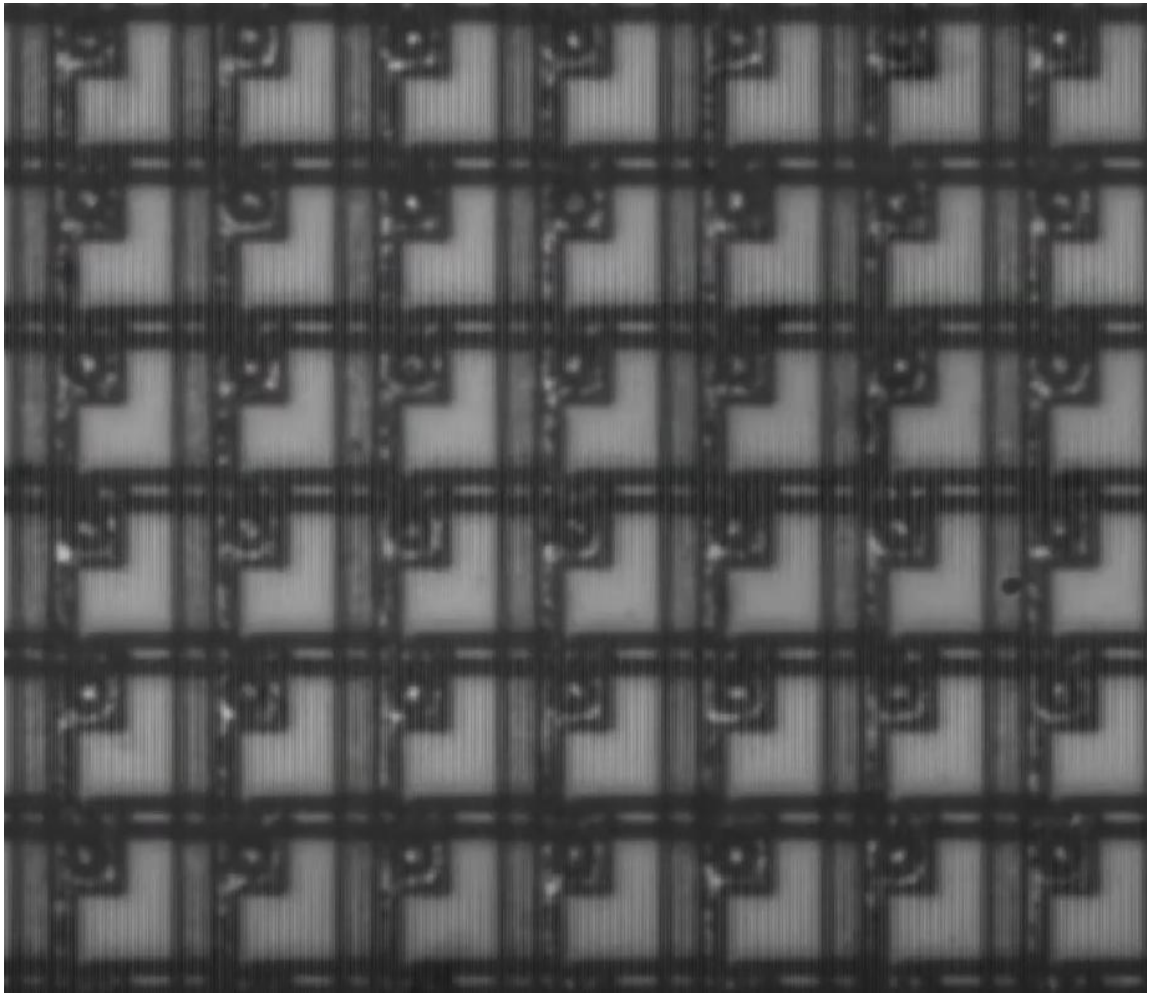
To use a matrix of
- CCD Photodiodes
- CMOS Photodiodes

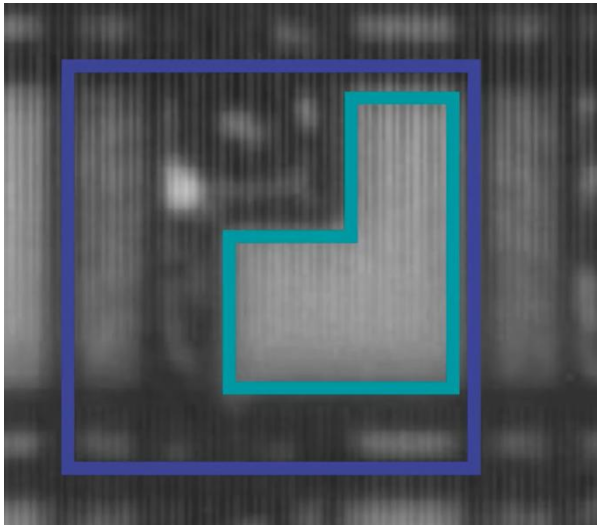






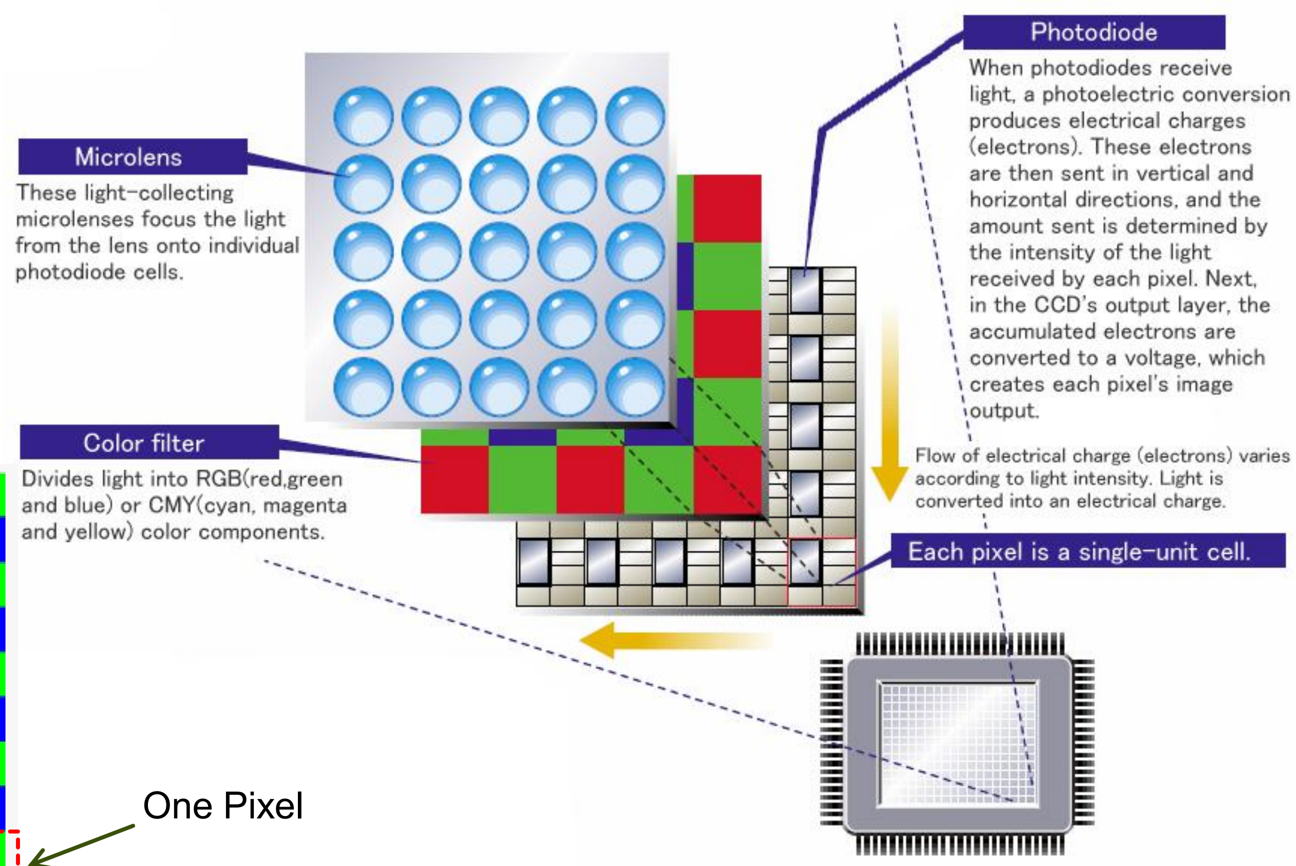
Example of CCD Photodiode Array

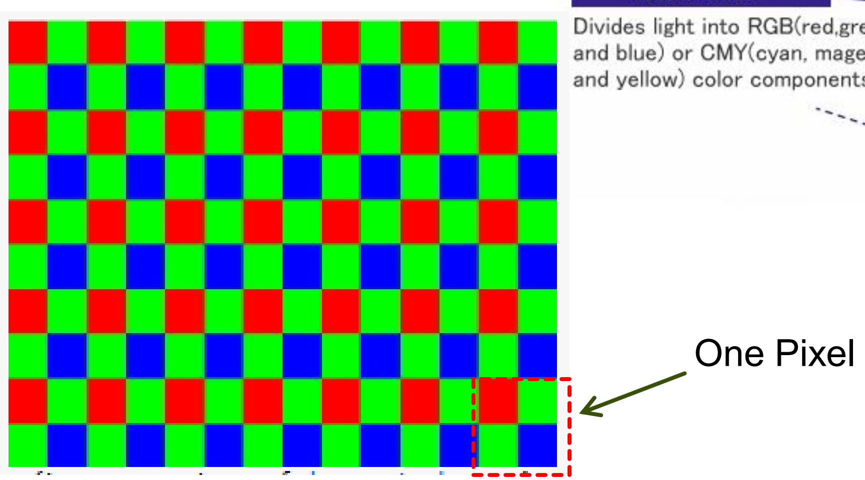




Single Cell

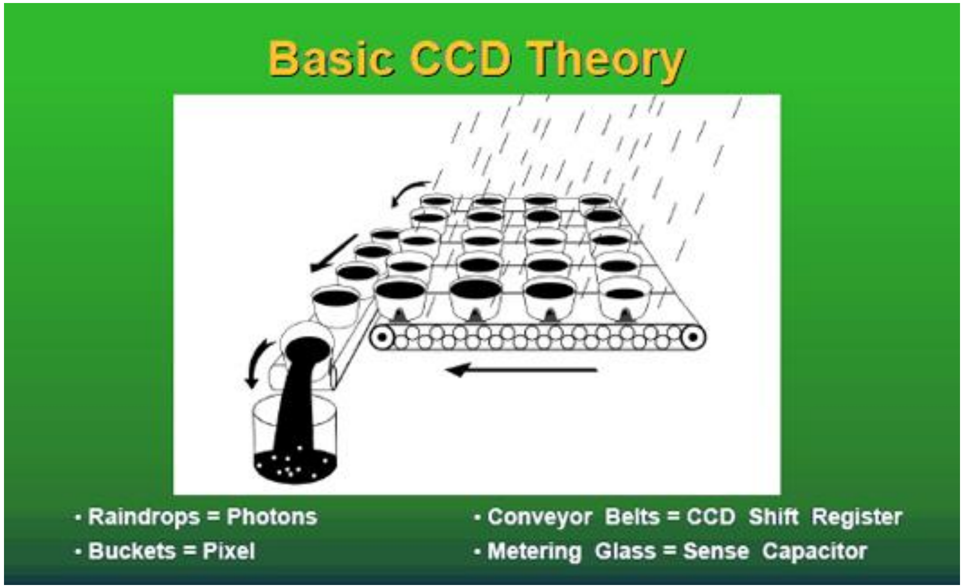
How to convert the light chrominance at each point of an optical image into a set of voltages?

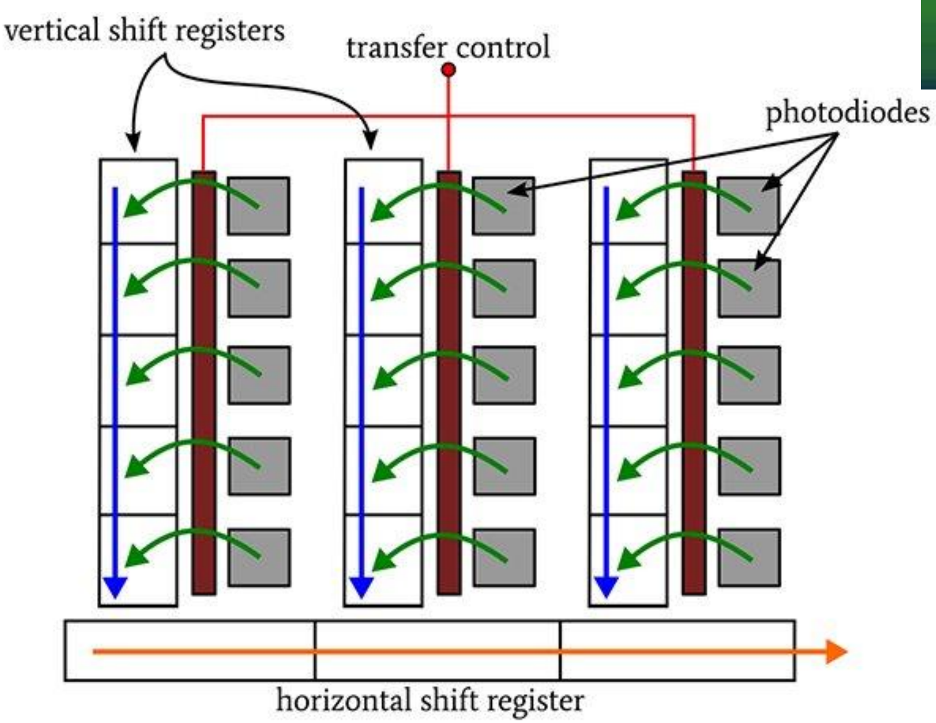


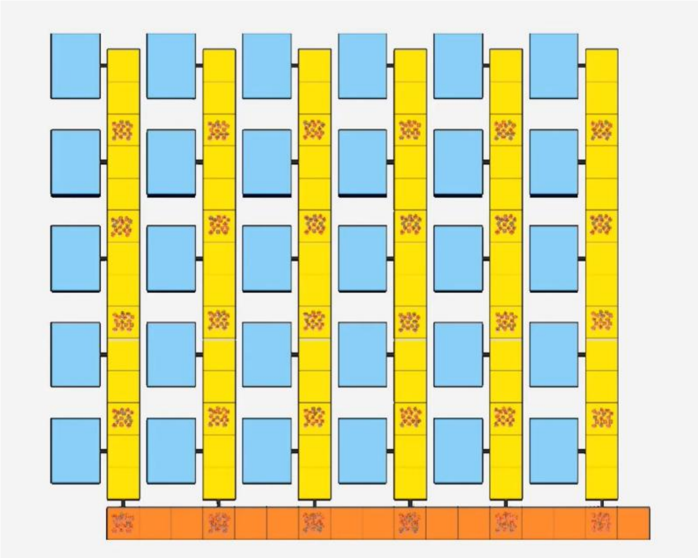


How to convert analogue voltage images into time functions of voltage?

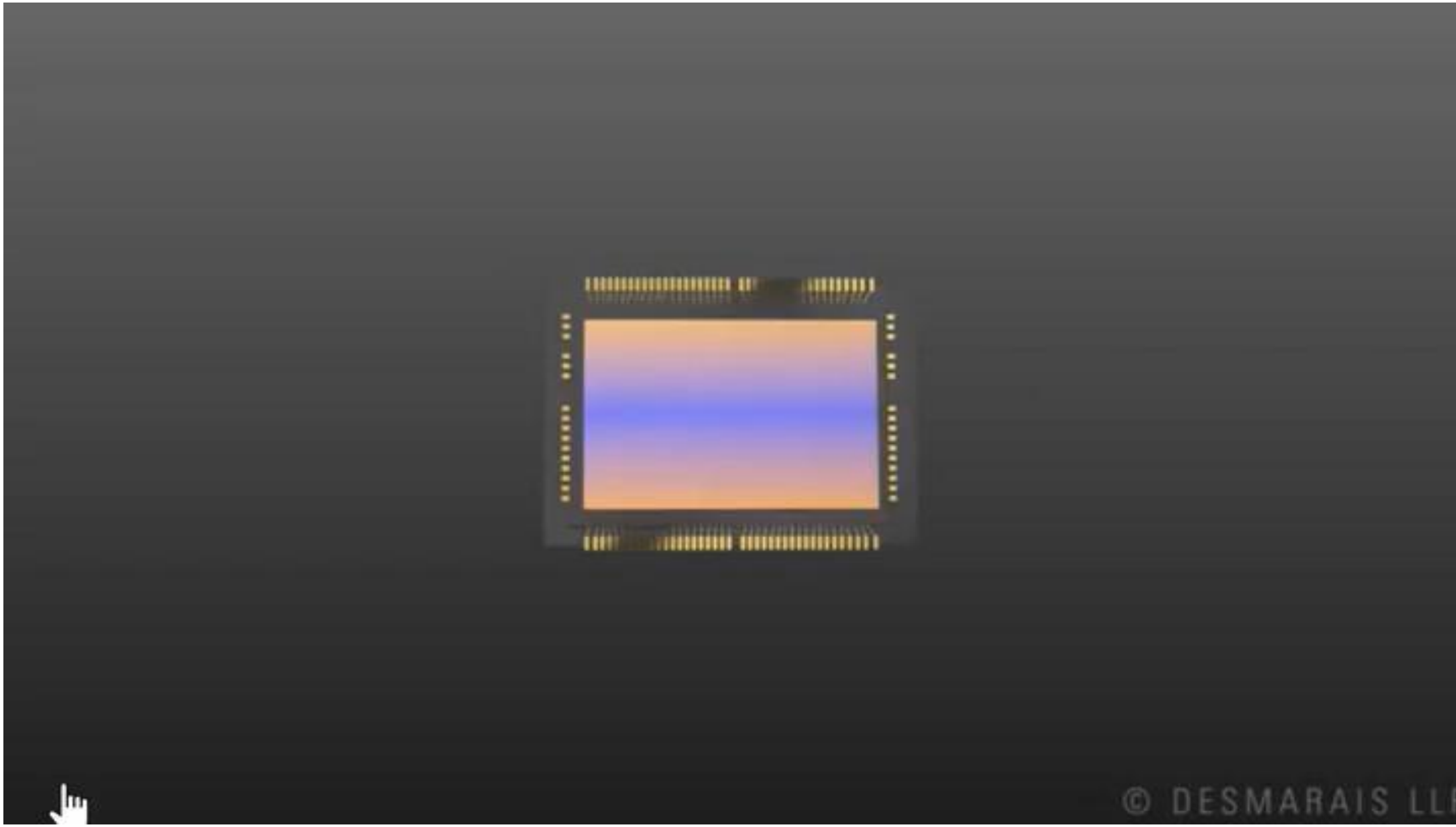
- Row shift followed by column shift.

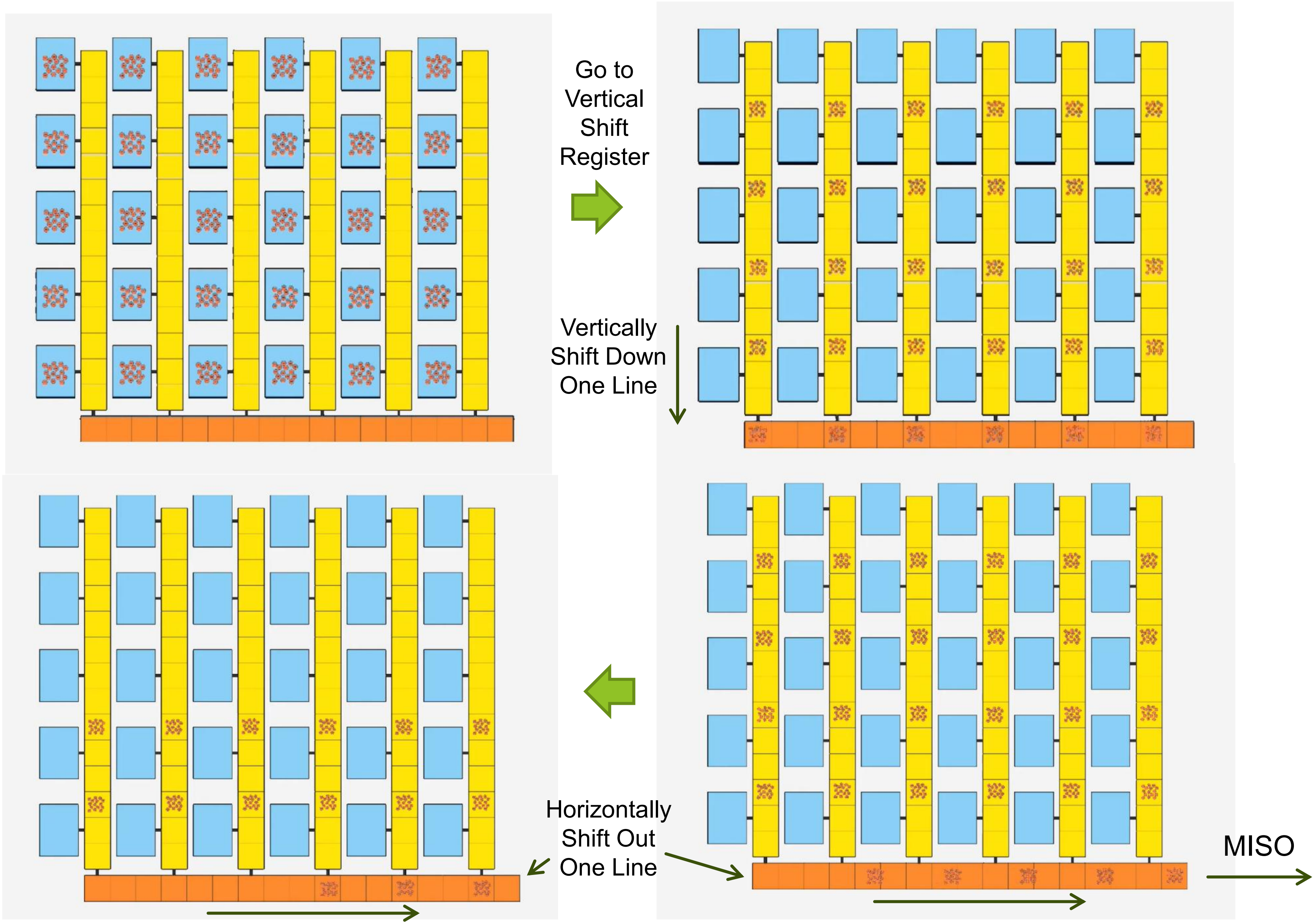






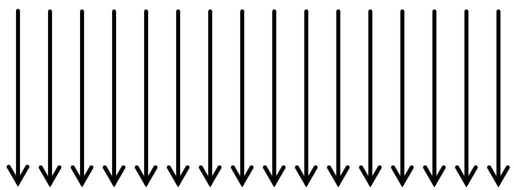
Video of Illustration …



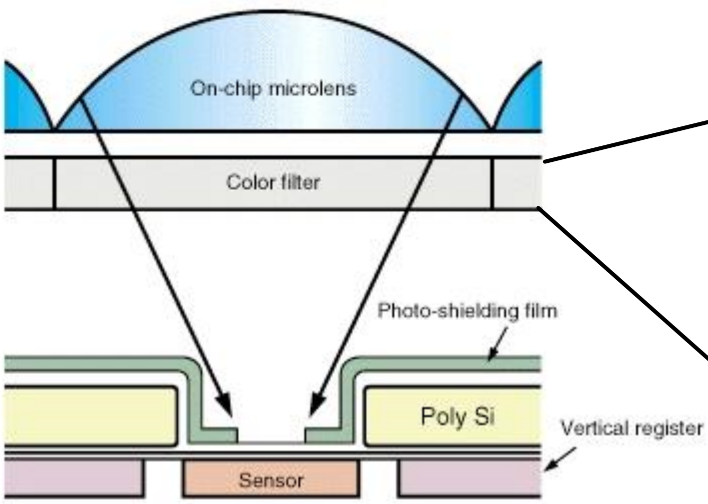

Go to
Vertical
Shift
Register
Vertically
Shift Down
One Line
Horizontally
Shift Out
One Line
MISO

Standard Formats of Time Functions of Voltage from Video …

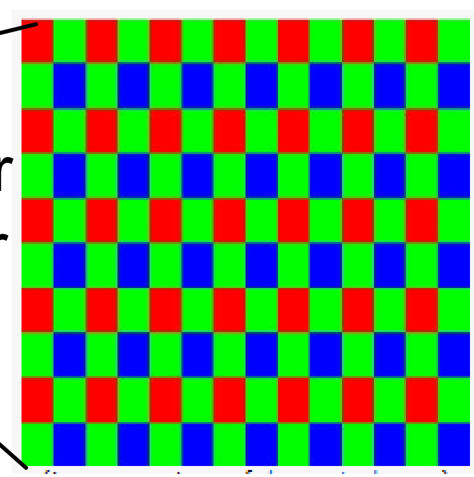
- NTSC, PAL, SECAM
- MP4, AVI, WMV, …



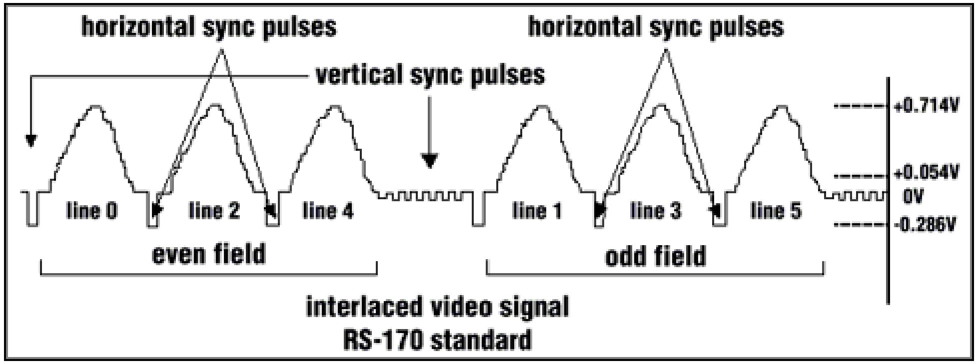
Light Rays



Color Filter



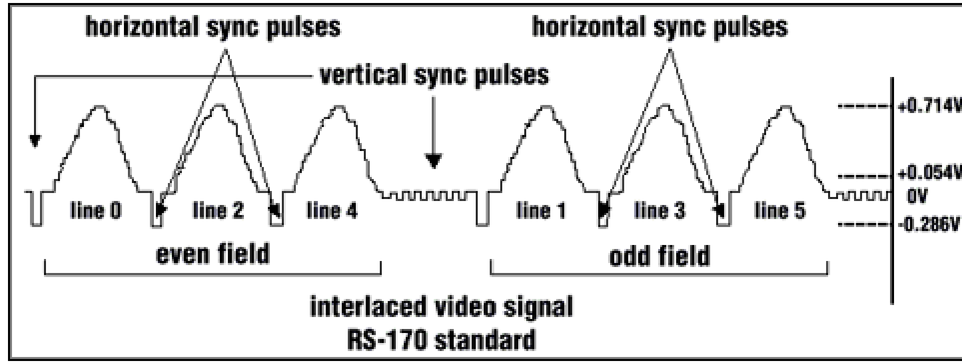
One Dimensional Time Signals
Which Consists of a Series of Line Signals



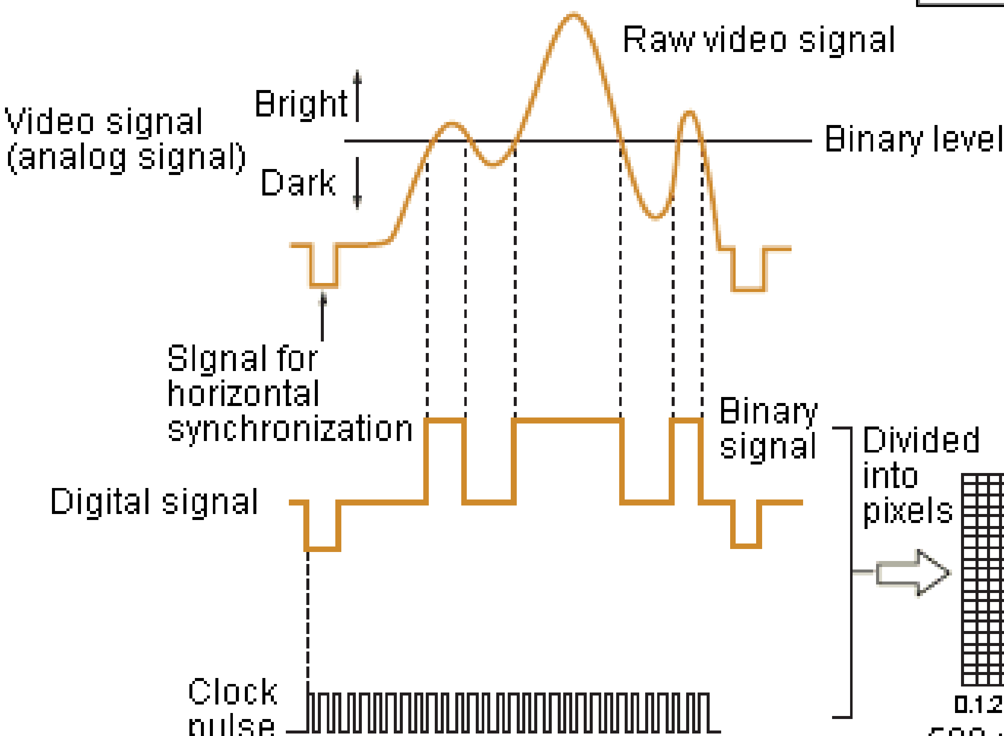
Two Dimensional Spatial Data (Matrix of Image)

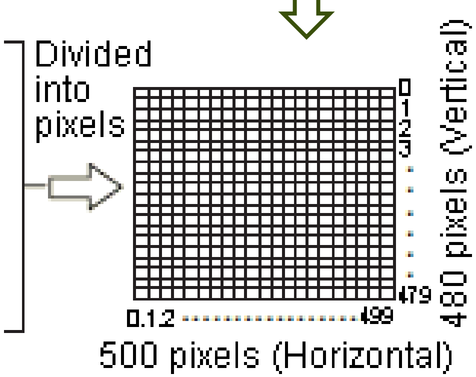
Outcome after Digitization

MISO



SIMO

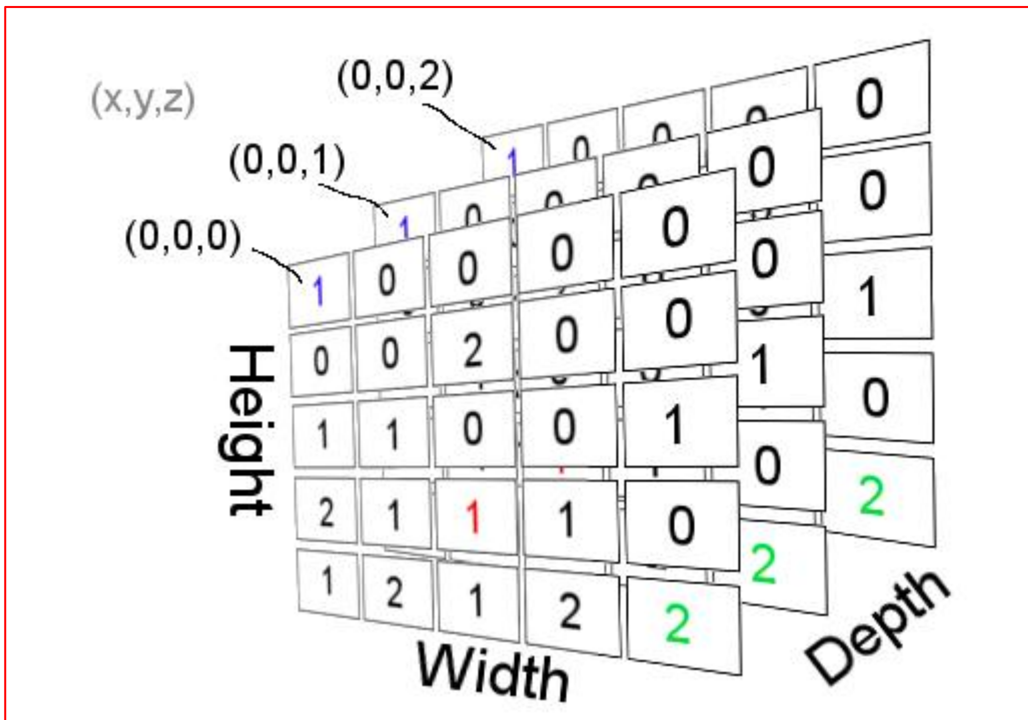




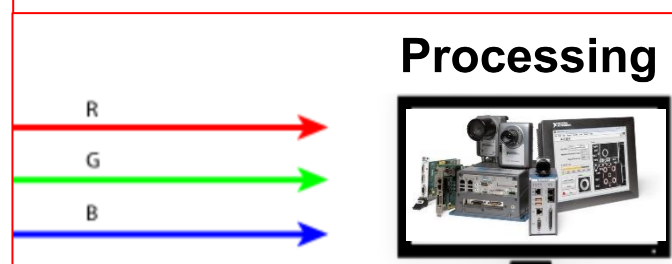
Byte image[480][500];

How to represent digital images?

- Output from digitization of visual signals is a series of three images: red component image, green component image and blue component image.
- Hence, an image is a two-dimensional matrix of vectors.



MA4829



Example of Product …

Outline

- Understanding of Visual Signals
- Computation of Visual Signals
- Measurement of Photometry
- Practices with MATLAB

Should seeing be believing?

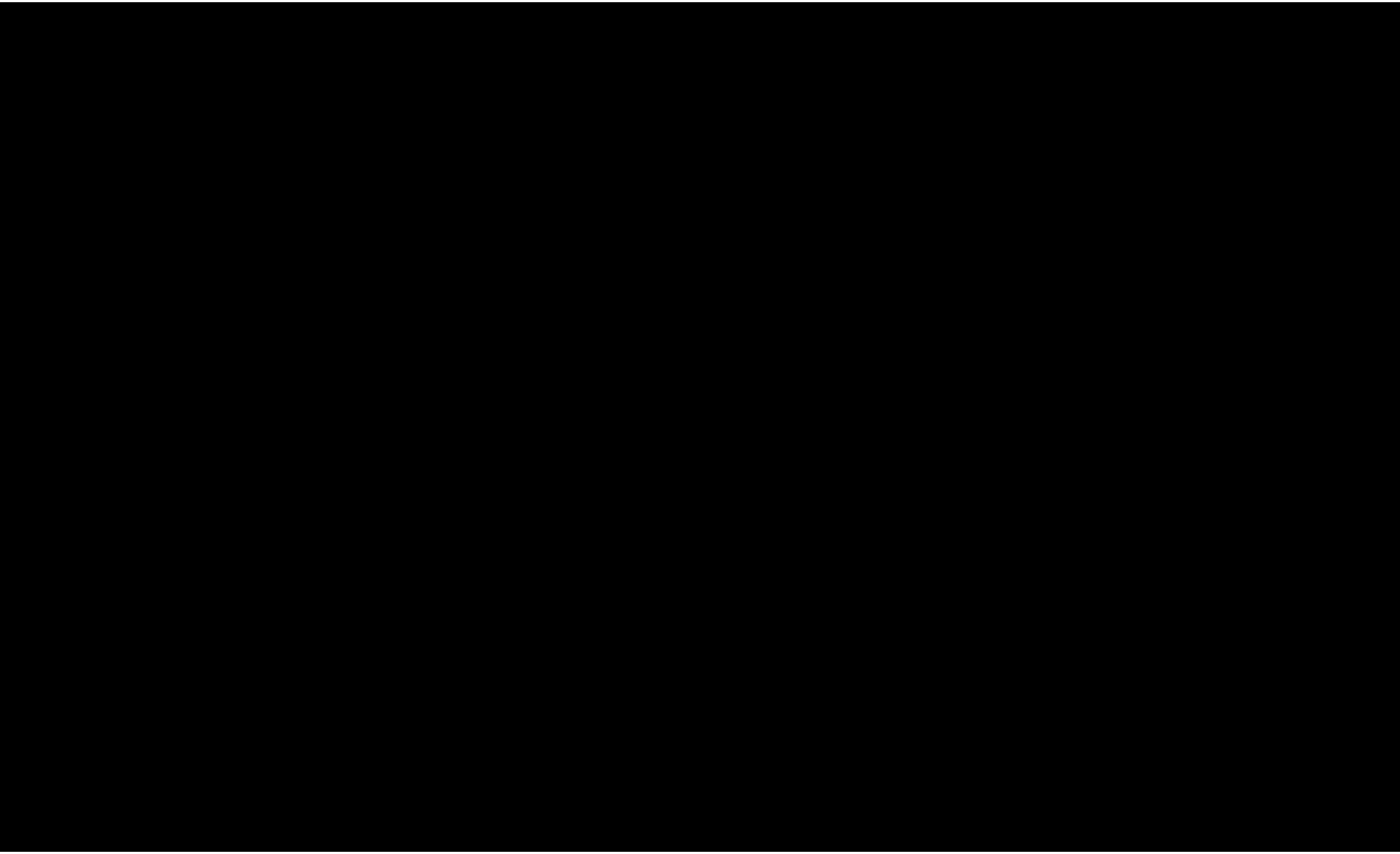
MATLAB Installation Note:

- Need of camera Interface.
- Installing **Webcam** and **Ipcam** **hardware support package** for **MATLAB**.
- Accessing Laptop's inbuilt webcam and external USB webcam with **MATLAB code** to take snapshot, preview and to record a video clip.
- Installing 3rd party Android application to convert **Mobile Phone as Ipcam**.
- Using Mobile Phone as Ipcam to take snapshot and video preview with **MATLAB code**.

https://www.youtube.com/watch?v=s1LPCyUlu3g

Practice 1: Webcam + MATLAB

```
clear all; clc;
cam = webcam(1);
preview(cam);
for i=1:10
    img = snapshot(cam);
    fname = ['webimage' num2str(i) '.jpg'];
    imwrite(img, fname);

    %% do processing here
    result = rgb2gray(img);

    %% do display here
    imshow(result);
    axis image; axis off;
    %pause(1);
end
pause(2);
clear cam;
```



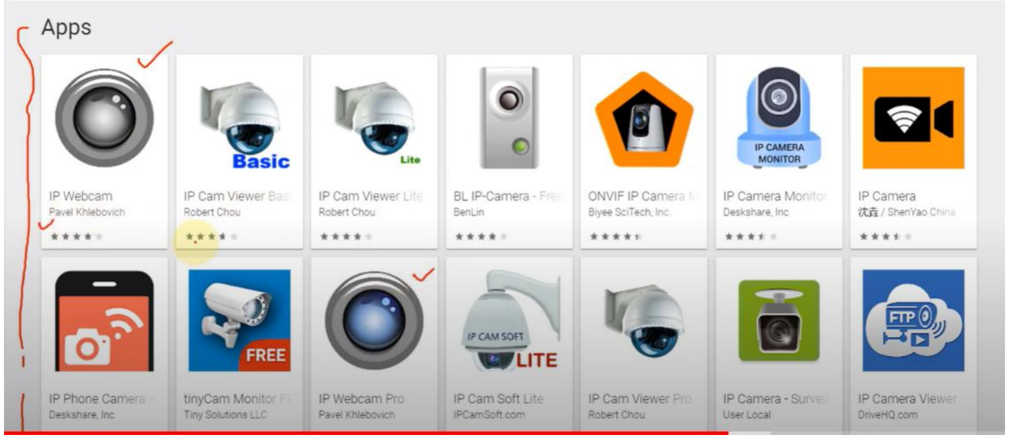
Practice 2: IPcam + MATLAB

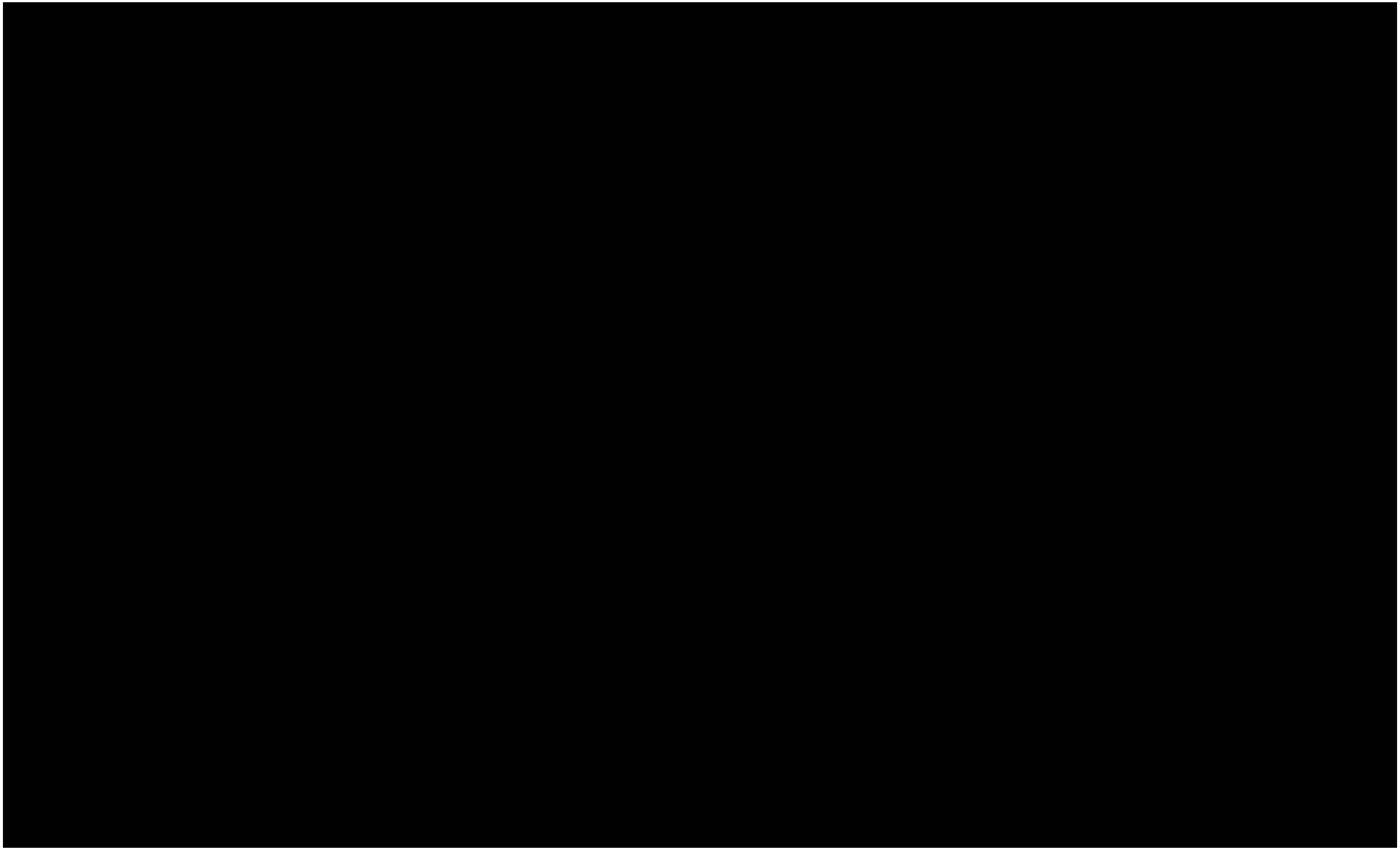
```
clear all; clc % First to Launch IP Webcam and to click on "Start Server"
cam = ipcam('http://192.168.1.20:8080/video');
preview(cam);
img = snapshot(cam);
for i=1:10
    img = snapshot(cam);
    fname = ['webimage' num2str(i) '.jpg'];
    imwrite(img, fname);

    %% do processing here
    bw = rgb2gray(img);
    result = edge(bw, 'canny');

    %% do display here
    imshow(result);
    axis image; axis off;
    %pause(1);
end
pause(10);
clear cam;
```

Your Smart Phone will show the IP address to you.

- Launch IP Webcam
- Click on “Start Server”

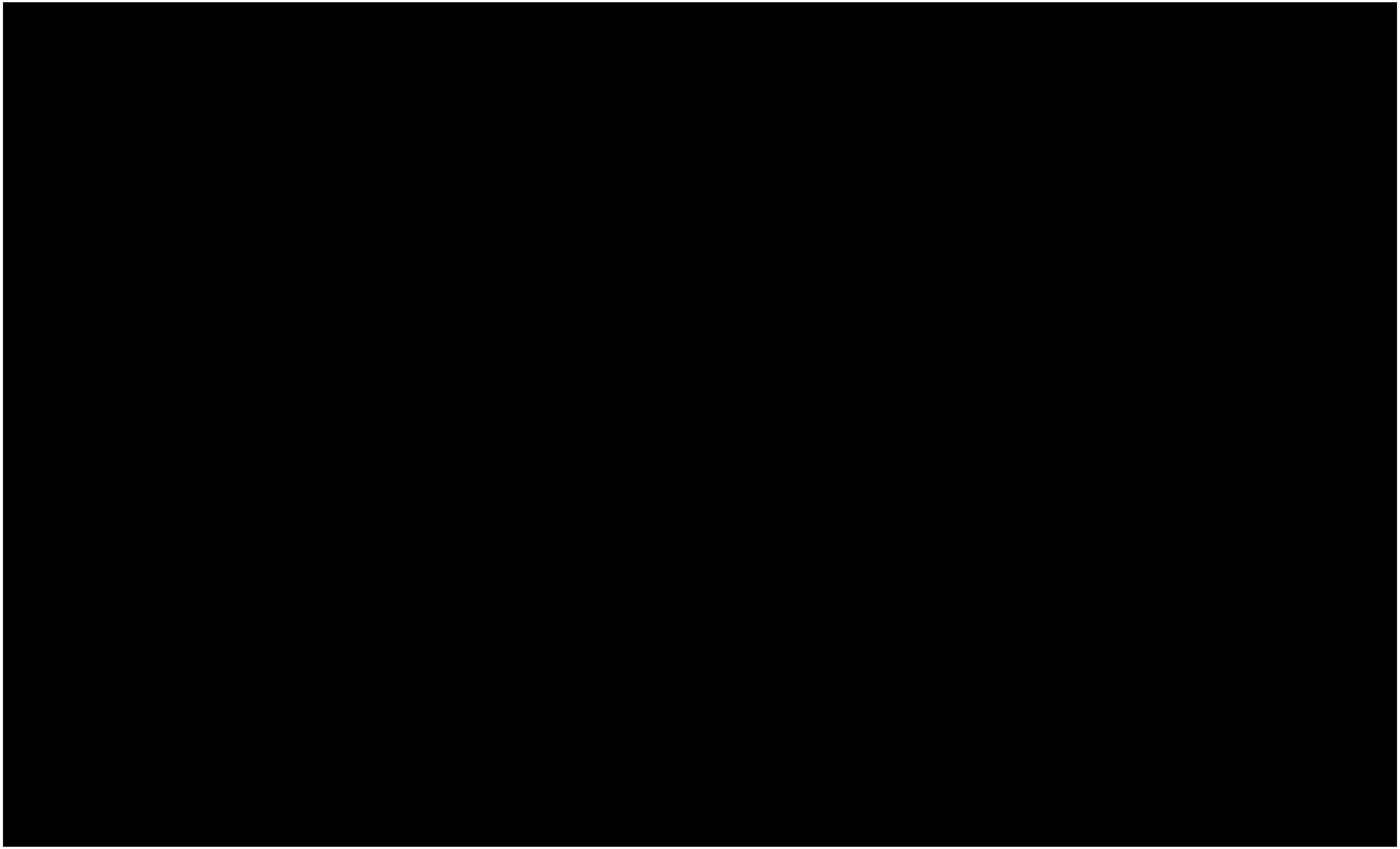
Choose an Apps to be installed into your Android Smartphone





Practice 3: Files + MATLAB

```
clear all;
clc;

for i=1:10
    fname = ['webimage' num2str(i) '.jpg'];
    img = imread(fname);
    message = ['Read ' fname];
    disp(message);

    %% do processing here
    bw = rgb2gray(img);
    result = edge(bw, 'canny');

    %% do display here
    imshow(result);
    axis image; axis off;
end
```



One Idea for Your Project …

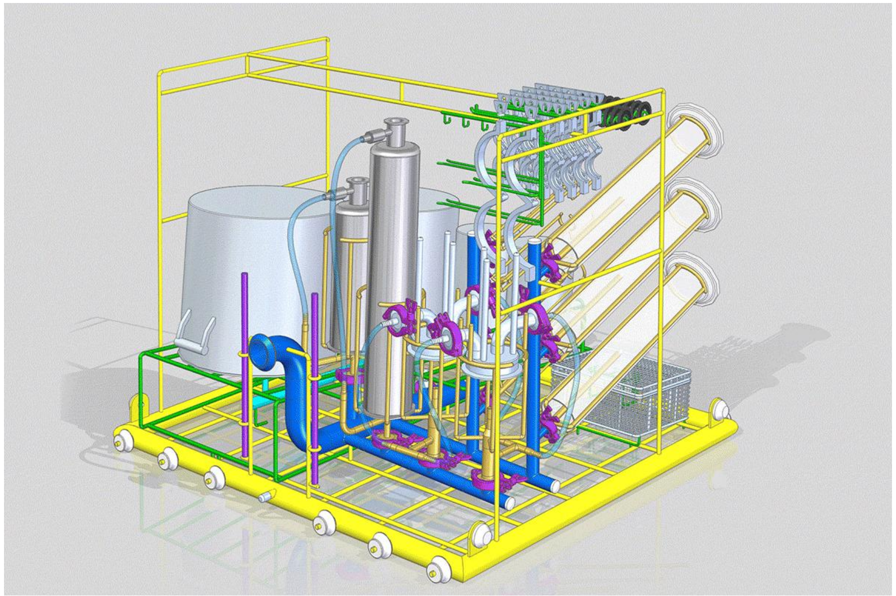
Summary

- Understanding of Visual Signals
- Computation of Visual Signals
- Measurement of Photometry
- Practices with MATLAB

Should seeing be believing?

Outline of Module 5

- Lecture 1:
  - Measurement of Fluid Level
- Lecture 2:
  - Measurement of Flow Rate
- Lecture 3:
  - Measurement of Sound/Voice
- Lecture 4:
  - Measurement of Photometry
- Lecture 5:
  - Measurement of Geometry



NANYANG TECHNOLOGICAL UNIVERSITY

School of Mechanical & Aerospace Engineering

Design, Machine, Control, Intelligence

Module 5 Lecture 5

MA4822

Measurement of Geometry

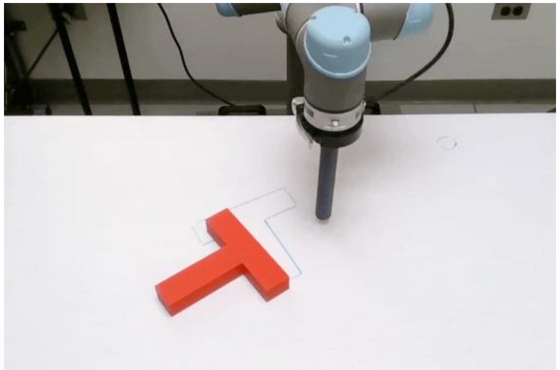
Xie Ming, PhD (France)

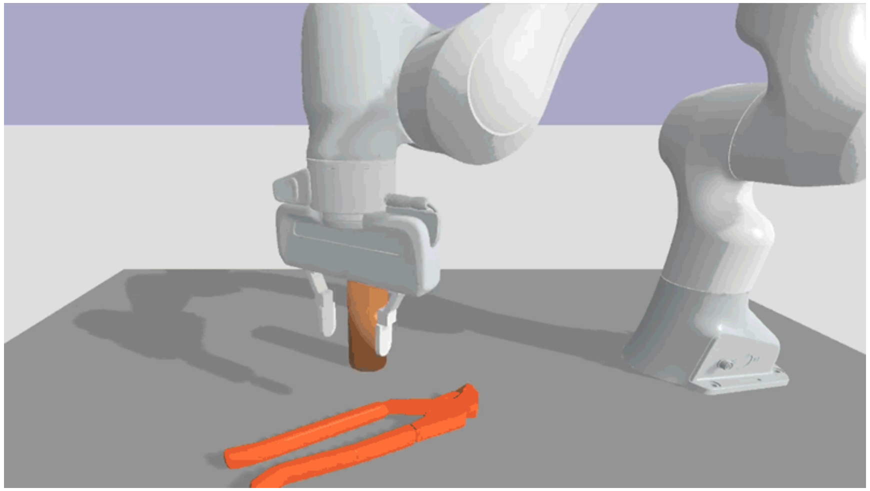
mmxie@ntu.edu.sg

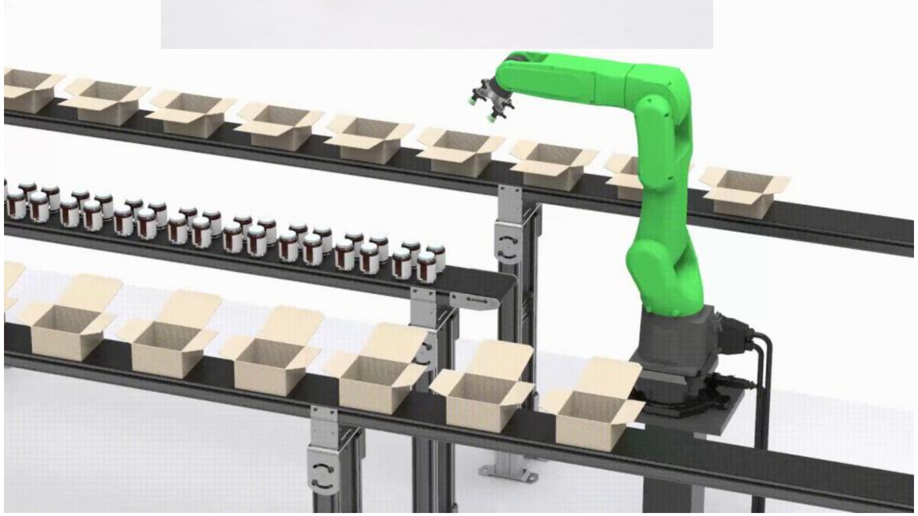
http://personal.ntu.edu.sg/mmxie

Outline

- Understanding of Geometry
- Computation of Geometry
- Measurement of Geometry

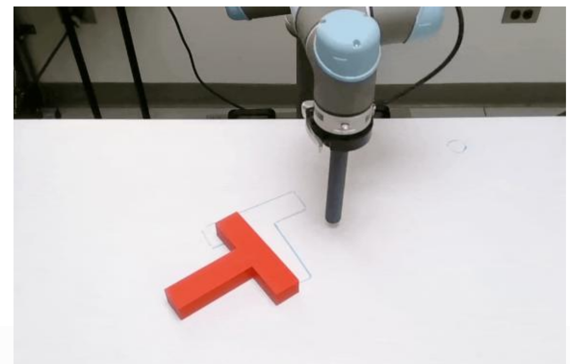


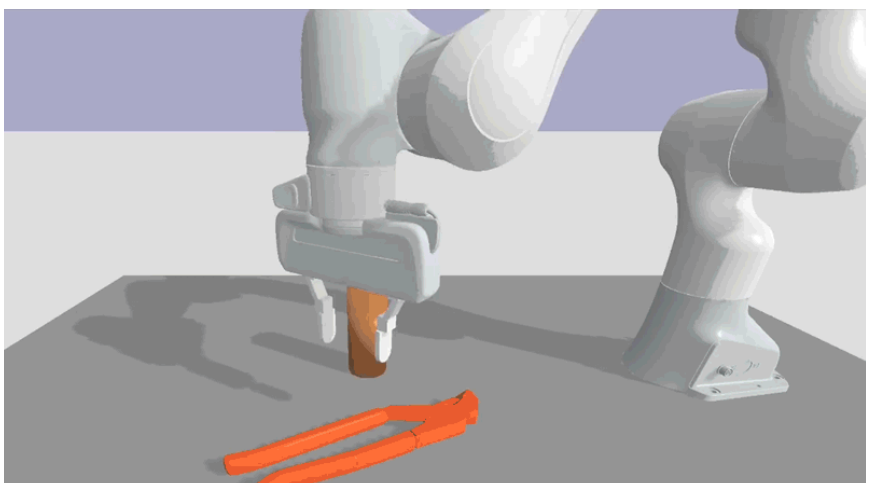


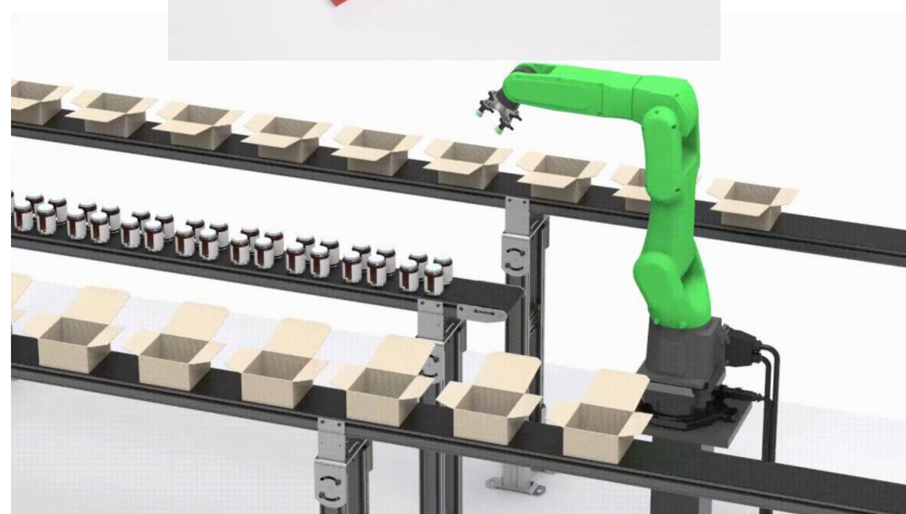


Outline

- Understanding of Geometry
- Computation of Geometry
- Measurement of Geometry

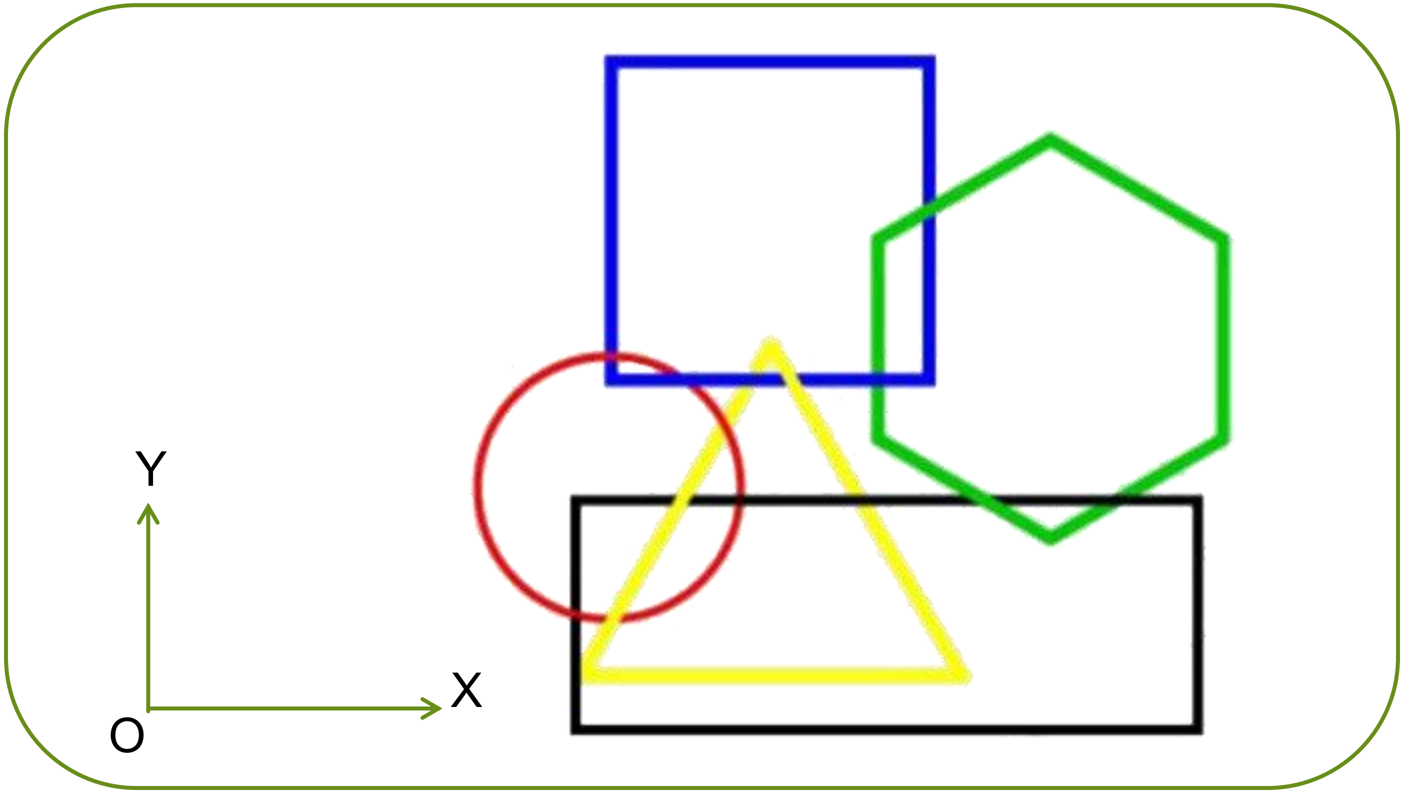






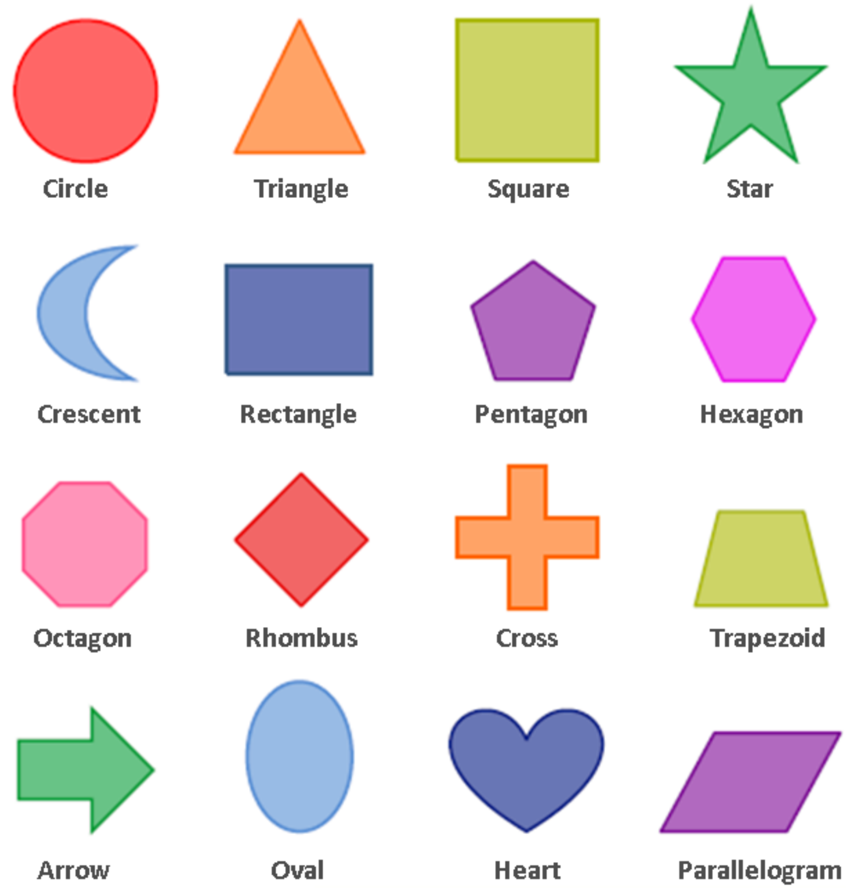
Understanding 2D Geometry (1)

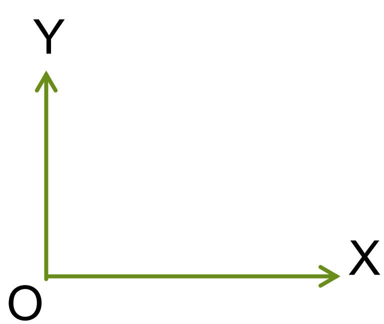
- 2D geometry refers to the appearance of physical entities in a two-dimensional space.
- 2D space consists of a set of positions which are fully determined with two coordinates.



Understanding 2D Geometry (2)

- The appearance of physical entities in a 2D space is manifested in the form of shapes.



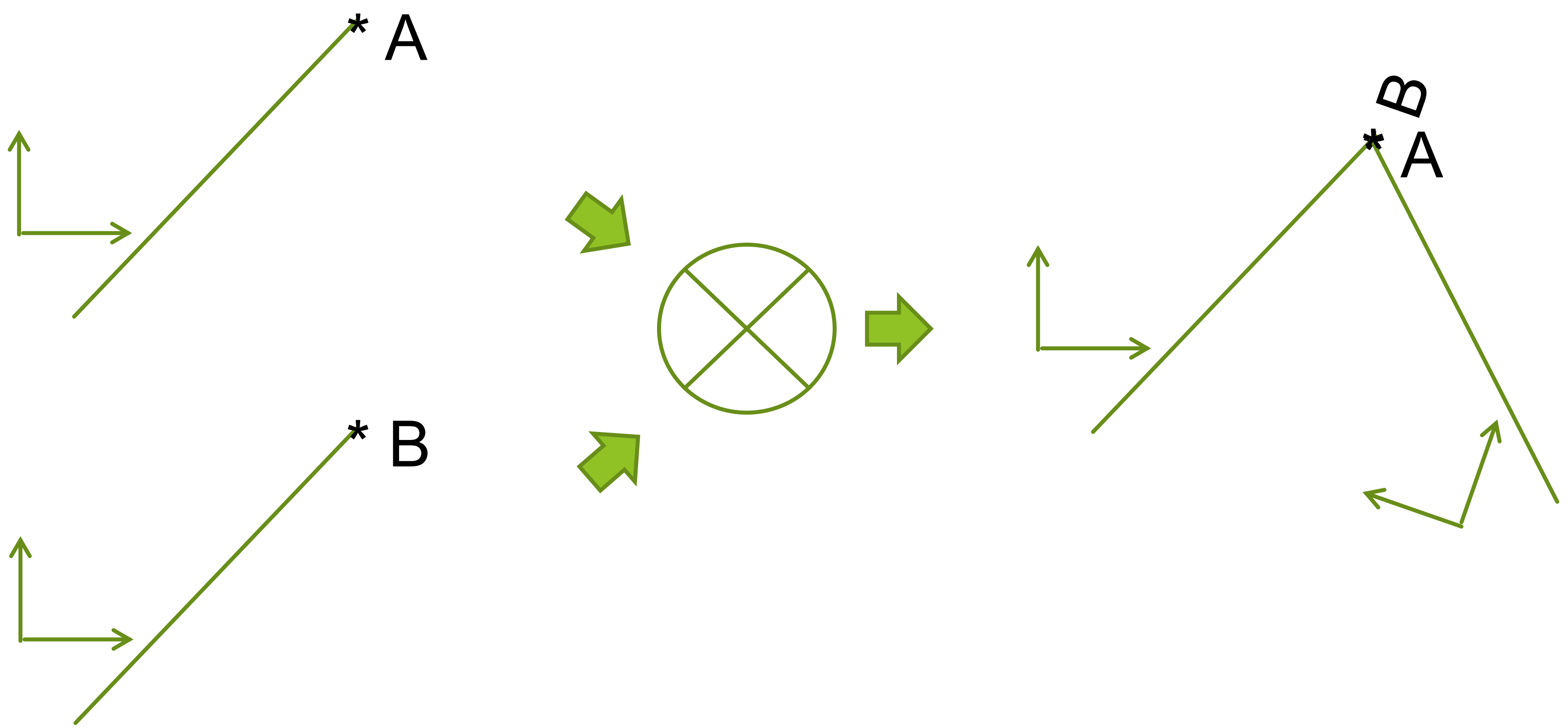


Understanding 2D Geometry (3)

- Complex shapes in a 2D space are the results of compositional rules such as:
  - Connect Between Points(point of shape 1, point of shape 2) at Angle(angle between shape 1 and shape 2):
    - ConnectPointsAtAngle(point, point, angle)
  - Connect Between Curves(curve of shape 1, curve of shape 2) with Offset(distance between the endpoints of two curves)
    - ConnectCurvesAtOffset(curve, curve, offset)

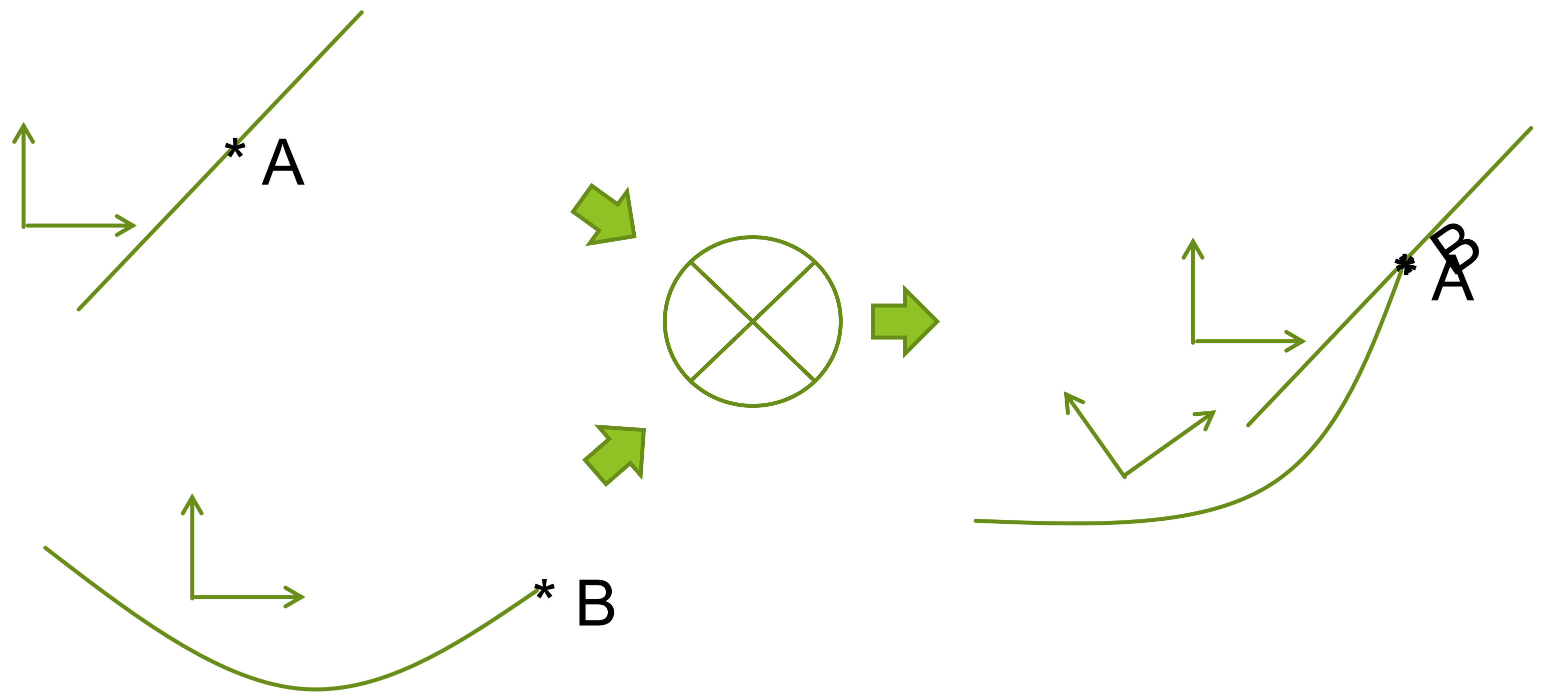
Example

- Connect Between Points(A, B) with Angle(60°)



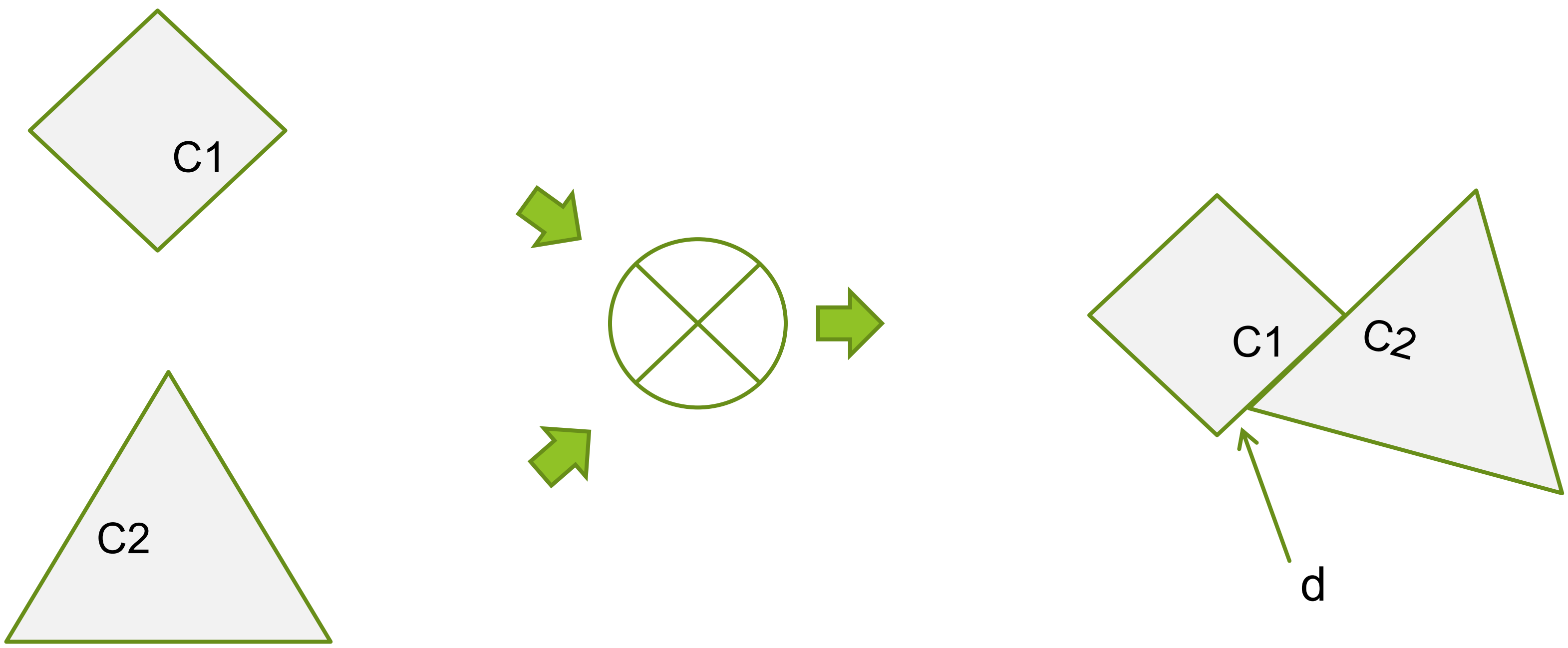
Example

- Connect Between Points(A, B) with Angle(45°)



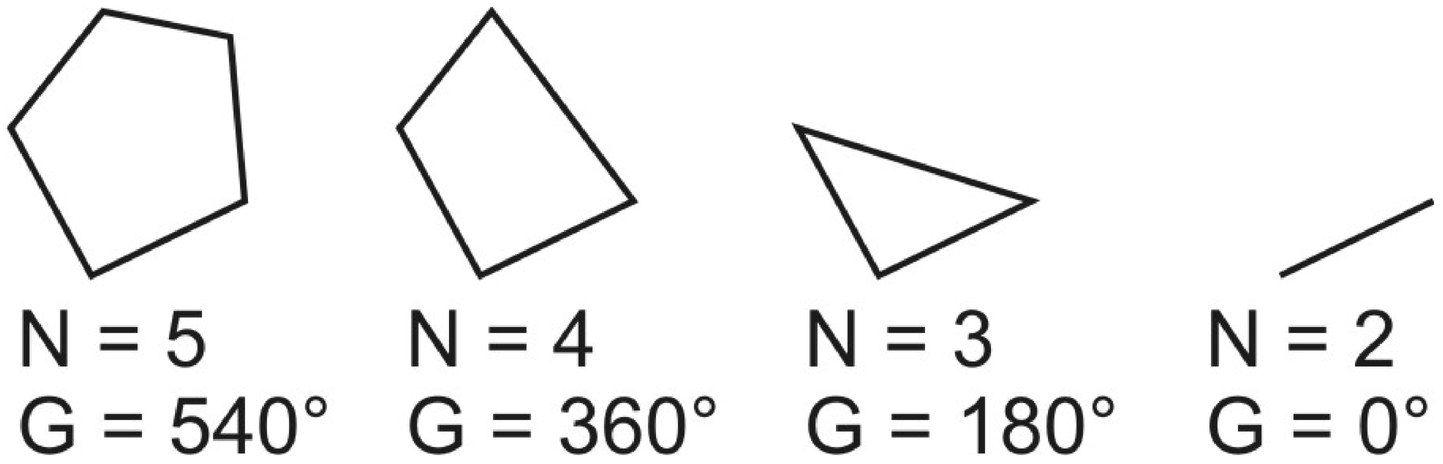
Example

- Connect Between Lines(C1, C2) with Offset(d)



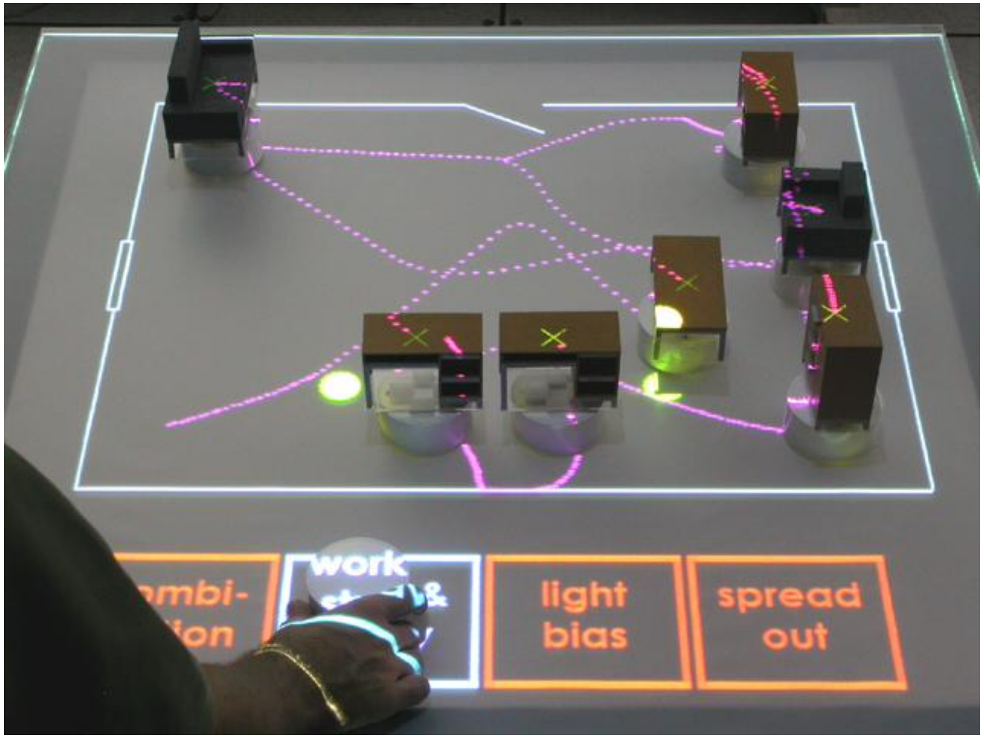
Understanding 2D Geometry (4)

- The sum of inter angles of a 2D polygon is equal to (N-2) x 180 degrees.



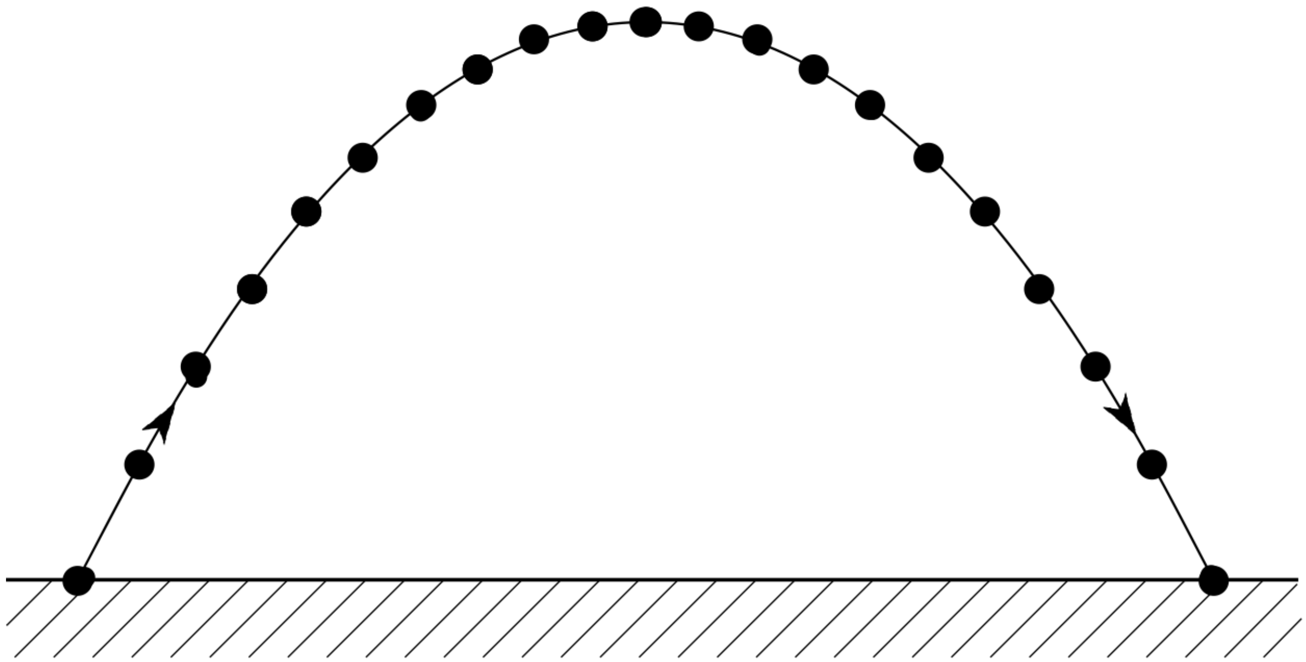
Understanding 2D Geometry (5)

- The appearance of physical entities in a 2D space also includes the travelled locations.

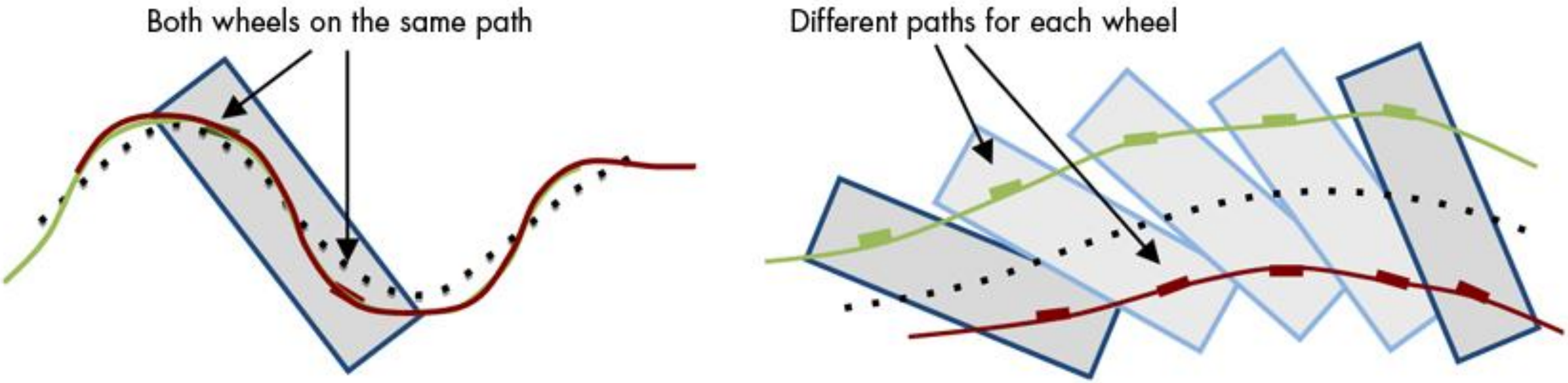


Understanding 2D Geometry (6)

- The spatial locations travelled or to be travelled are called paths.

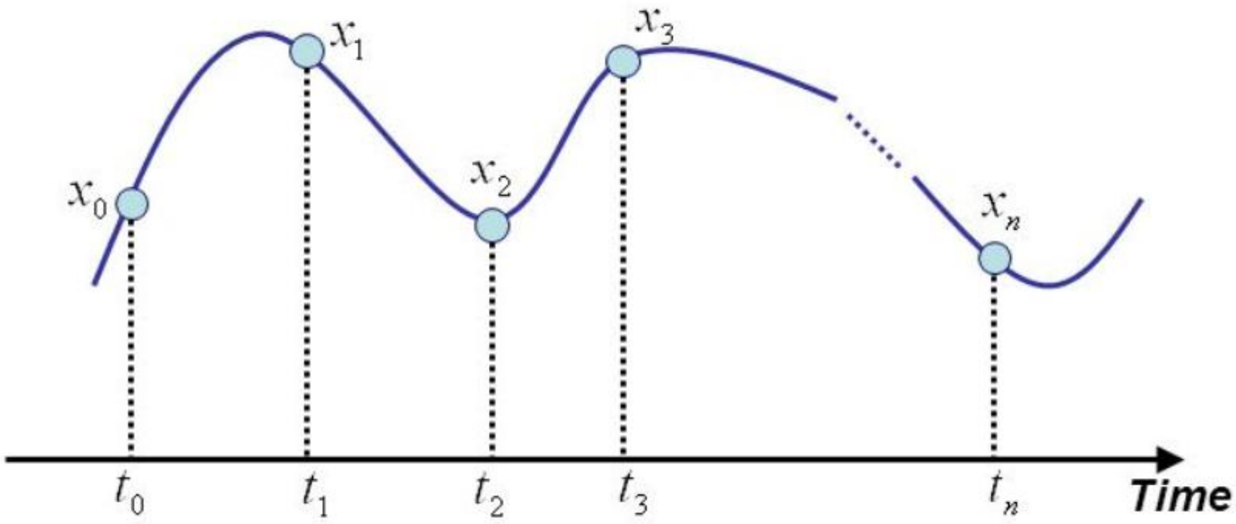


Example of Path

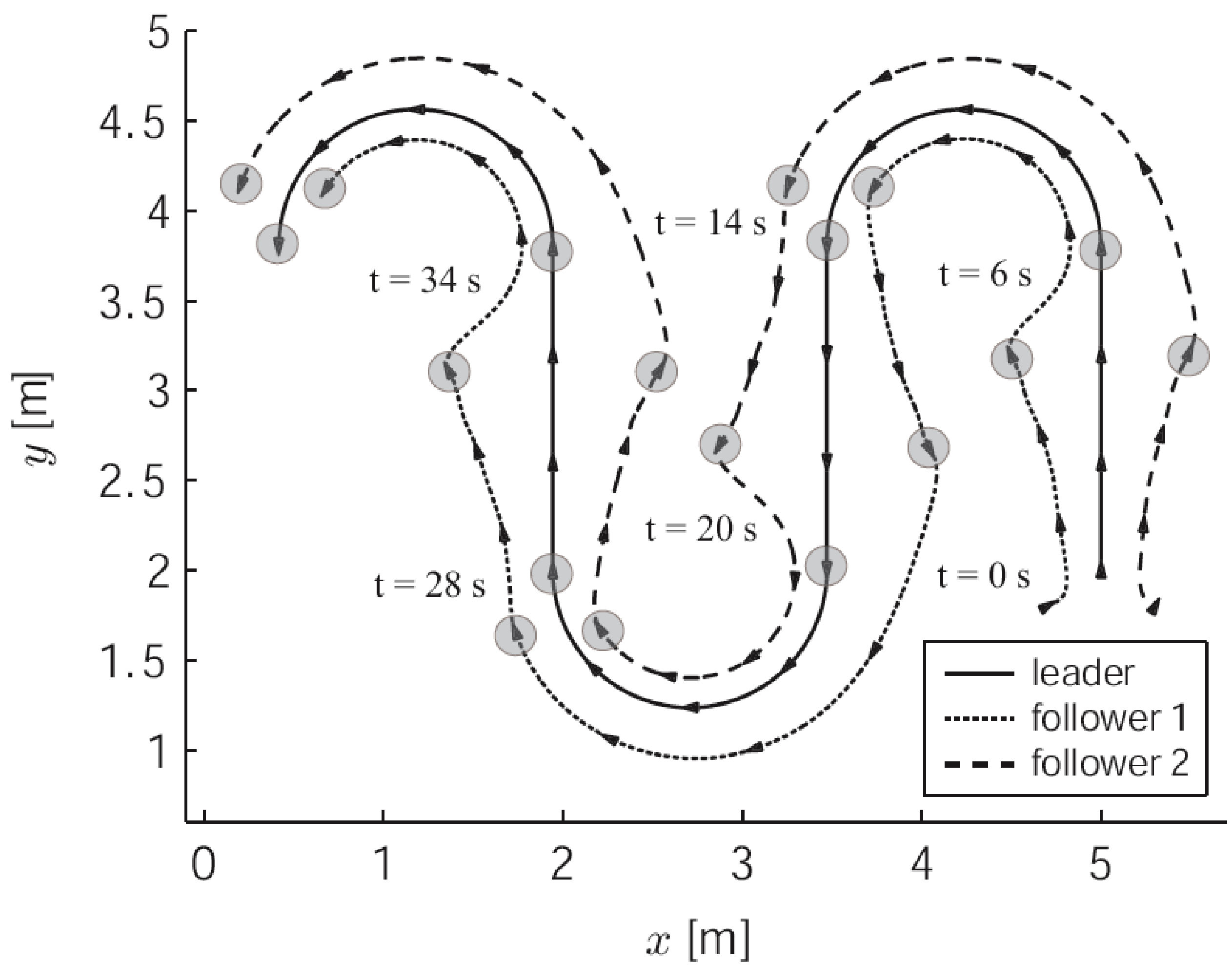


Understanding 2D Geometry (7)

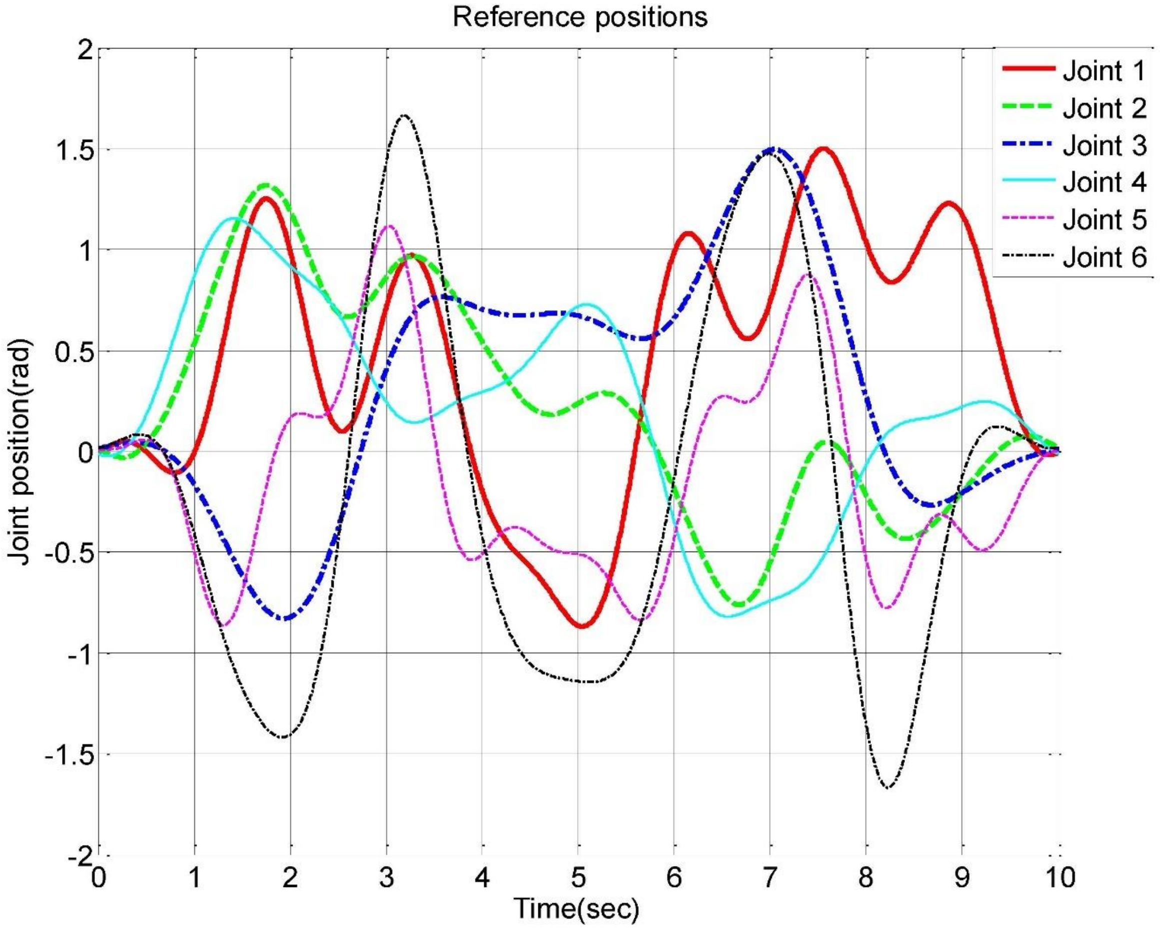
- The spatial locations with time constraint are called trajectories.



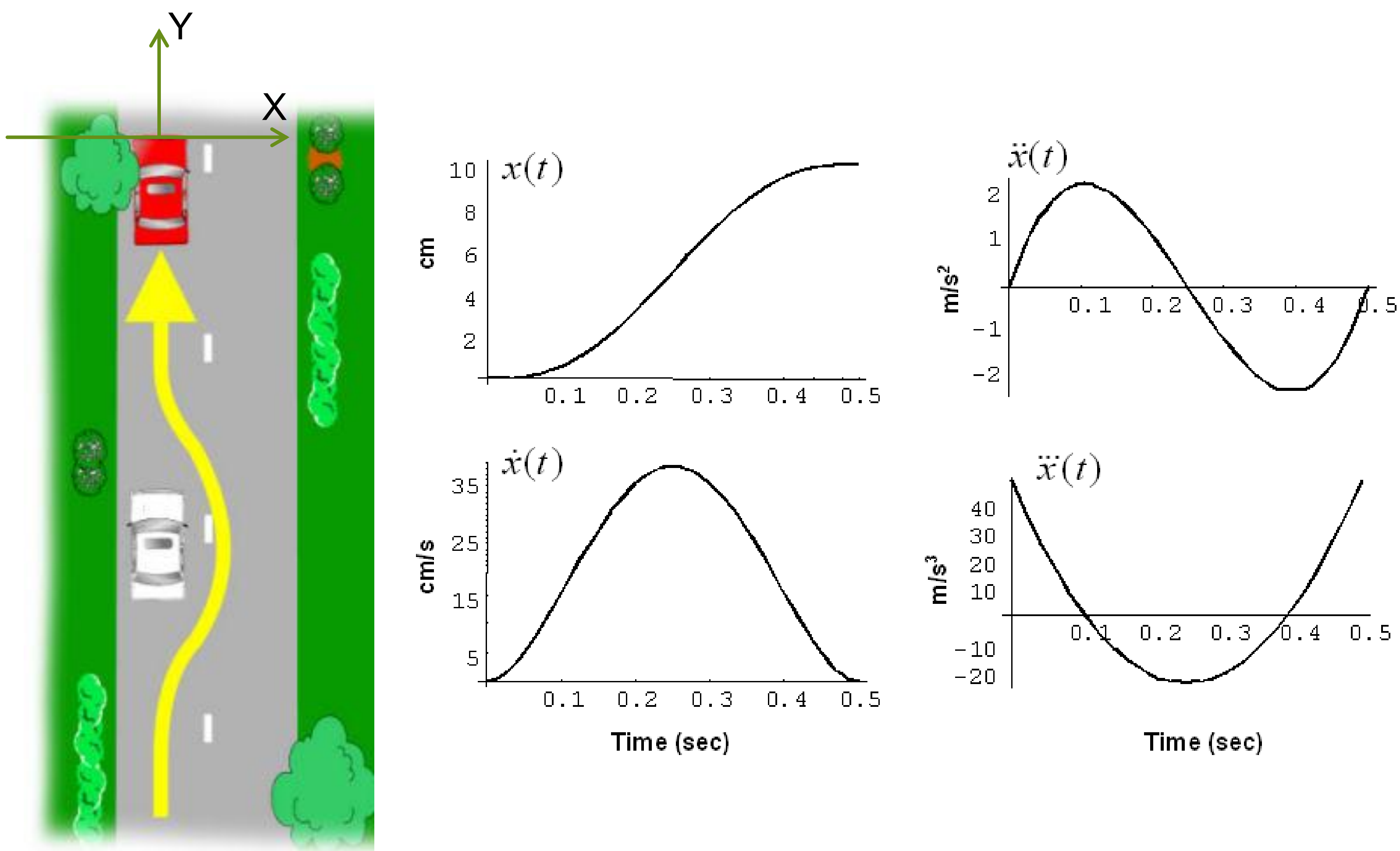
Example of Trajectories



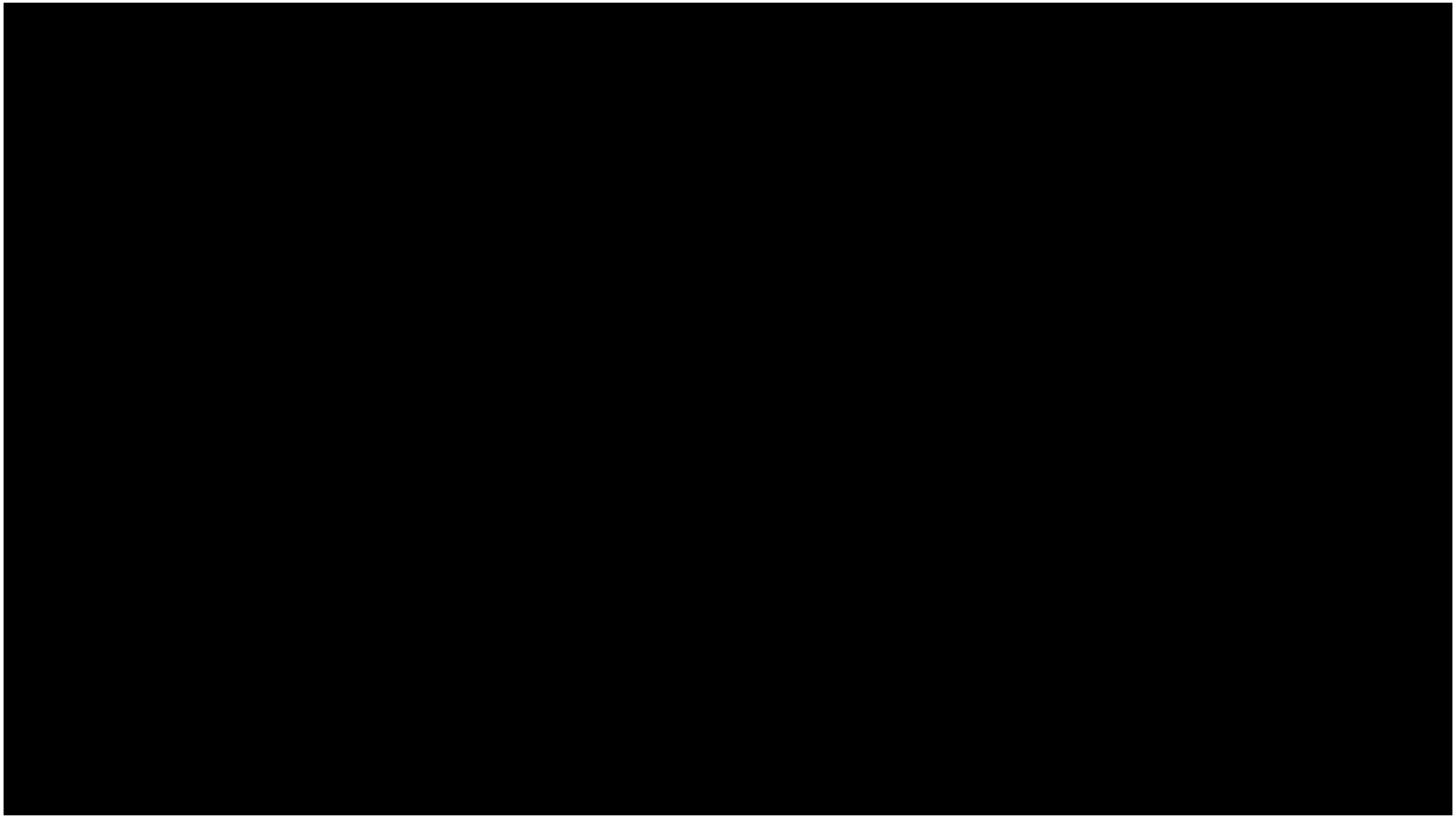
Example of Trajectories of Angular Positions



Example of Motion Planning and Control



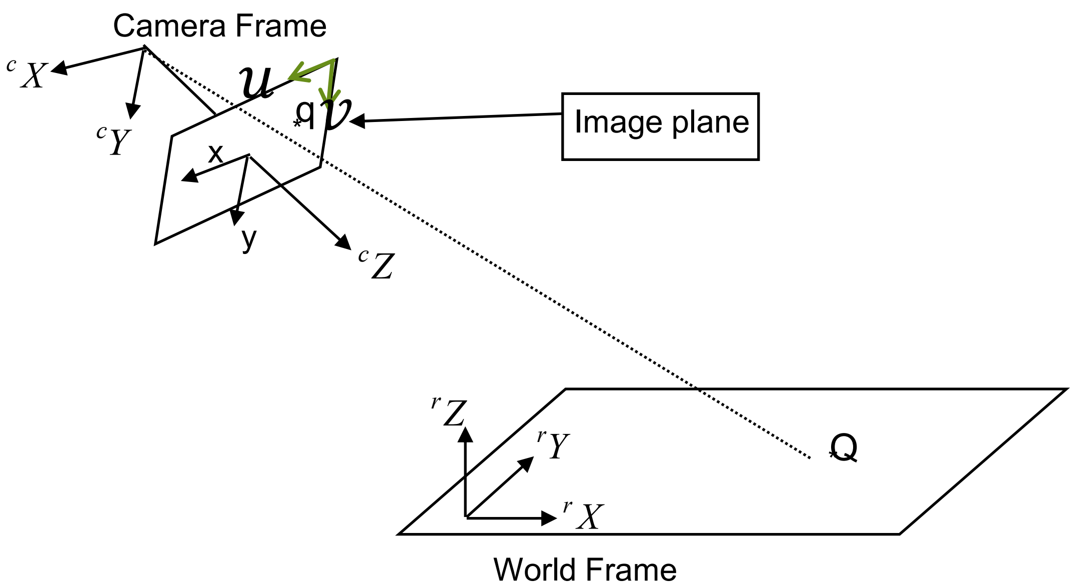
What is the scenario of coordinate transformations in general?



Basics of Homogeneous Transformation

$$H_{camera} = \begin{bmatrix} R_{camera} & T_{camera} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix}$$

$$H_{world} = \begin{bmatrix} R^{-1}_{camera} & -R^{-1}_{camera} \times T_{camera} \\ 0 \quad 0 \quad 0 & 1 \end{bmatrix}$$



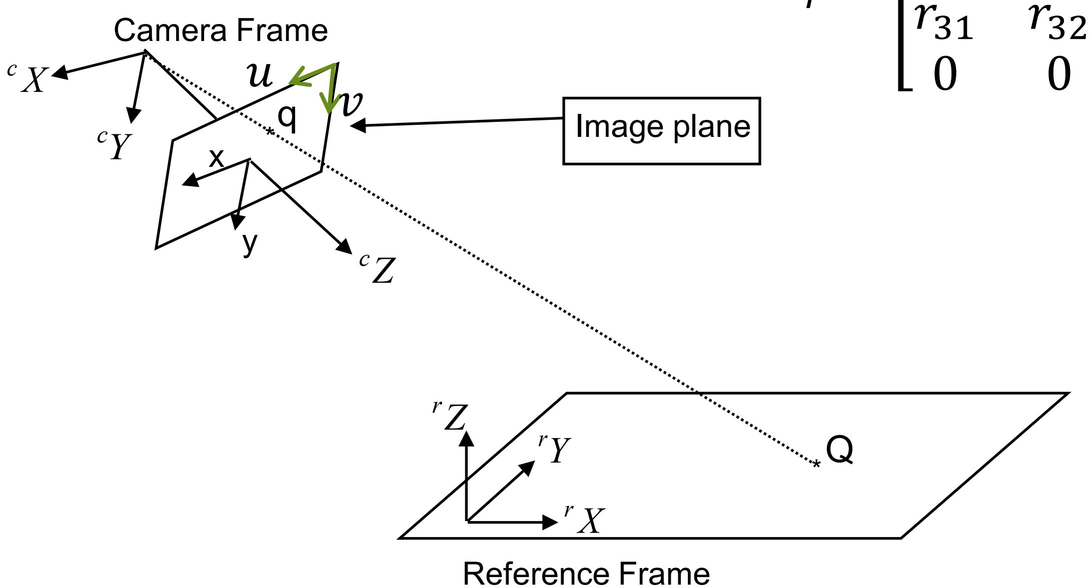
$$H_{camera} \times H_{world} = I_{4\times4}$$

$$H_{camera} = H^{-1}_{world}$$

Transformation of Coordinates in 3D Space

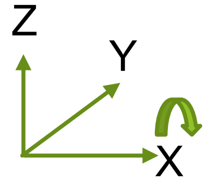
- The coordinates in the reference frame can be transformed into the coordinates in the camera frame.

$$^{c}H_{r} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



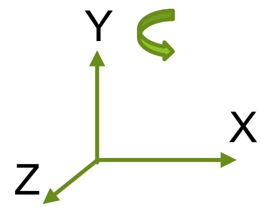
$$\begin{bmatrix} ^{c}X \\ ^{c}Y \\ ^{c}Z \\ 1 \end{bmatrix} = {}^{c}H_{r} \bullet \begin{bmatrix} ^{r}X \\ ^{r}Y \\ ^{r}Z \\ 1 \end{bmatrix}$$

Practices with Rotational Transformation

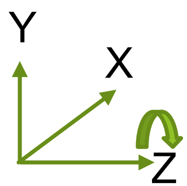


Before Rotation

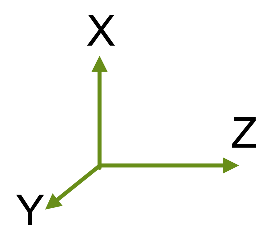
After Rotation About X Axis

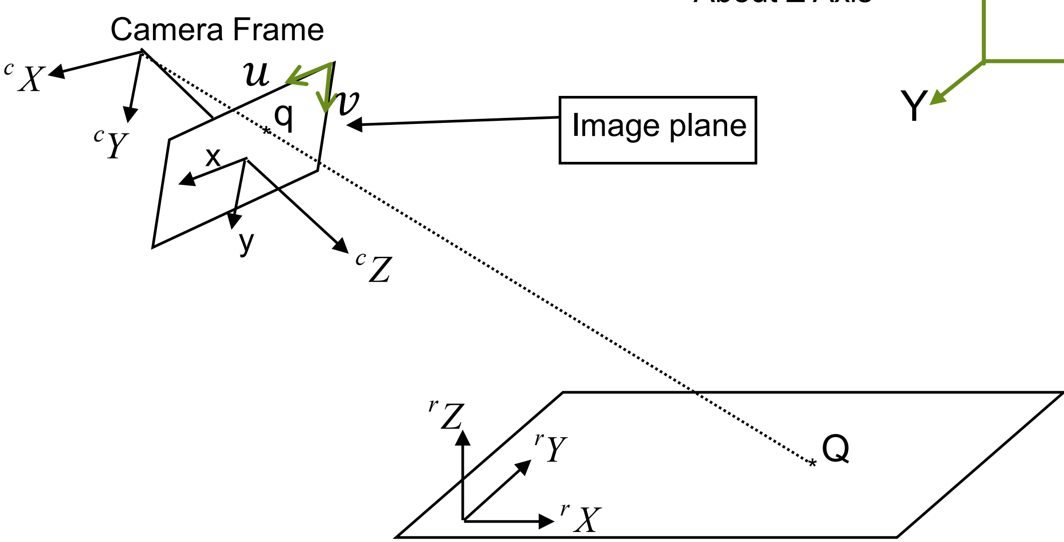


After Rotation About Y Axis



After Rotation About Z Axis






```
ax = 90*pi/180;
rx = [1     0            0 ;
      0   cos(ax)    -sin(ax);
      0   sin(ax)     cos(ax)];

ay = 90*pi/180;
ry = [cos(ay)    0     sin(ay);
         0       1     0 ;
      -sin(ay)  0     cos(ay)];

az = 90*pi/180;
rz = [cos(az)    -sin(az)   0;
      sin(az)     cos(az)   0;
      0           0         1];

r = rx*ry*rz
```

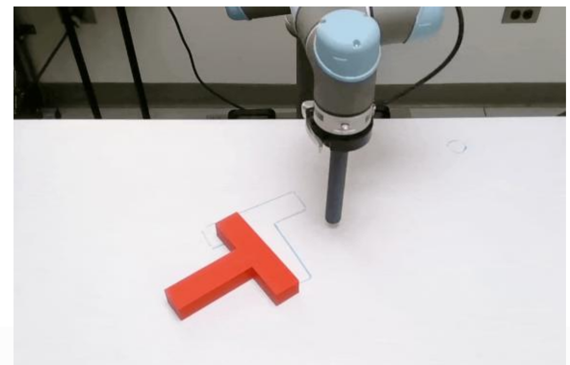
Command Window

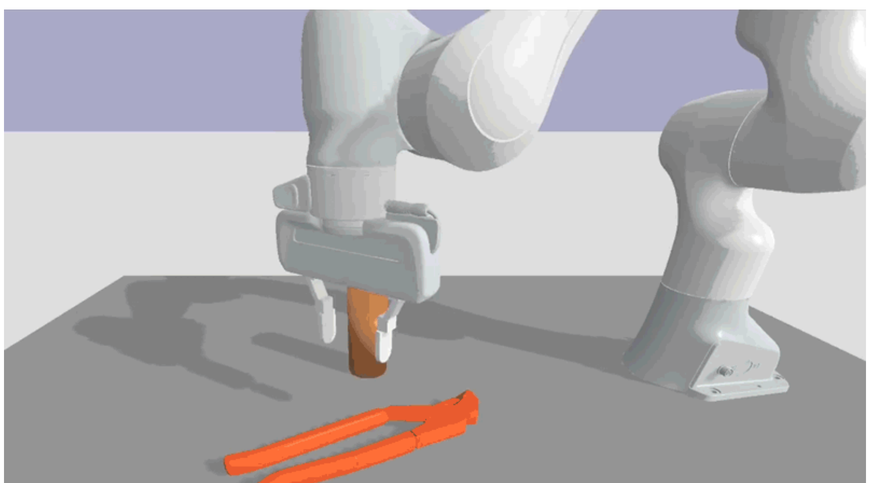
New to MATLAB? See resources for Getting Started.

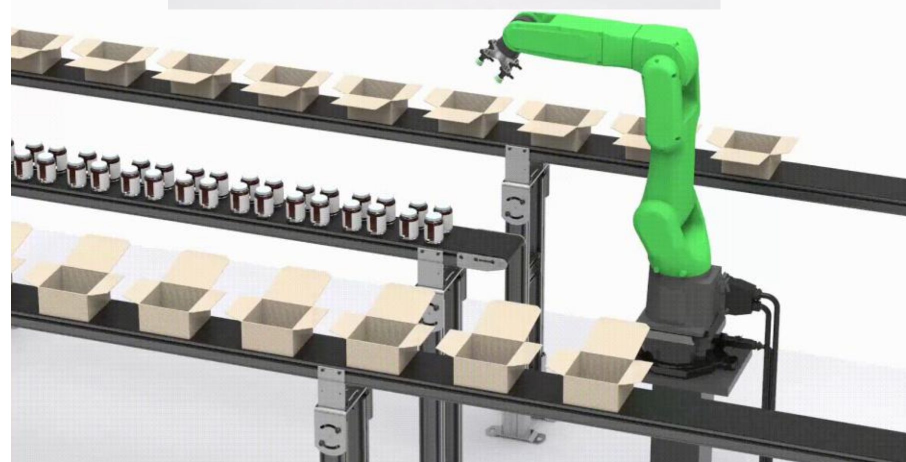
```
r =

    0.0000   -0.0000    1.0000
    0.0000   -1.0000   -0.0000
    1.0000    0.0000    0.0000
```

Outline

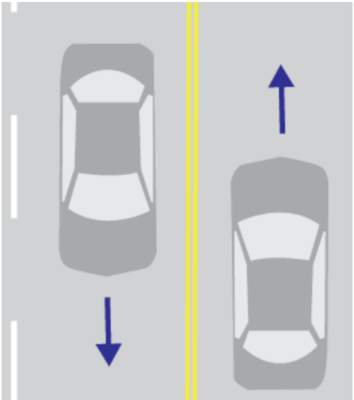
- Understanding of Geometry
- Computation of Geometry
- Measurement of Geometry



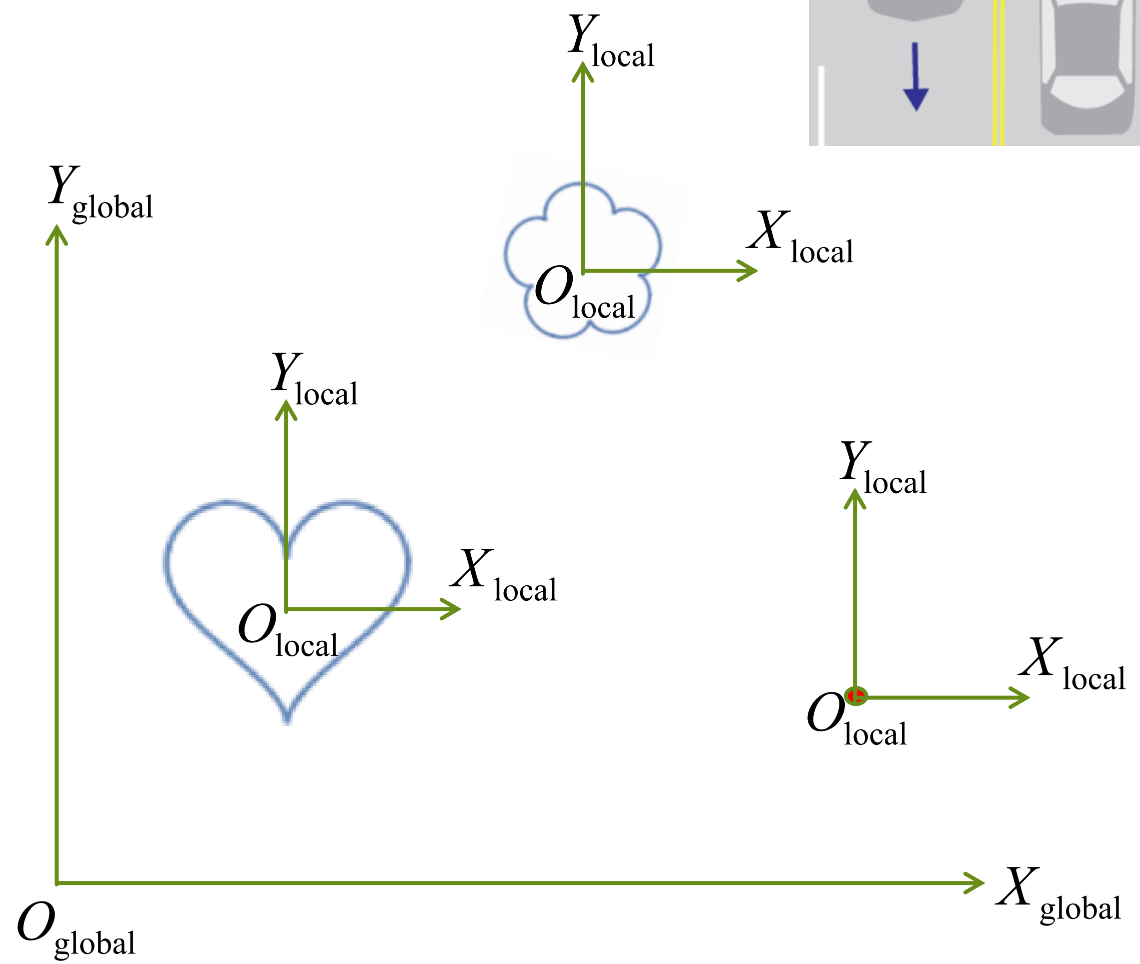




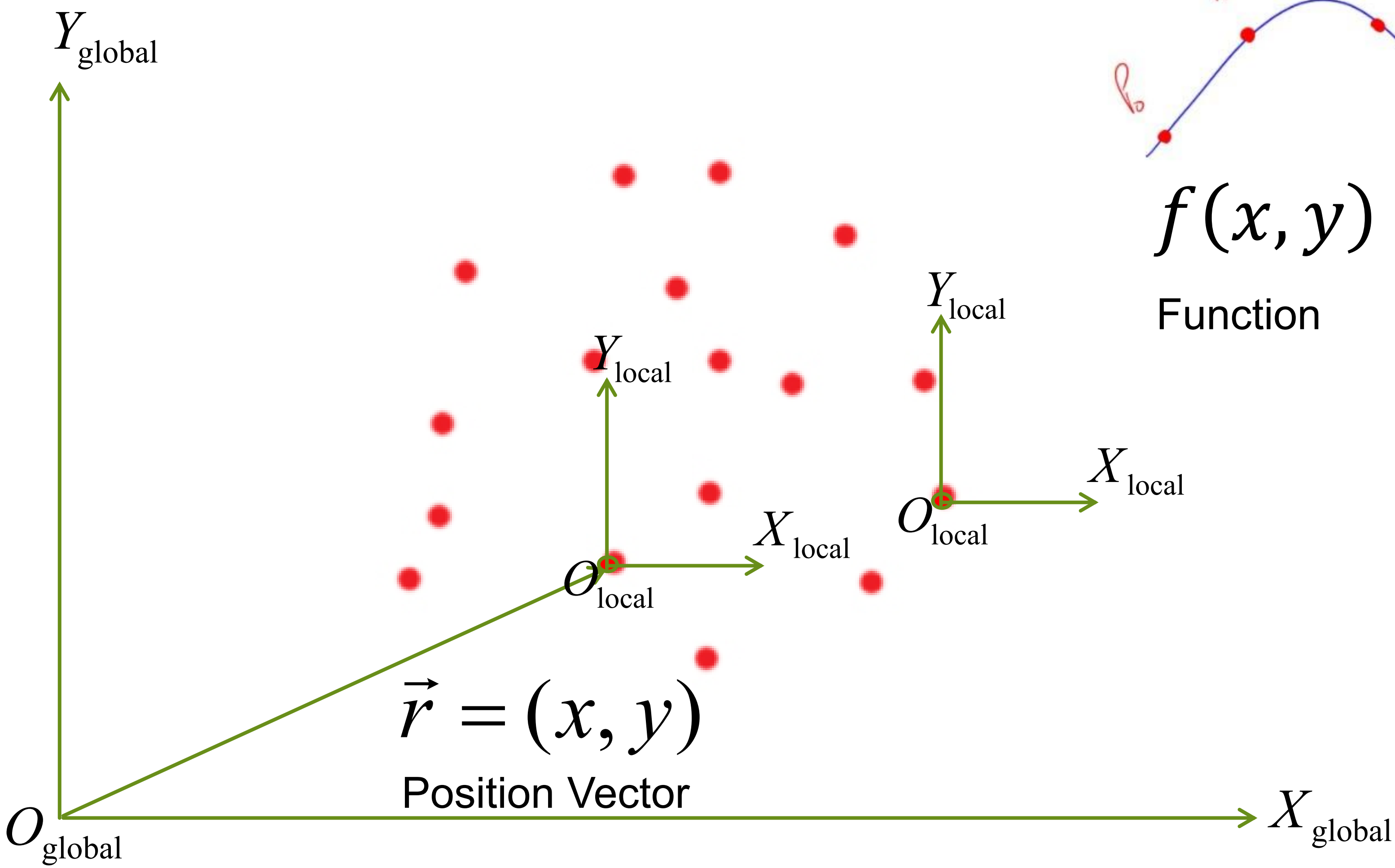
What are the geometrical parameters to compute?



- Pose:
  - It refers to positions and orientations of entities with respect to a Global Coordinate System.
- Shape:
  - It refers to outlines of entities with respect to Local Coordinate Systems assigned to these shapes, respectively.

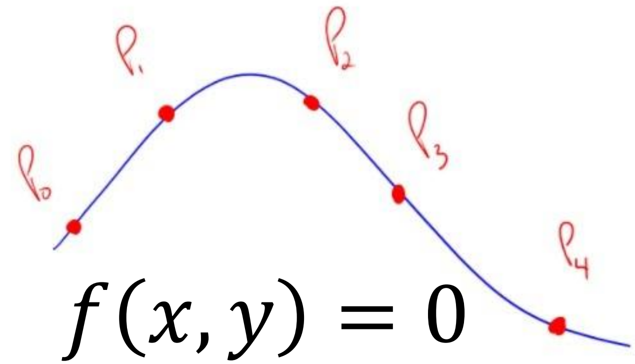


Representation of Positions in 2D Space without Time Constraints



$$\vec{r} = (x, y)$$

Position Vector



$$f(x, y) = 0$$

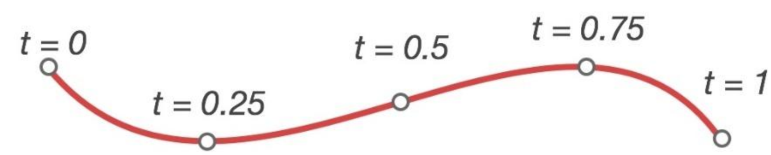
Function

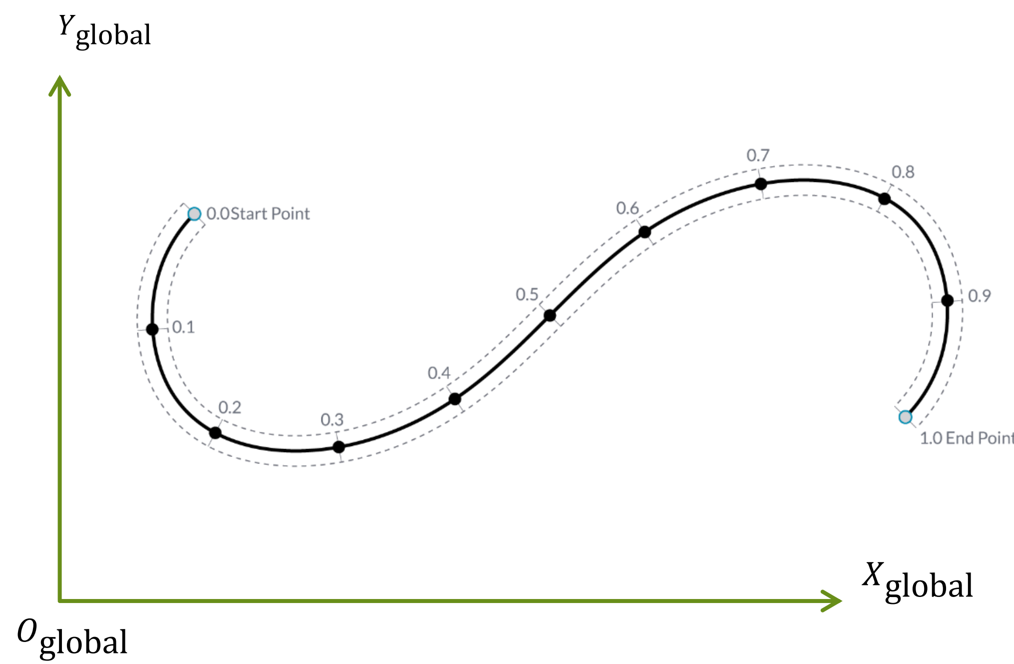
Representation of Positions in 2D Space with Time Constraints

$$\vec{r}(t) = \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \begin{pmatrix} a_x t^3 + b_x t^2 + c_x t + d_x \\ a_y t^3 + b_y t^2 + c_y t + d_y \end{pmatrix}$$

$$\vec{r}(t) = \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \begin{pmatrix} a_x t^2 + b_x t + c_x \\ a_y t^2 + b_y t + c_y \end{pmatrix}$$

$$\vec{r}(t) = \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \begin{pmatrix} a_x t + b_x \\ a_y t + b_y \end{pmatrix}$$





Example

- A mobile robot moves on a floor by following a straight line. It passes point A(2.0, 2.0) (cm) at time t1=1.0 s, and point B(4.0, 7.0) (cm) at t2=3.0 s. What are the time functions representing the coordinates of the origin of the local coordinate system assigned to the mobile robot?
- Answer:

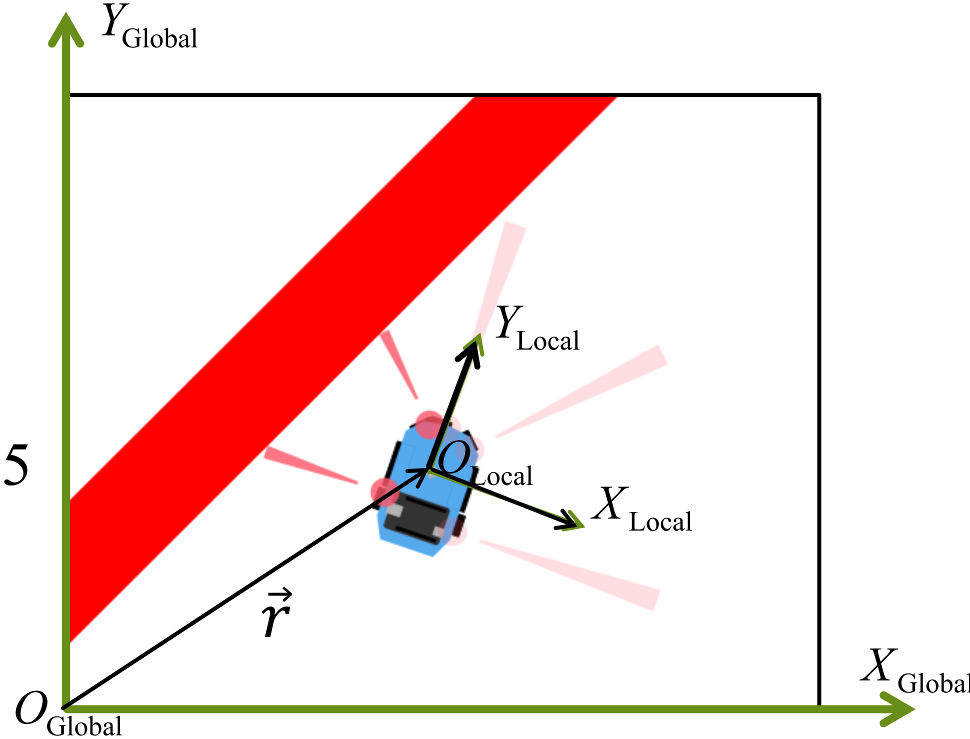
$$a_x \times 1.0 + b_x = 2.0$$
$$a_x \times 3.0 + b_x = 4.0$$

$$\Rightarrow \quad a_x = 1.0, \quad b_x = 1.0$$

$$a_y \times 1.0 + b_y = 2.0$$
$$a_y \times 3.0 + b_y = 7.0$$

$$\Rightarrow \quad a_y = 2.5, \quad b_y = -0.5$$

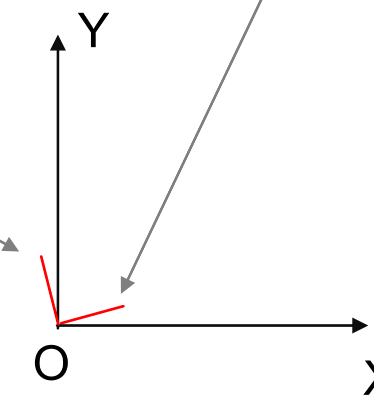
$$\vec{r}(t) = \begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \begin{pmatrix} t + 1.0 \\ 2.5t - 0.5 \end{pmatrix}$$

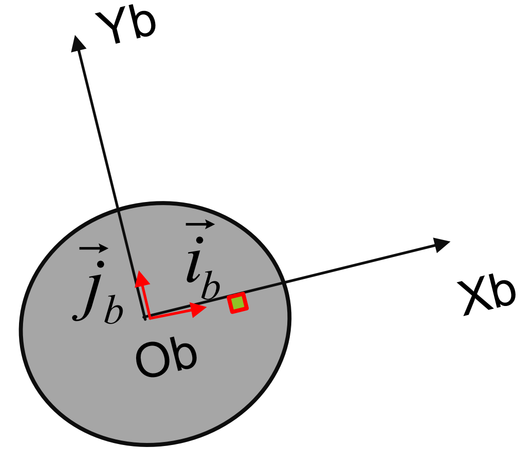


Representation of Orientations in 2D Space

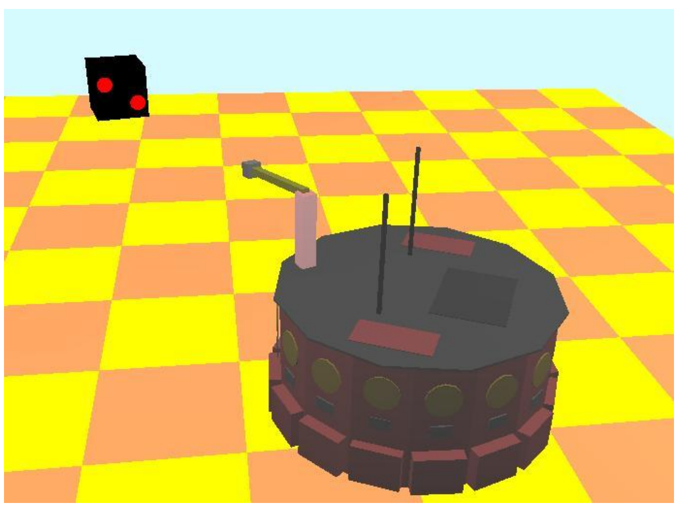
$$\vec{j}_b = \begin{pmatrix} -\sin(\theta) \\ \cos(\theta) \end{pmatrix}$$

$$\vec{i}_b = \begin{pmatrix} \cos(\theta) \\ \sin(\theta) \end{pmatrix}$$





Robot's Base



$$R_{t_0,t} = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{pmatrix}$$

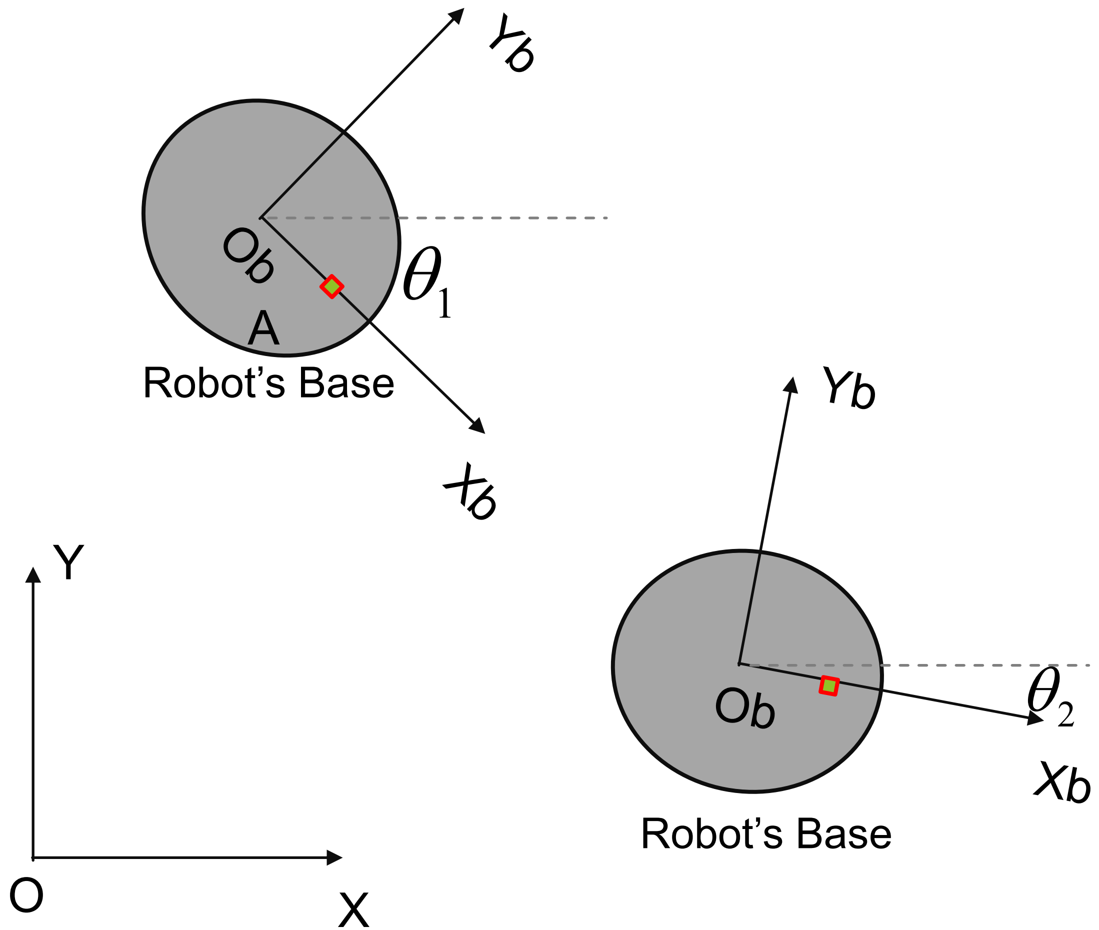
This is the orientation at time t, as the result of the change of orientation from time t0 to time t.

Example

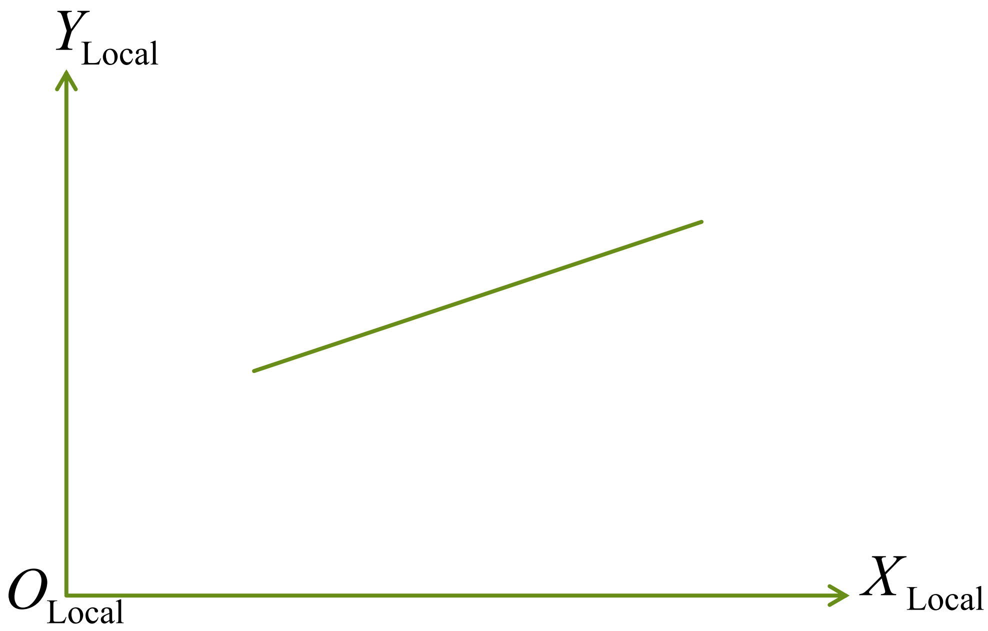
- What are the orientations of the mobile base at times t1 and t2?
- Answer:

$$\theta(t_1) = \theta_1$$

$$\theta(t_2) = \theta_2$$

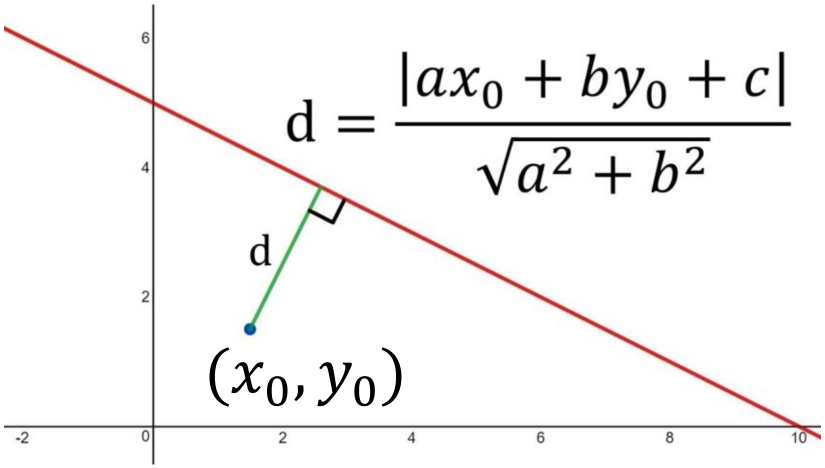


Representation of Line-type Shape in 2D Space



$$y = ax + b$$

$$ax + by + c = 0$$

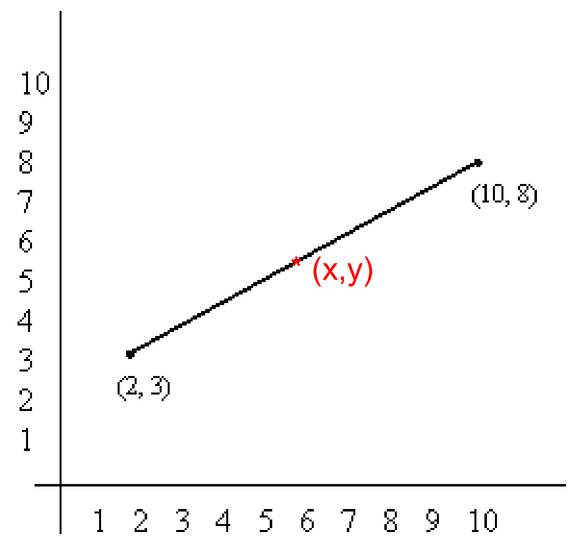


Example

- A line in a 2D space passes through two points: (2,3) and (10,8). What are the parameters of the line?

- Answer:

$$\frac{y-3}{x-2} = \frac{8-3}{10-2}$$

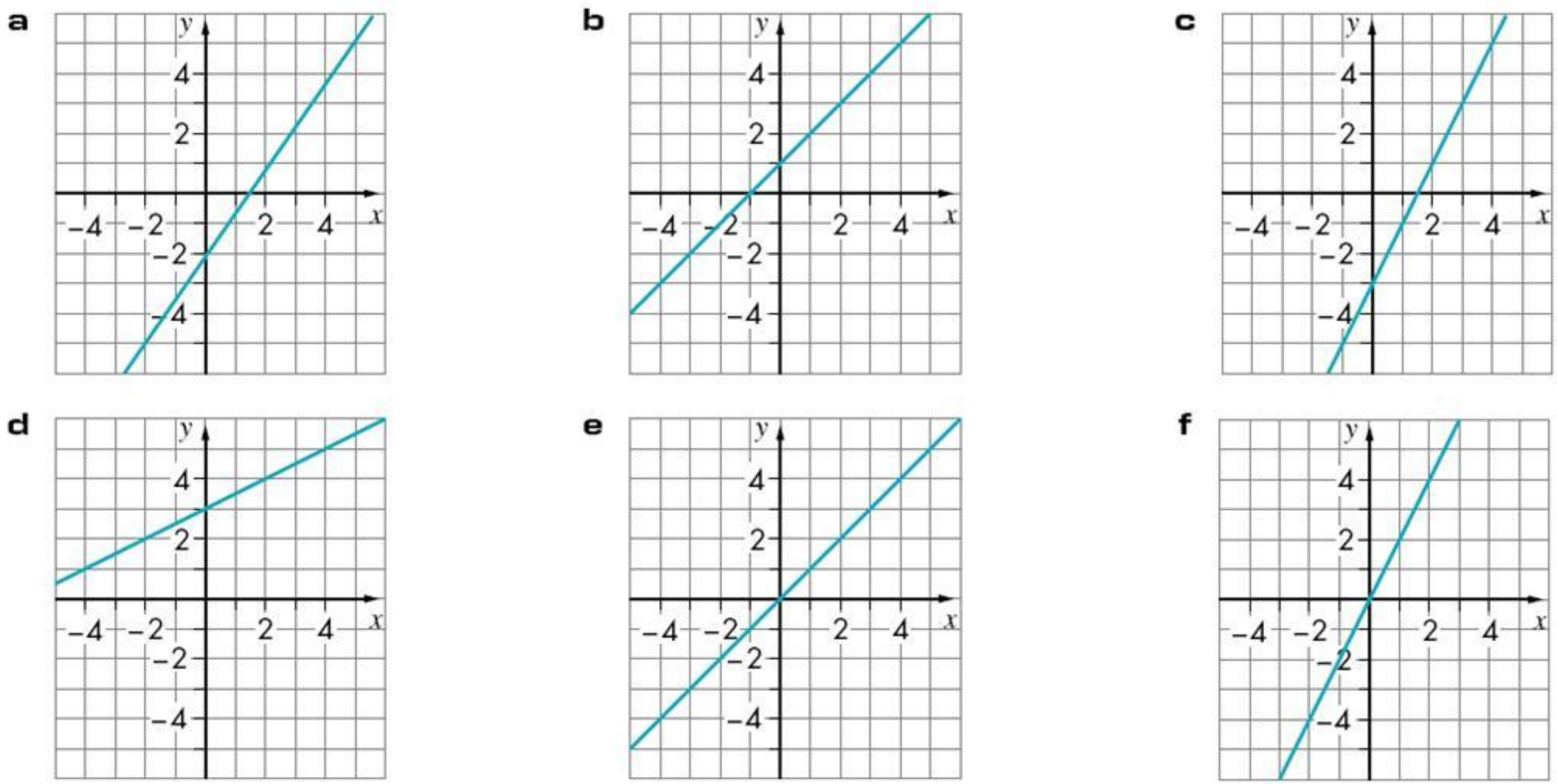


$$y = \frac{5}{8}(x-2)+3$$

$$y = \frac{5}{8}x + \frac{7}{4} \quad \Rightarrow \quad (a,b) = (\frac{5}{8}, \frac{7}{4})$$

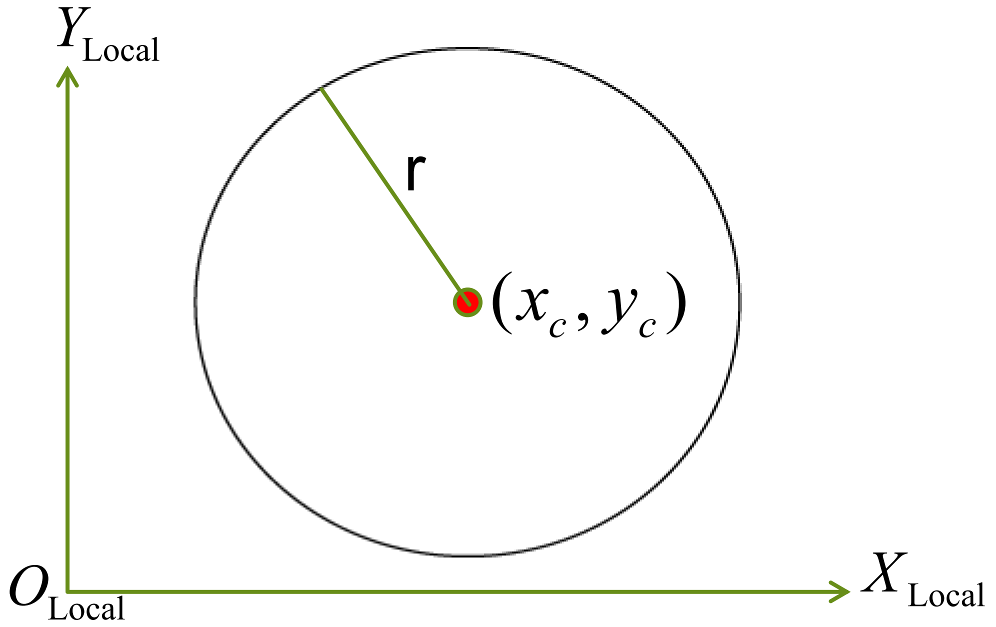
Exercises

Find the equations of these straight lines.



Representation of Circle-type Shape in 2D Space

$$(x - x_c)^2 + (y - y_c)^2 = r^2$$

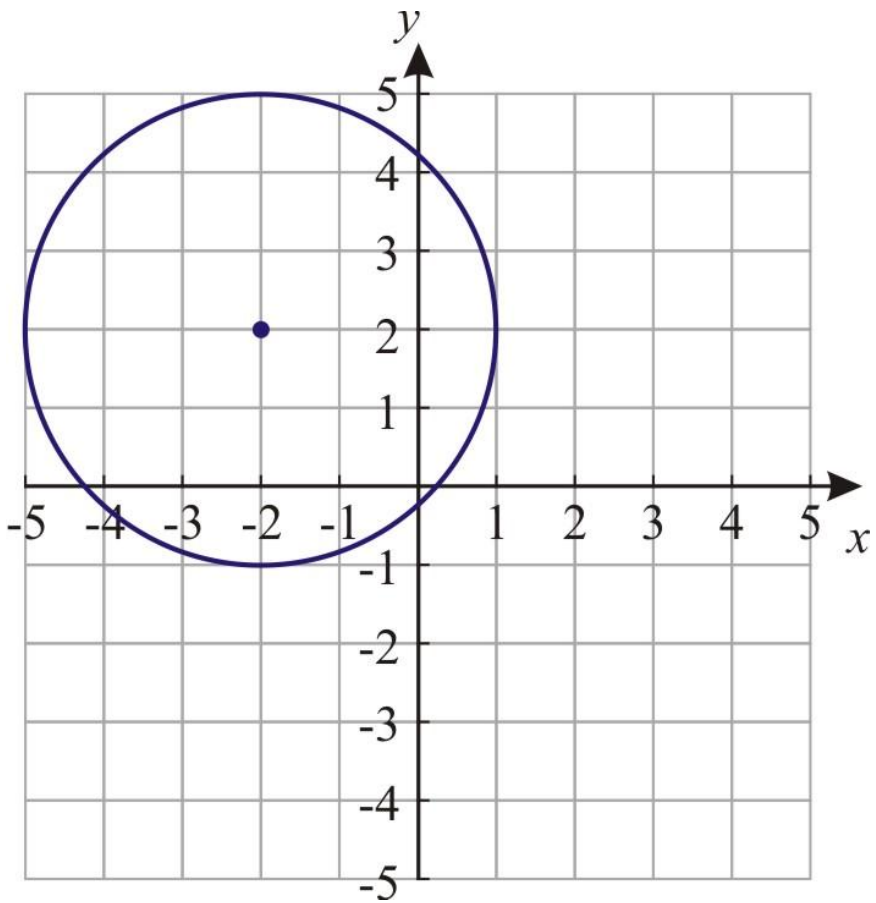


Example

- What are the parameters of the circle shown in the figure?

- Answer:

$$\begin{pmatrix} x_c \\ y_c \\ r \end{pmatrix} = \begin{pmatrix} -2 \\ 2 \\ 3 \end{pmatrix}$$



Example

- A mechanical gear is under visual inspection. If the tips of the gear's three teeth are at the positions (x1, y1), (x2, y2) and (x3, y3), what are the parameters of the circle which envelopes the tips of all the teeth of the gear?

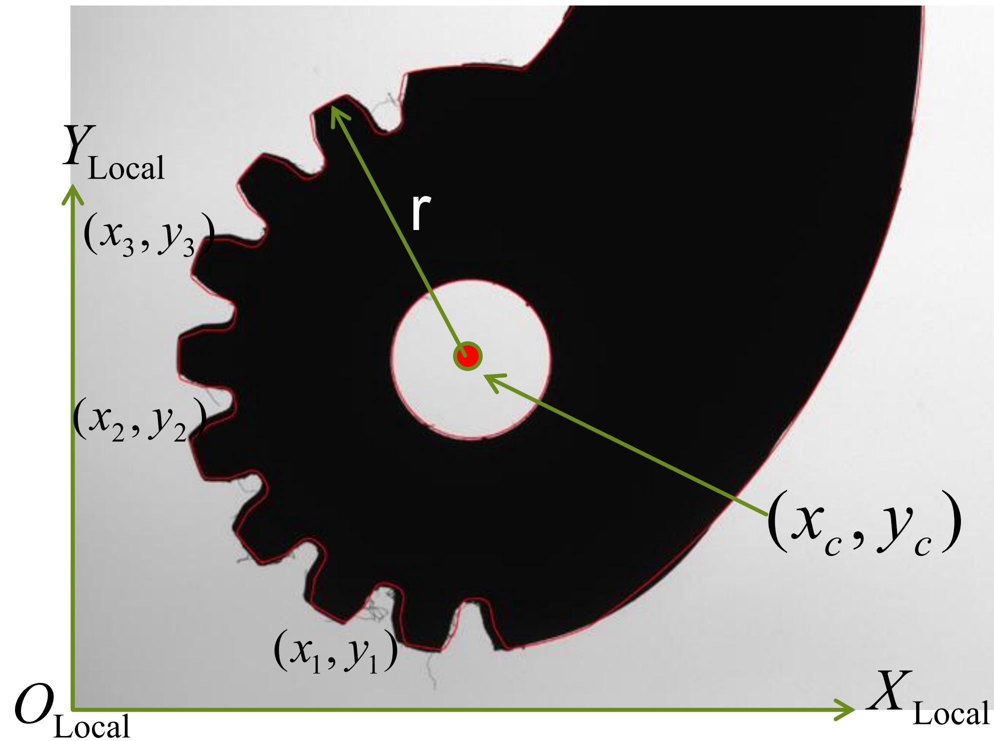
- Answer:

$$(x_1 - x_c)^2 + (y_1 - y_c)^2 = r^2$$

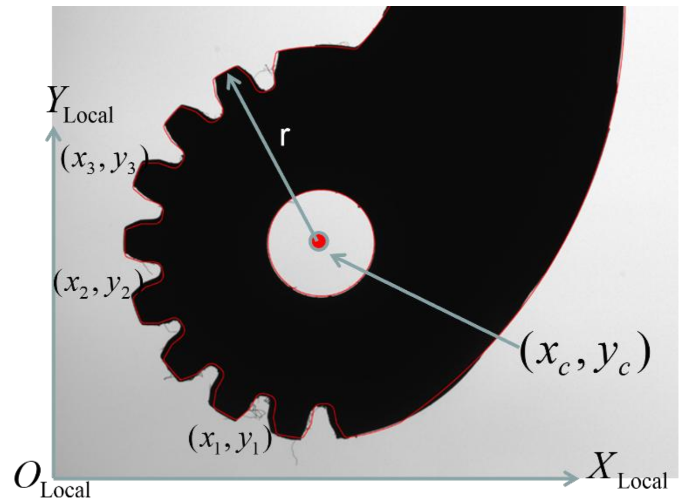
$$(x_2 - x_c)^2 + (y_2 - y_c)^2 = r^2$$

$$(x_3 - x_c)^2 + (y_3 - y_c)^2 = r^2$$

(to continue)



$$\begin{cases} x_1^2 - 2x_1x_c + x_c^2 + y_1^2 - 2y_1y_c + y_c^2 = r^2 & (1) \\ x_2^2 - 2x_2x_c + x_c^2 + y_2^2 - 2y_2y_c + y_c^2 = r^2 & (2) \\ x_3^2 - 2x_3x_c + x_c^2 + y_3^2 - 2y_3y_c + y_c^2 = r^2 & (3) \end{cases}$$

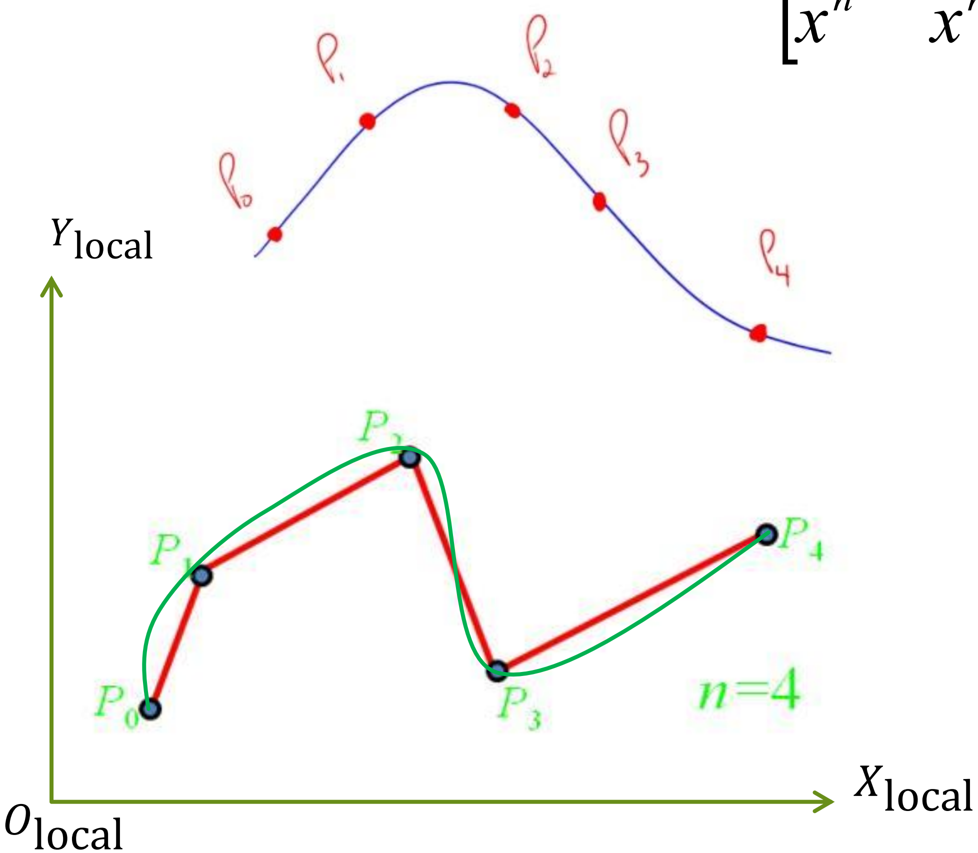


$$\begin{cases} 2(x_1 - x_2)x_c + 2(y_1 - y_2)y_c = x_1^2 - x_2^2 + y_1^2 - y_2^2 \\ 2(x_1 - x_3)x_c + 2(y_1 - y_3)y_c = x_1^2 - x_3^2 + y_1^2 - y_3^2 \end{cases}$$

$$\begin{bmatrix} 2(x_1 - x_2) & 2(y_1 - y_2) \\ 2(x_1 - x_3) & 2(y_1 - y_3) \end{bmatrix} \bullet \begin{bmatrix} x_c \\ y_c \end{bmatrix} = \begin{bmatrix} x_1^2 - x_2^2 + y_1^2 - y_2^2 \\ x_1^2 - x_3^2 + y_1^2 - y_3^2 \end{bmatrix}$$

$$\begin{bmatrix} x_c \\ y_c \end{bmatrix} = \begin{bmatrix} 2(x_1 - x_2) & 2(y_1 - y_2) \\ 2(x_1 - x_3) & 2(y_1 - y_3) \end{bmatrix}^{-1} \bullet \begin{bmatrix} x_1^2 - x_2^2 + y_1^2 - y_2^2 \\ x_1^2 - x_3^2 + y_1^2 - y_3^2 \end{bmatrix}$$

Representation of Curve-type Shape in 2D Space



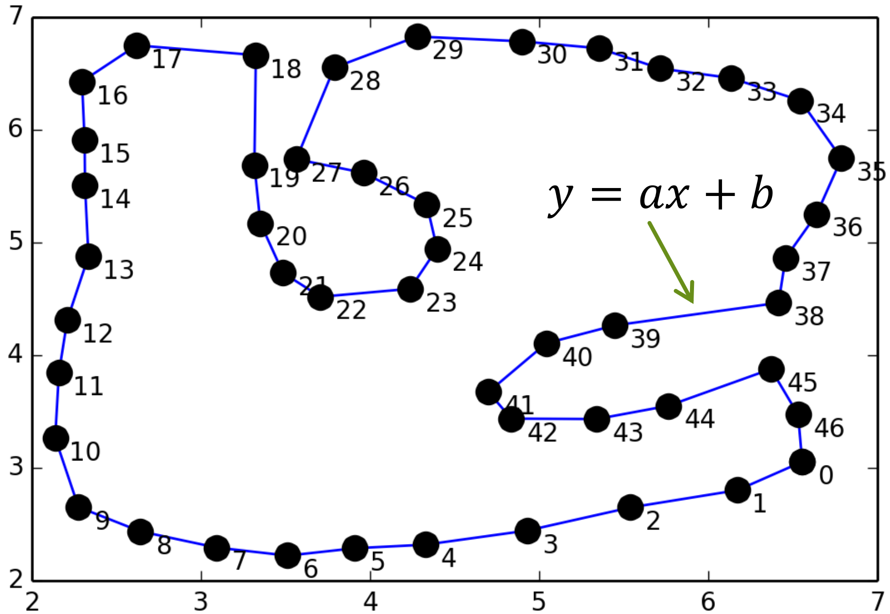
$$\begin{bmatrix} x^n & x^{n-1} & \dots & 1 \end{bmatrix} P_{n\times n} \begin{bmatrix} y^n \\ y^{n-1} \\ \dots \\ 1 \end{bmatrix} = 0$$

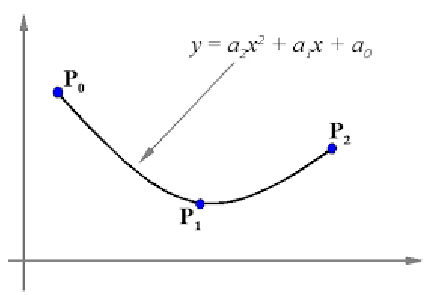
n=1,2,…

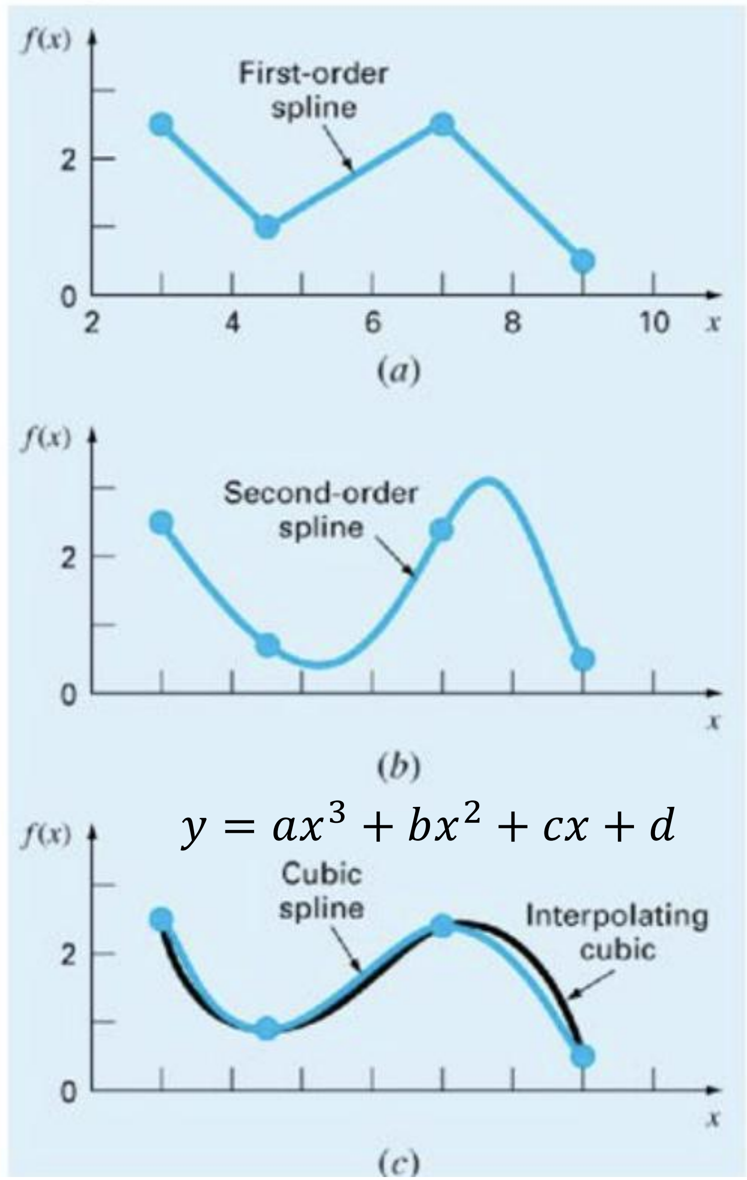
Any curve could be approximated by a set of line segments and arcs

Next Slide

Example of Using Splines …

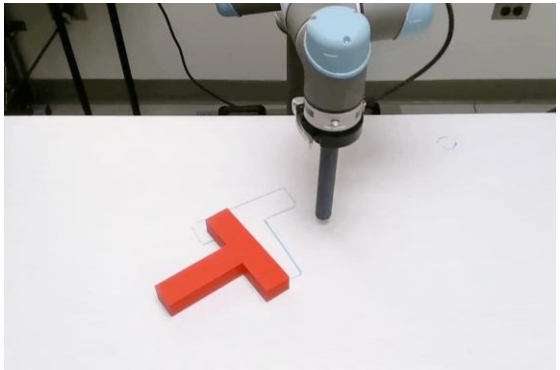
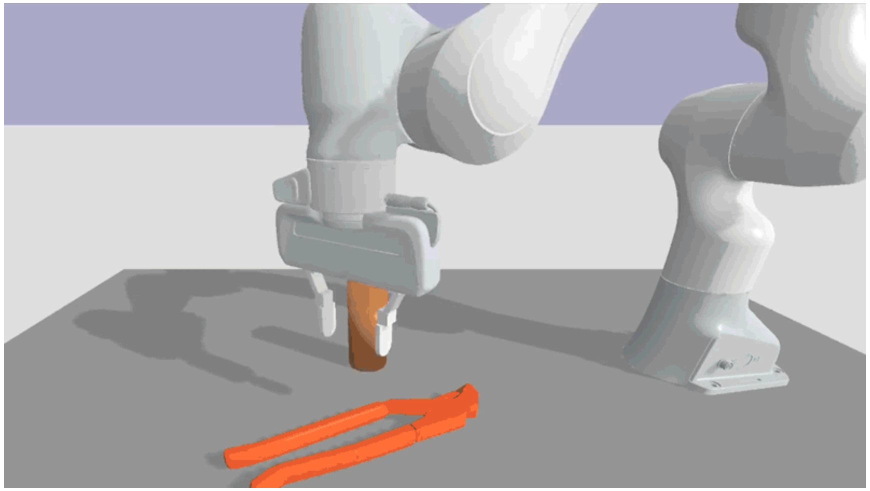
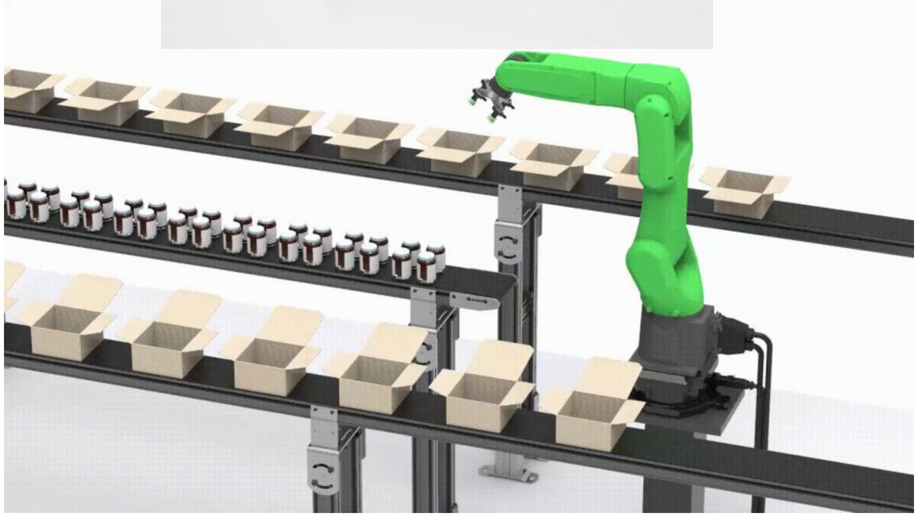






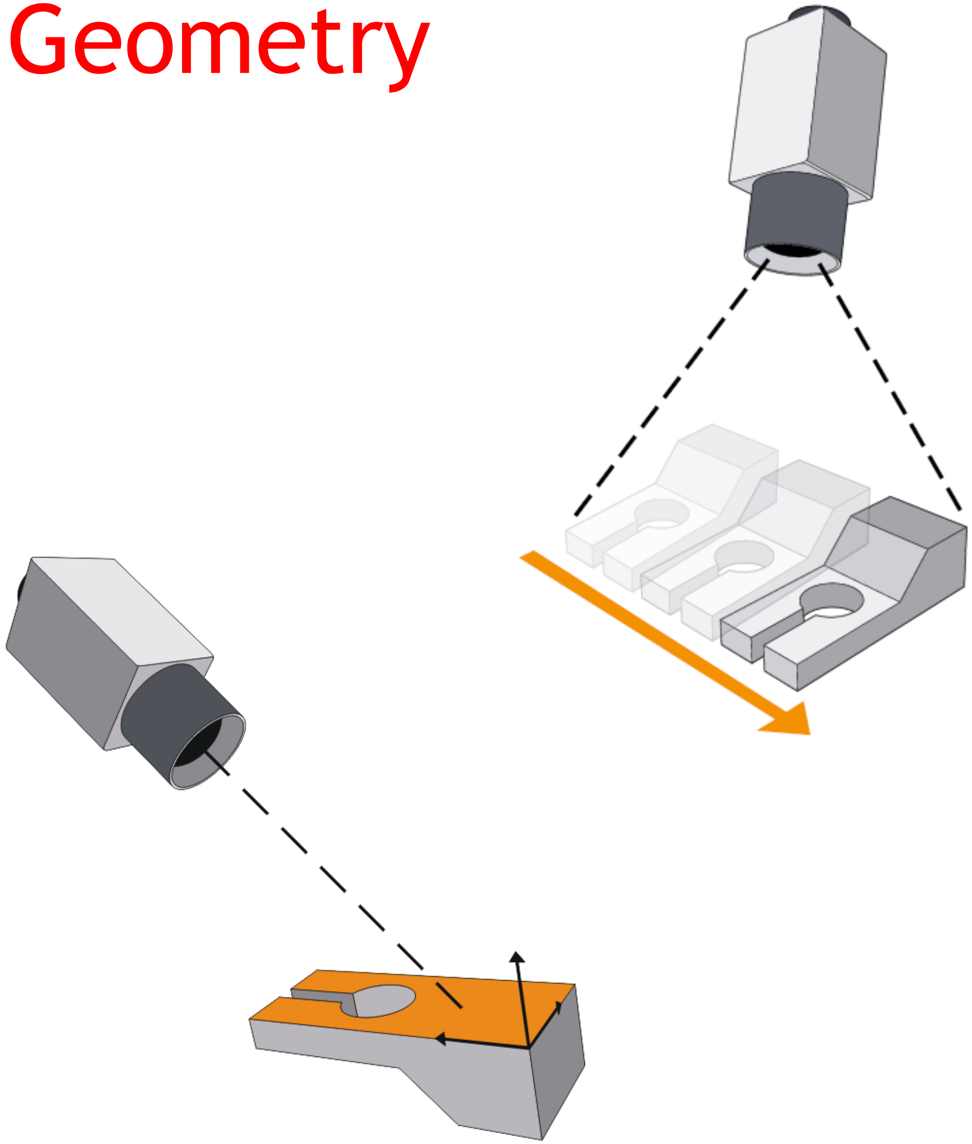
Outline

- Understanding of Geometry
- Computation of Geometry
- Measurement of Geometry

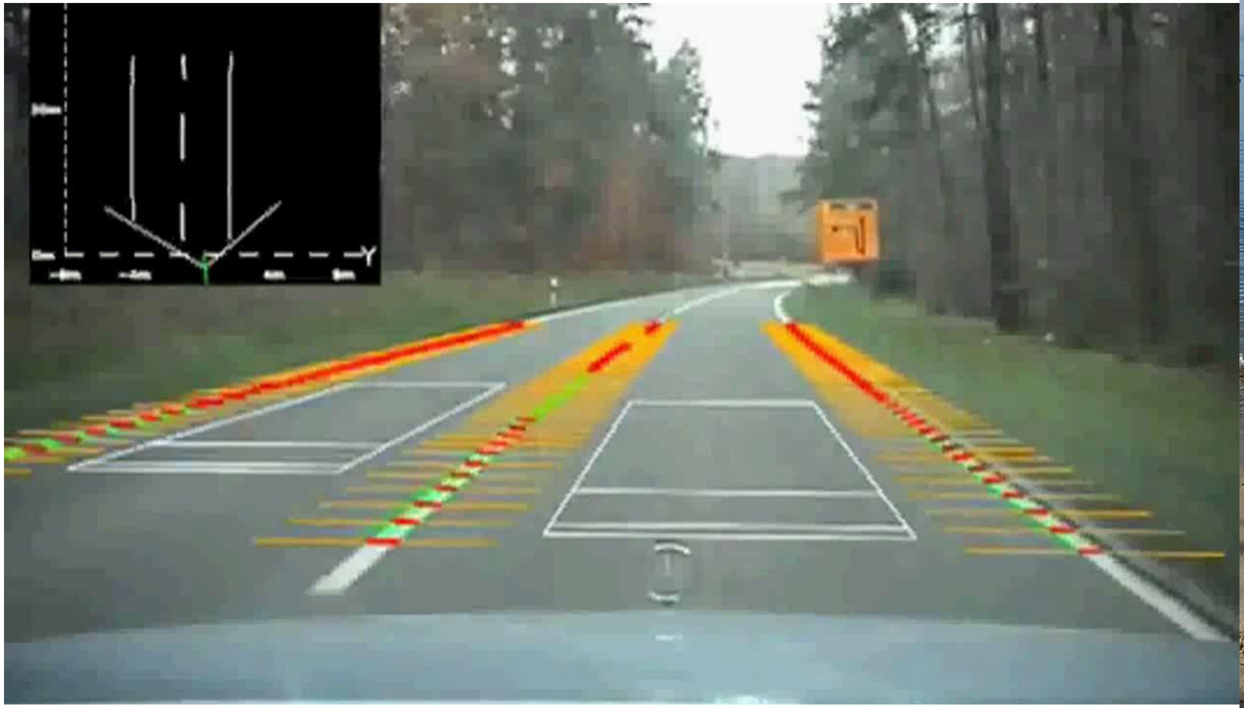





Applications of Geometry

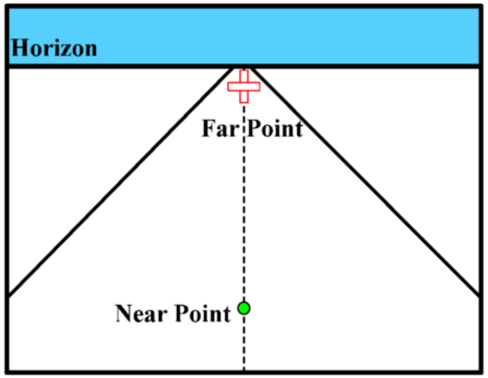
- Inspection
- Grasping
- Manipulation
- Guidance
- Cognition / Recognition



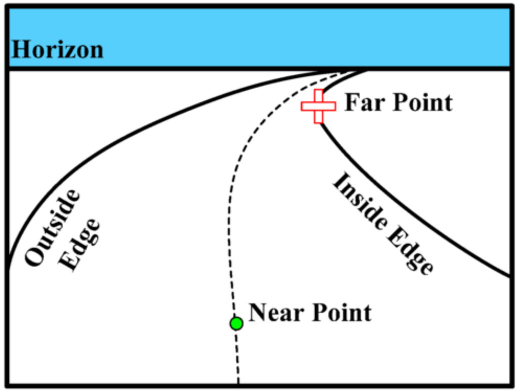
Vision-Guided Navigation



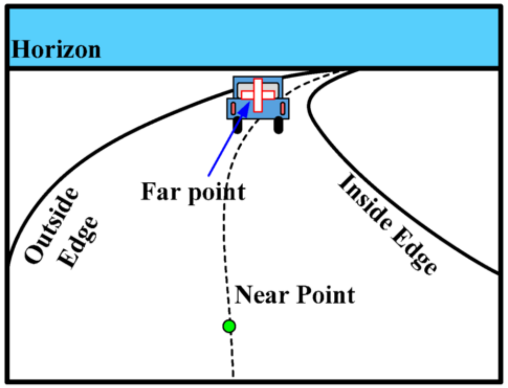
Vision-Guided Navigation



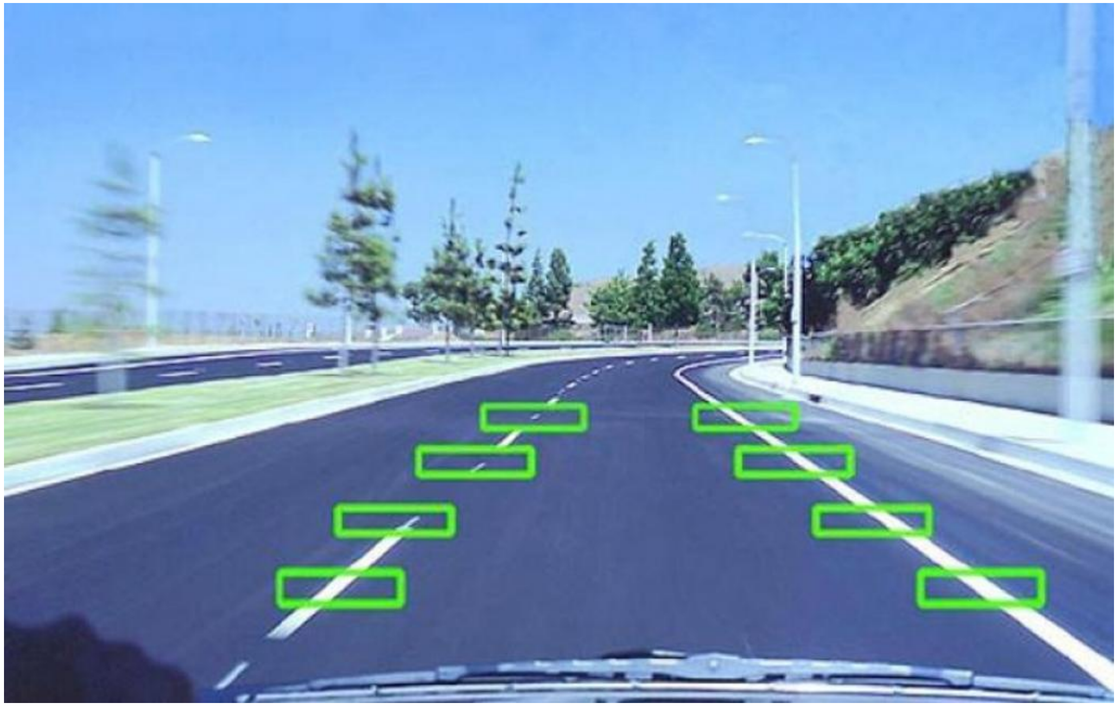
(a)



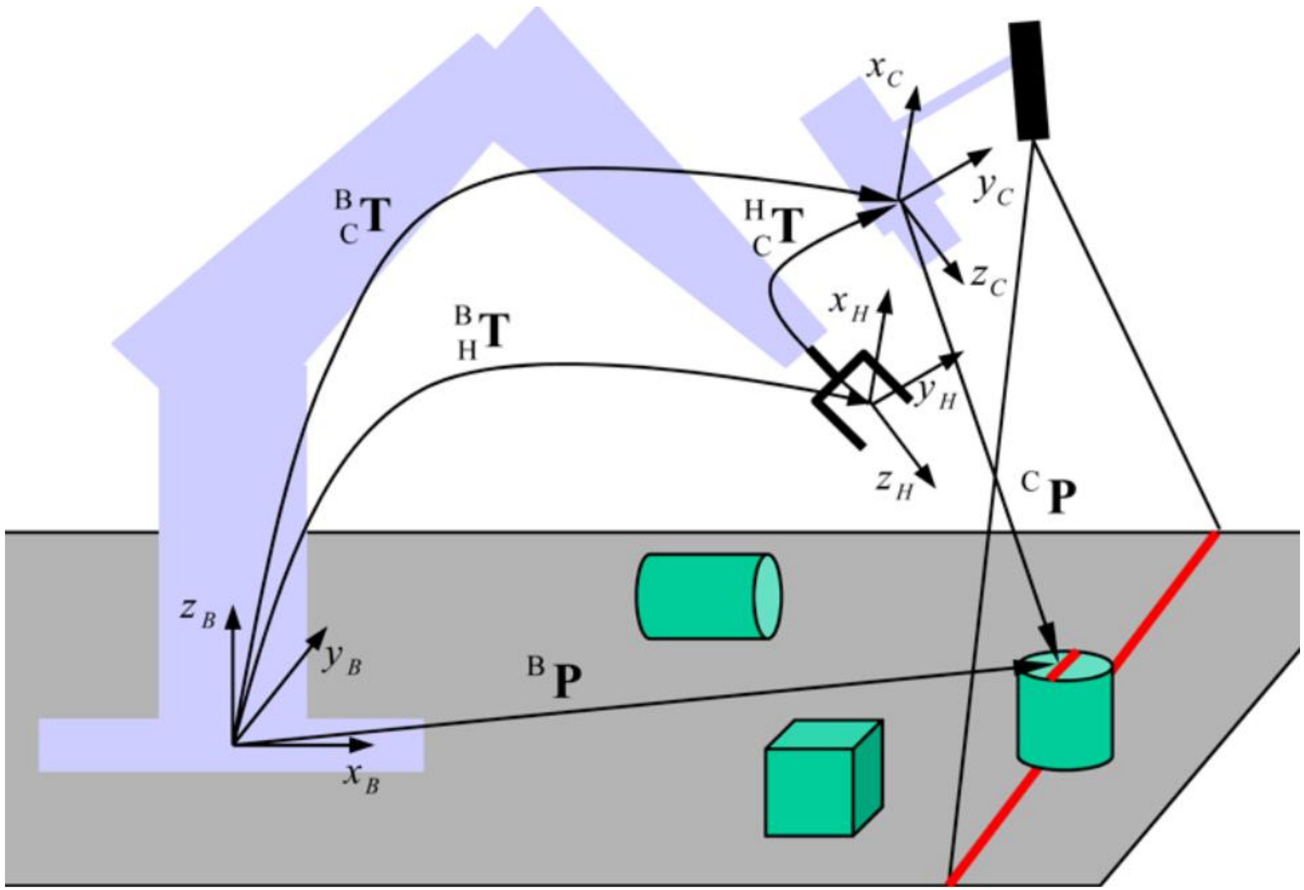
(b)



(c)

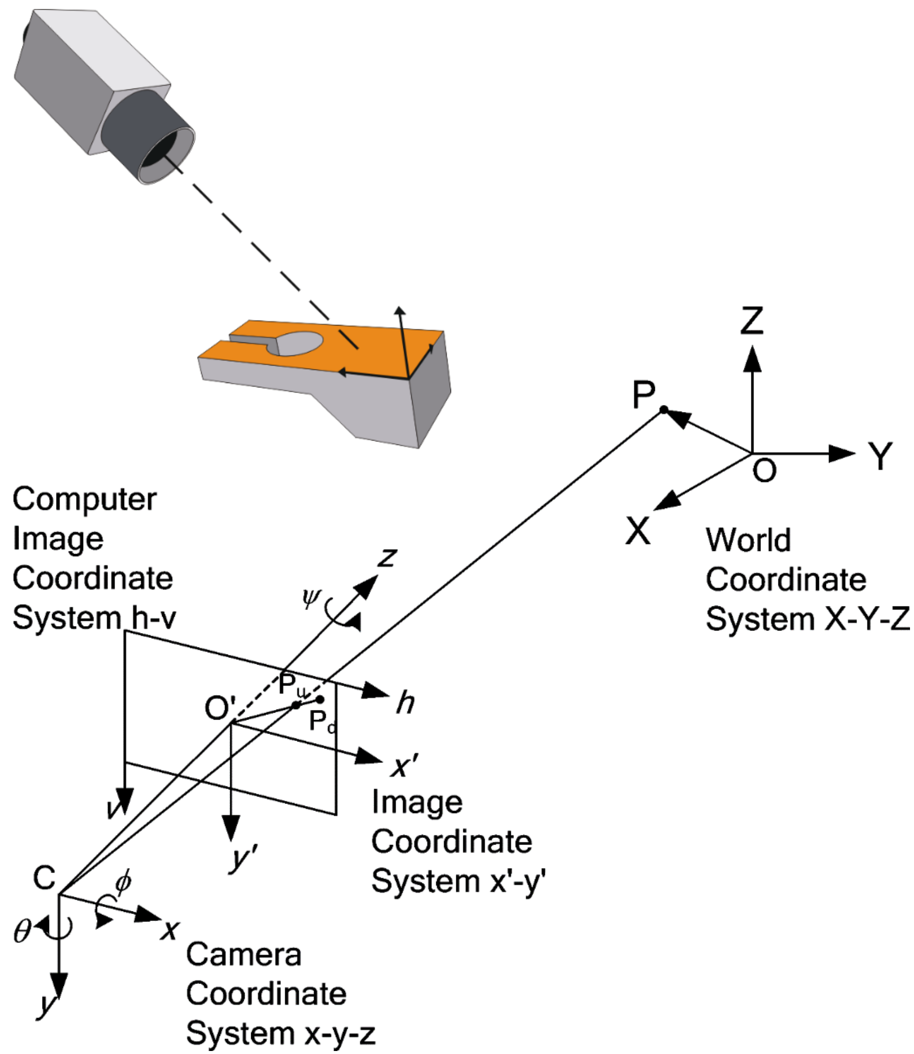


Vision-Guided Manipulation/Grasping



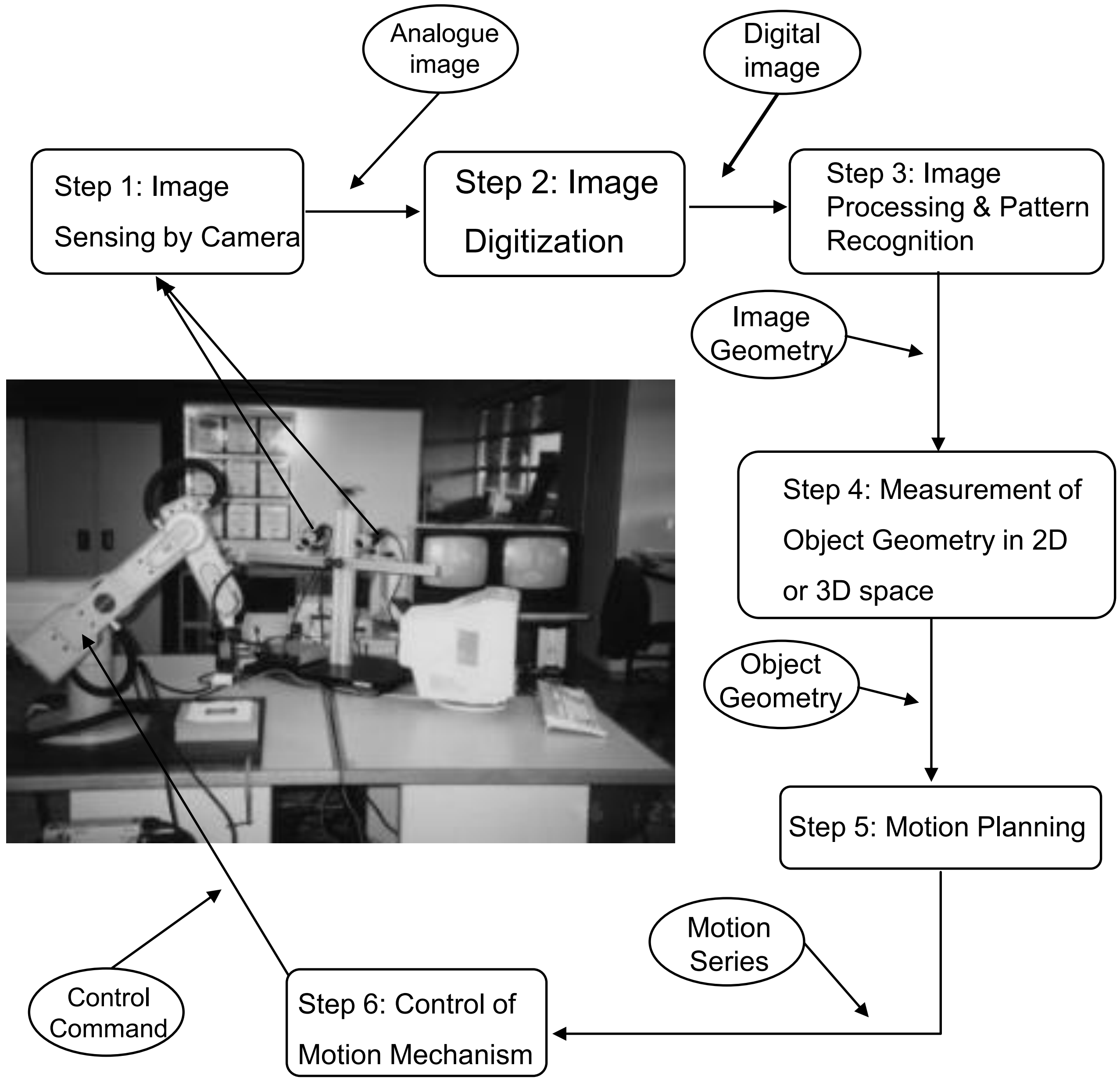
Principle of Monocular Vision

- The geometry of physical entities in a 2D space depends on the coordinates of points.
- The measurement of coordinates of points in a 2D space can be achieved with a single camera or monocular vision system.
- A monocular vision system relates the coordinates of points in 2D space to the coordinates in image space in a unique way.

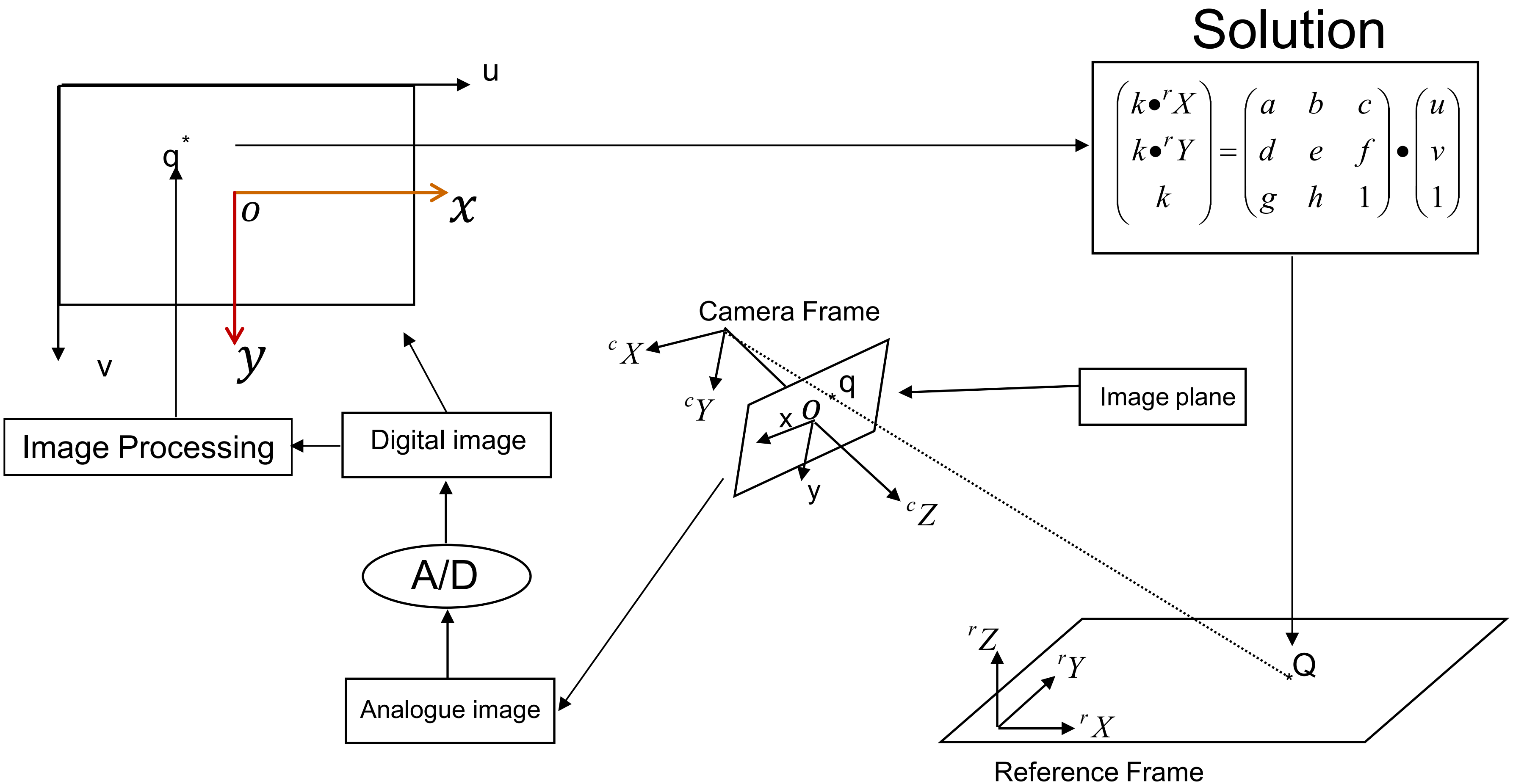


Motion Flow in Monocular Vision …

What is a motion flow? It refers to a flow of coordinate systems

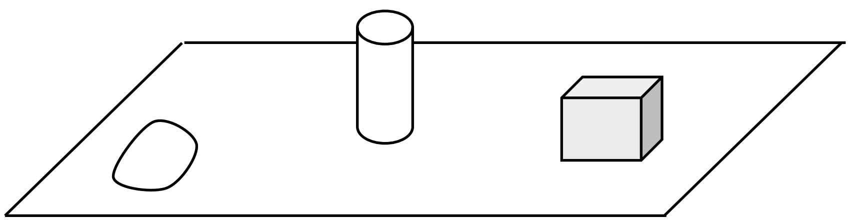


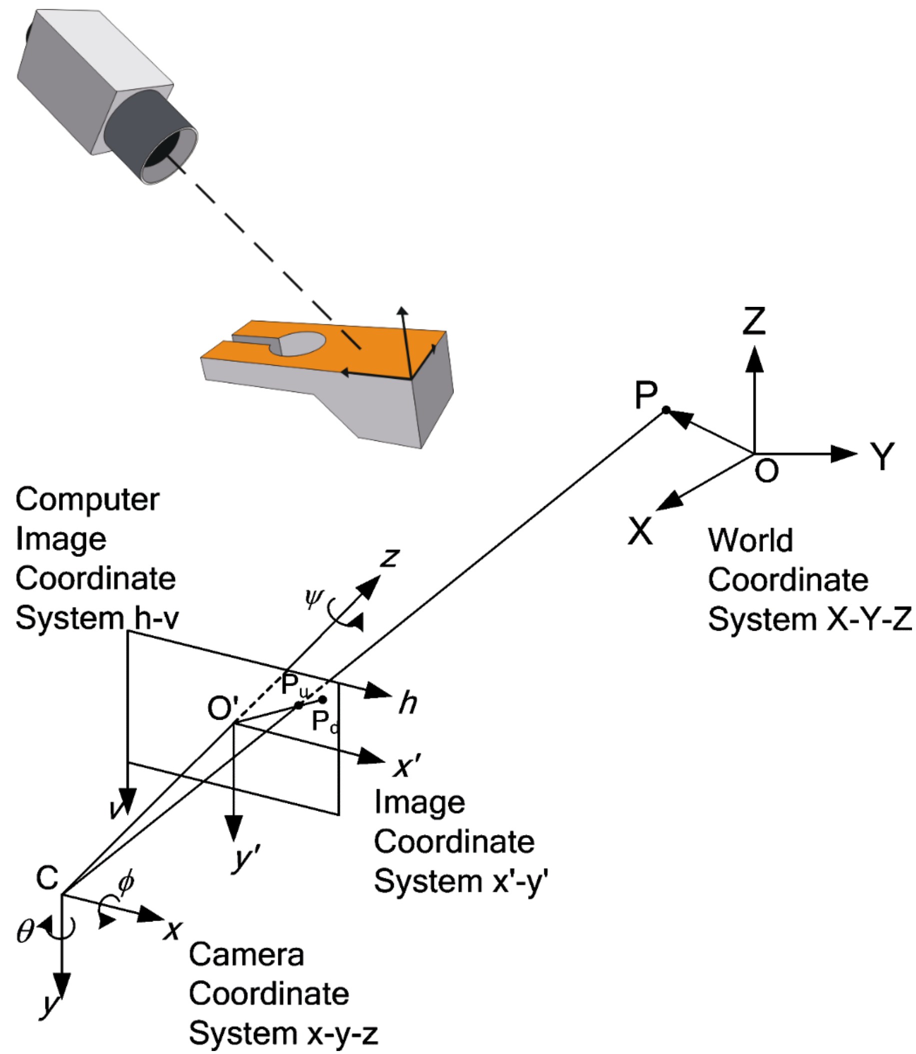
Matrix Equation of Monocular Vision



Step 1 of Proof:

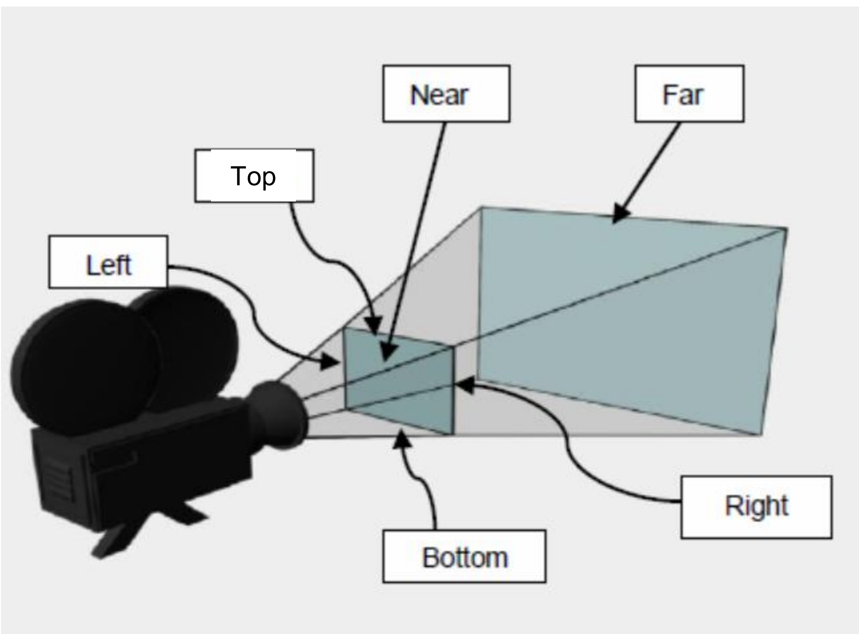
- We consider the case of the measurement of points on a 2D plane:

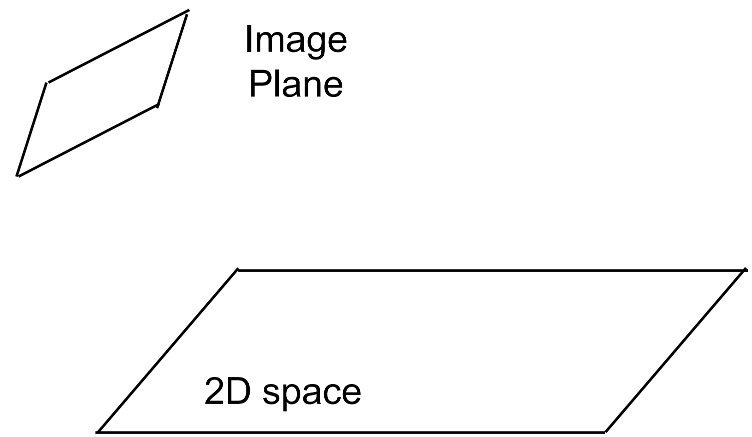




Step 2 of Proof:

- We use a single camera as the sensing device:

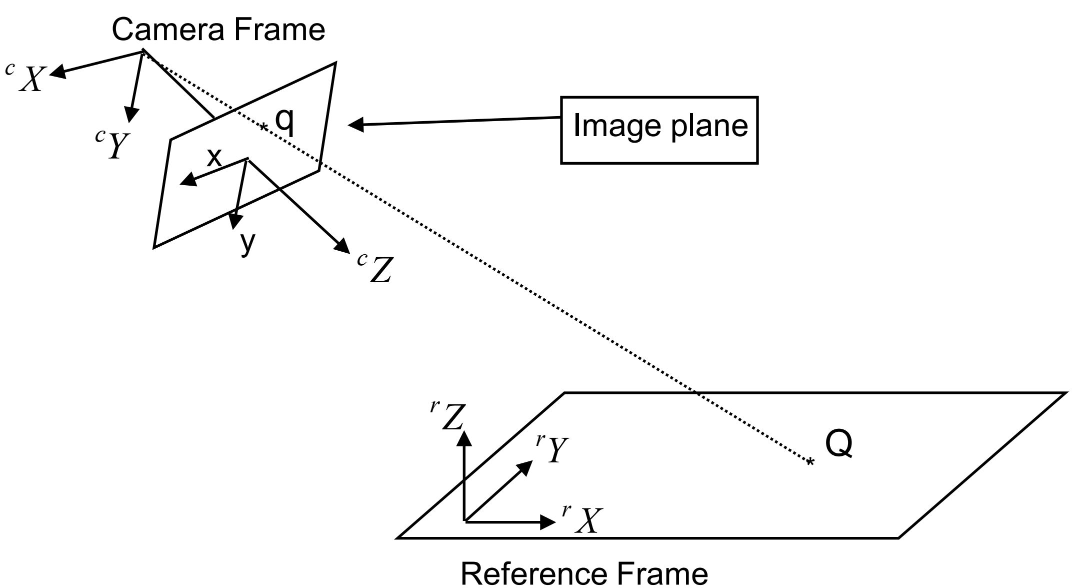




Step 3 of Proof:

- The coordinates in the reference frame can be transformed into the coordinates in the camera frame:

$$^{c}H_{r} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$



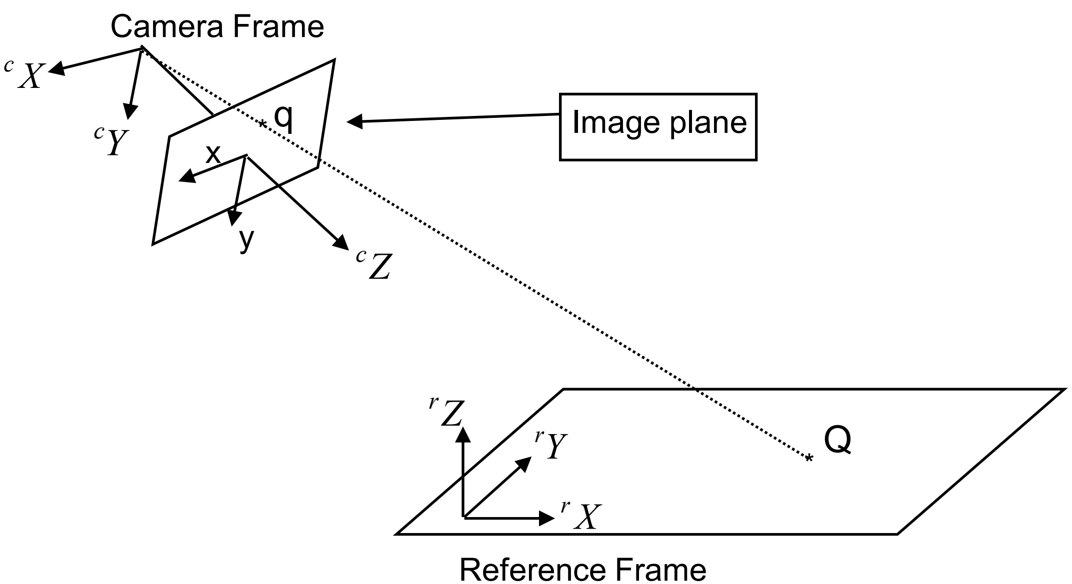
$$\begin{bmatrix} ^{c}X \\ ^{c}Y \\ ^{c}Z \\ 1 \end{bmatrix} = {^{c}H_{r}} \bullet \begin{bmatrix} ^{r}X \\ ^{r}Y \\ ^{r}Z \\ 1 \end{bmatrix}$$

Step 4 of Proof:

- The coordinates in camera frame can be projected into the coordinates in image plane:

$$x = f \bullet \frac{{}^{c}X}{{}^{c}Z} \quad \text{and} \quad y = f \bullet \frac{{}^{c}Y}{{}^{c}Z}$$

$$\begin{pmatrix} s \bullet x \\ s \bullet y \\ s \end{pmatrix} = \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \bullet \begin{pmatrix} {}^{c}X \\ {}^{c}Y \\ {}^{c}Z \\ 1 \end{pmatrix}$$

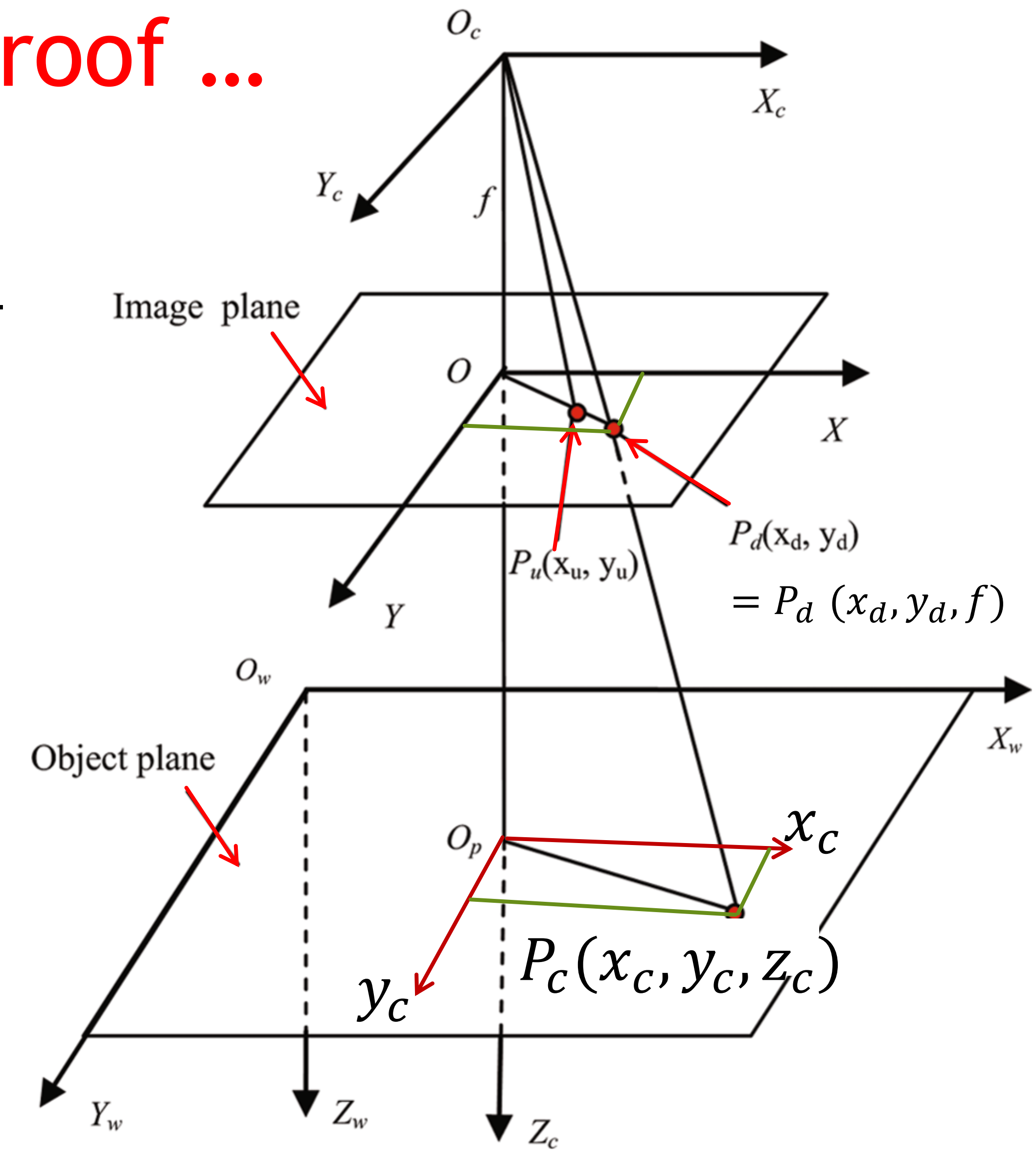


Further Detail of Proof …

$$\frac{O_pO_c}{OO_c} = \frac{P_cO_p}{P_dO} = \frac{z_c}{f} = \frac{x_c}{x_d} = \frac{y_c}{y_d}$$

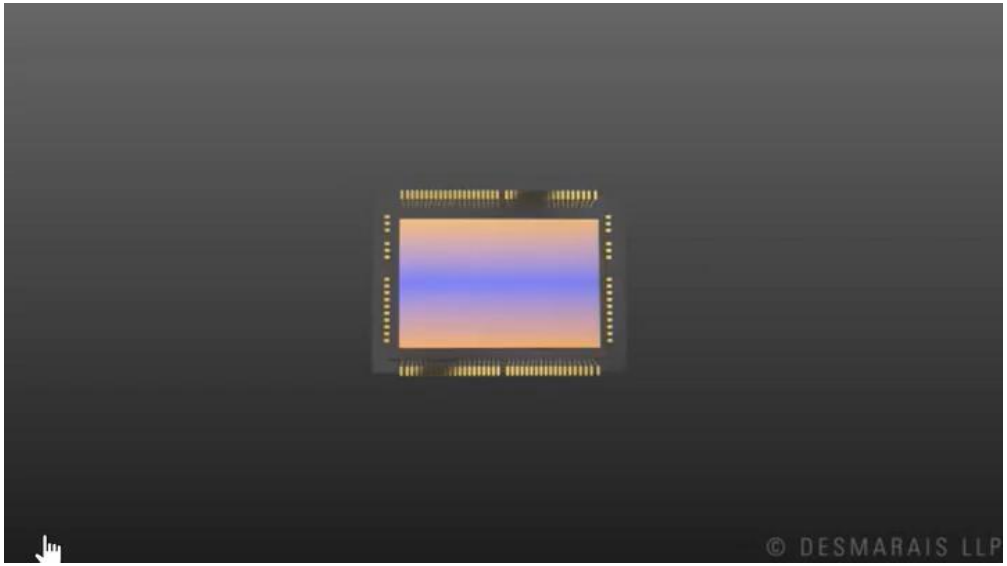
$$\frac{z_c}{f} = \frac{x_c}{x_d} \Rightarrow x_d = f\frac{x_c}{z_c}$$

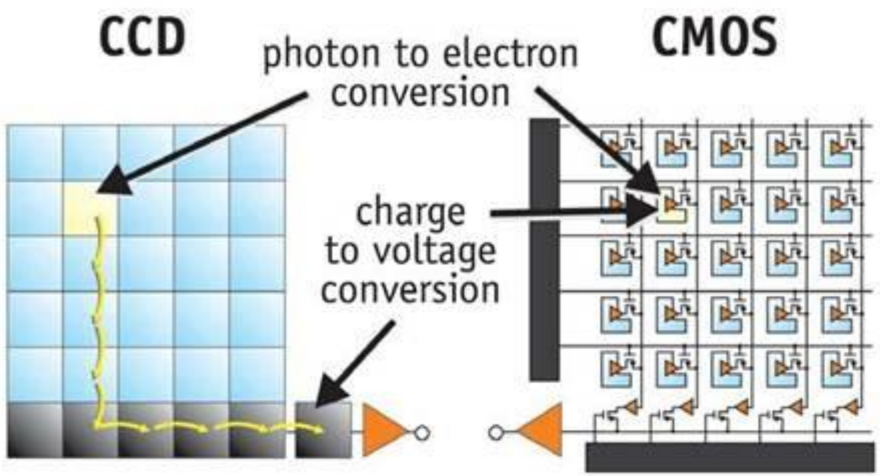
$$\frac{z_c}{f} = \frac{y_c}{y_d} \Rightarrow y_d = f\frac{y_c}{z_c}$$



Step 5 of Proof:

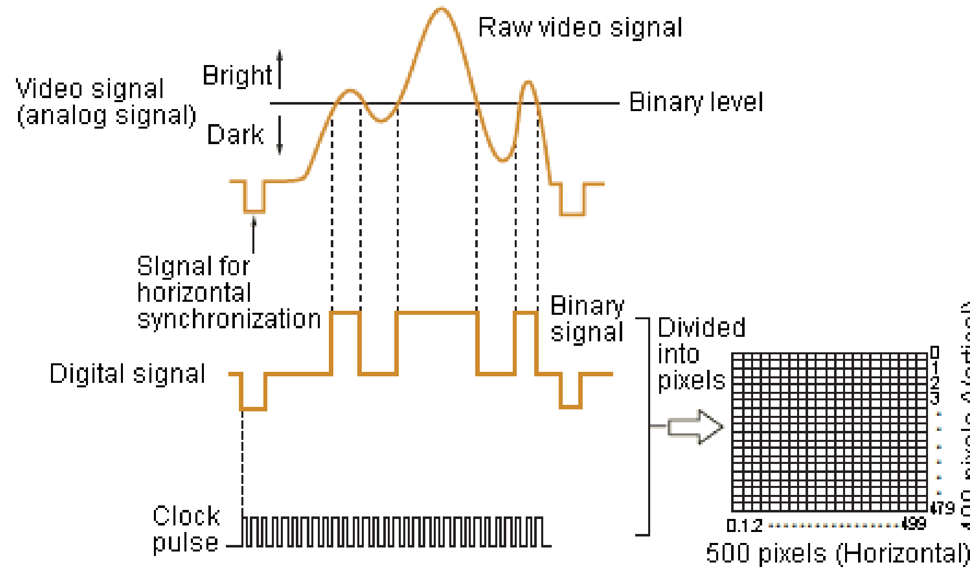
- The image sensor creates an analogue image from the optical image in the image plane:

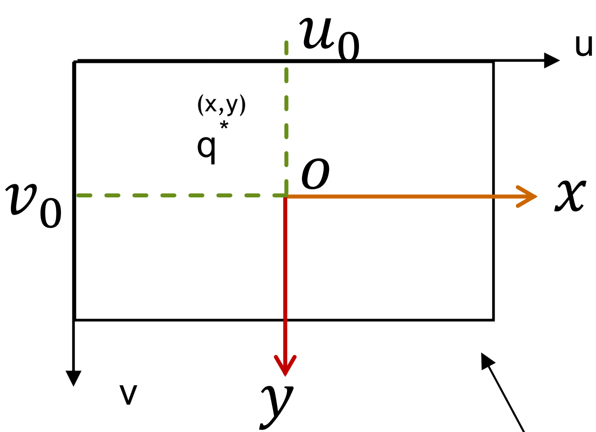


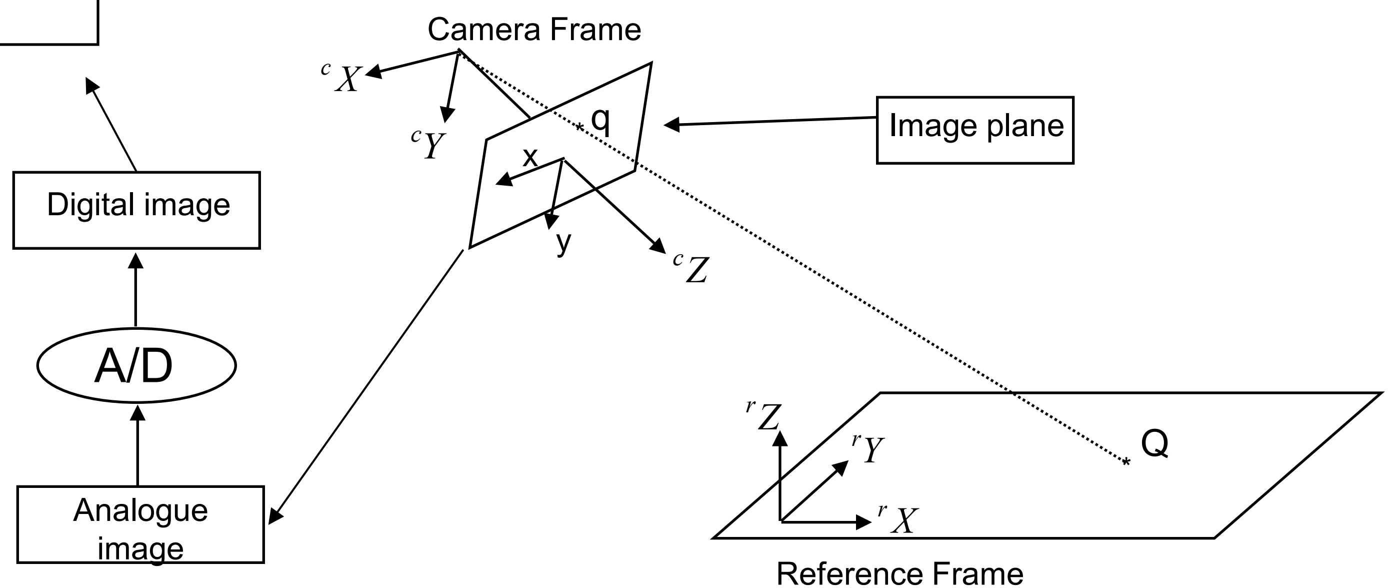


Step 6 of Proof:

- The analogue image produced at the image plane is digitized into the corresponding digital image:





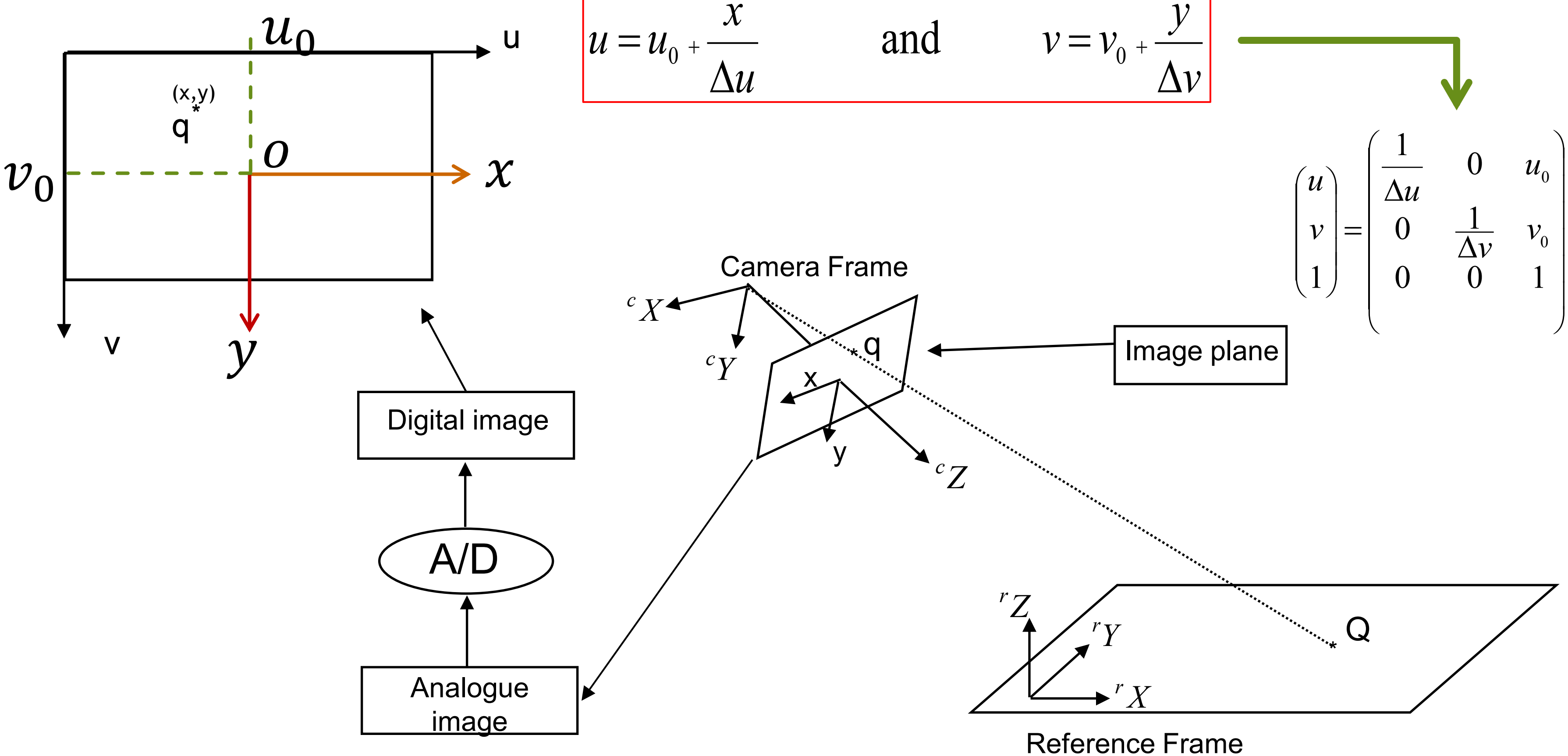


Step 7 of Proof:

- The coordinates (x, y) in image plane can be converted into the index coordinates (u, v) inside image matrix:

$$u = u_0 + \frac{x}{\Delta u} \quad \text{and} \quad v = v_0 + \frac{y}{\Delta v}$$

$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} \frac{1}{\Delta u} & 0 & u_0 \\ 0 & \frac{1}{\Delta v} & v_0 \\ 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$



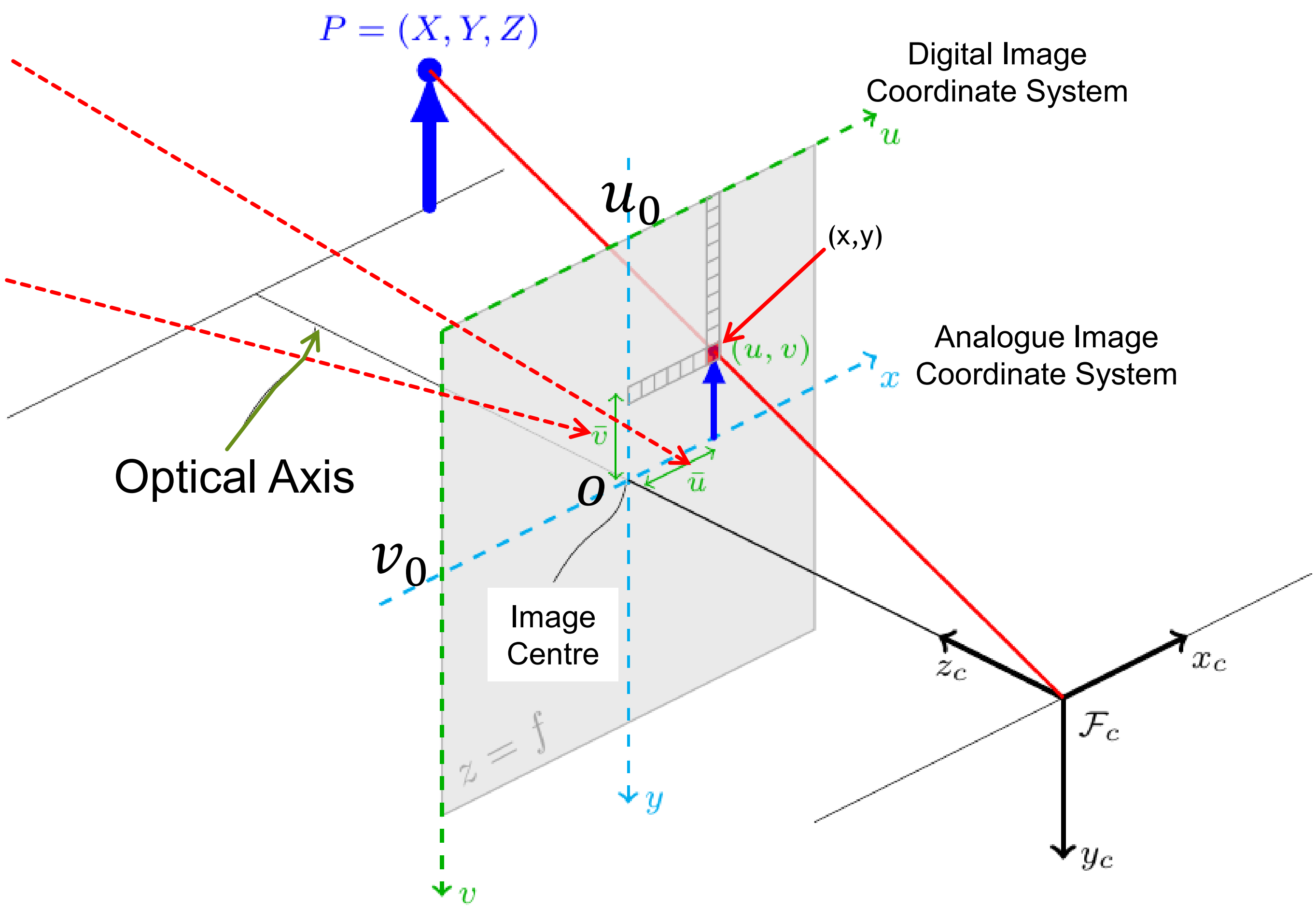
Further Detail of Proof …

$$u = u_0 + \bar{u} = u_0 + \frac{x}{\Delta u}$$

$$v = v_0 + \bar{v} = v_0 + \frac{y}{\Delta v}$$

$$\Updownarrow$$

$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} \frac{1}{\Delta u} & 0 & u_0 \\ 0 & \frac{1}{\Delta v} & v_0 \\ 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} x \\ y \\ 1 \end{pmatrix}$$



Both sides can be multiplied by s

Step 8 of Proof:

- The coordinates (X, Y, Z) in reference frame can be related to the coordinates (x, y) in image plane:

$$\begin{bmatrix} {}^{c}X \\ {}^{c}Y \\ {}^{c}Z \\ 1 \end{bmatrix} = {}^{c}H_{r} \bullet \begin{bmatrix} {}^{r}X \\ {}^{r}Y \\ {}^{r}Z \\ 1 \end{bmatrix}$$

$$\begin{pmatrix} s \bullet x \\ s \bullet y \\ s \end{pmatrix} = \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \bullet \begin{pmatrix} {}^{c}X \\ {}^{c}Y \\ {}^{c}Z \\ 1 \end{pmatrix}$$

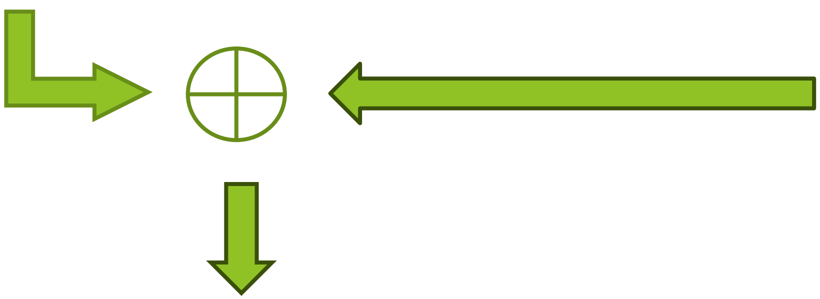
$${}^{c}H_{r} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{pmatrix} s \bullet x \\ s \bullet y \\ s \end{pmatrix} = \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} {}^{r}X \\ {}^{r}Y \\ {}^{r}Z \\ 1 \end{pmatrix}$$

Step 9 of Proof:

- The coordinates (X, Y, Z) in reference frame can further be related to the coordinates (u, v) in image matrix:

$$\begin{pmatrix} s \bullet x \\ s \bullet y \\ s \end{pmatrix} = \begin{pmatrix} f & 0 & 0 & 0 \\ 0 & f & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} {}^{r}X \\ {}^{r}Y \\ {}^{r}Z \\ 1 \end{pmatrix}$$



$$\begin{pmatrix} s \bullet u \\ s \bullet v \\ s \end{pmatrix} = \begin{pmatrix} \frac{1}{\Delta u} & 0 & u_0 \\ 0 & \frac{1}{\Delta v} & v_0 \\ 0 & 0 & 1 \end{pmatrix} \bullet \begin{pmatrix} s \bullet x \\ s \bullet y \\ s \end{pmatrix}$$

$$\begin{pmatrix} s \bullet u \\ s \bullet v \\ s \end{pmatrix} = \begin{pmatrix} \frac{f}{\Delta u} & 0 & u_0 & 0 \\ 0 & \frac{f}{\Delta v} & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} {}^{r}X \\ {}^{r}Y \\ {}^{r}Z \\ 1 \end{pmatrix}$$

Step 10 of Proof:

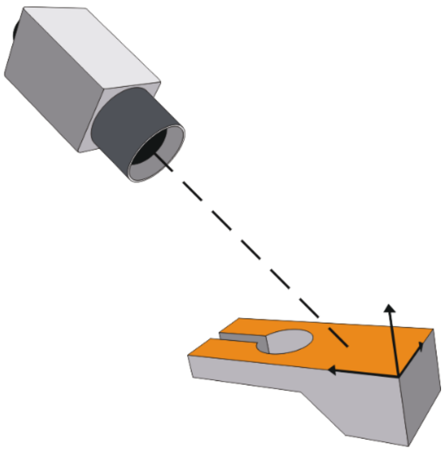
- Then, we obtain the equation of camera's forward projection:

$$\begin{pmatrix} s \bullet u \\ s \bullet v \\ s \end{pmatrix} = \begin{pmatrix} \frac{f}{\Delta u} & 0 & u_0 & 0 \\ 0 & \frac{f}{\Delta v} & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} {}^rX \\ {}^rY \\ {}^rZ \\ 1 \end{pmatrix}$$

Camera's Forward Projection Matrix

$$\begin{pmatrix} s \bullet u \\ s \bullet v \\ s \end{pmatrix} = C_{3\times4} \bullet \begin{pmatrix} {}^rX \\ {}^rY \\ {}^rZ \\ 1 \end{pmatrix}$$

Equation of Camera's Forward Projection

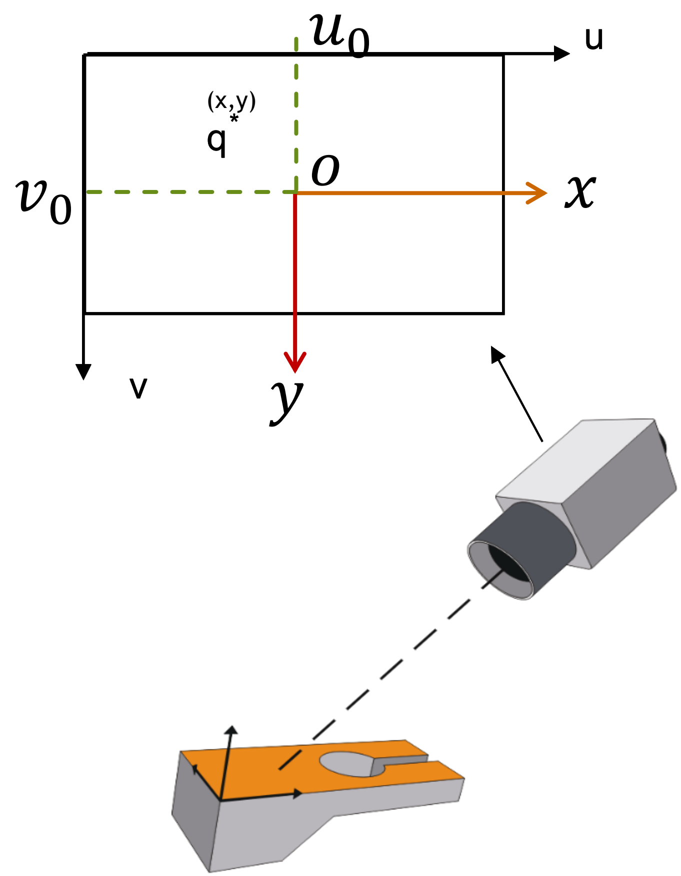


Step 11 of Proof:

- If we let Z coordinate to be zero, then we obtain the equation of monocular vision's forward projection:

$$\begin{pmatrix} s \bullet u \\ s \bullet v \\ s \end{pmatrix} = C_{3\times4} \bullet \begin{pmatrix} {}^{r}X \\ {}^{r}Y \\ 0 \\ 1 \end{pmatrix}$$

$$\begin{pmatrix} s \bullet u \\ s \bullet v \\ s \end{pmatrix} = \mathrm{D}_{3\times3} \bullet \begin{pmatrix} {}^{r}X \\ {}^{r}Y \\ 1 \end{pmatrix}$$



Equation of Monocular Vision's Forward Projection

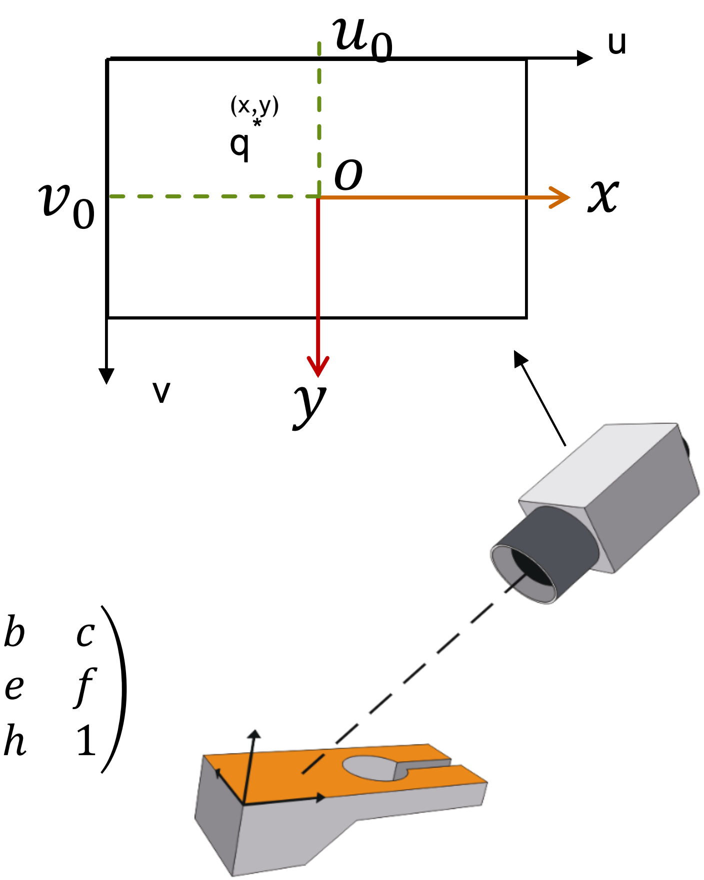
Step 12 of Proof:

- By inverting matrix D, then we obtain the equation of monocular vision's inverse projection:

$$\begin{pmatrix} s \bullet u \\ s \bullet v \\ s \end{pmatrix} = \mathrm{D}_{3\times3} \bullet \begin{pmatrix} {}^{r}X \\ {}^{r}Y \\ 1 \end{pmatrix}$$

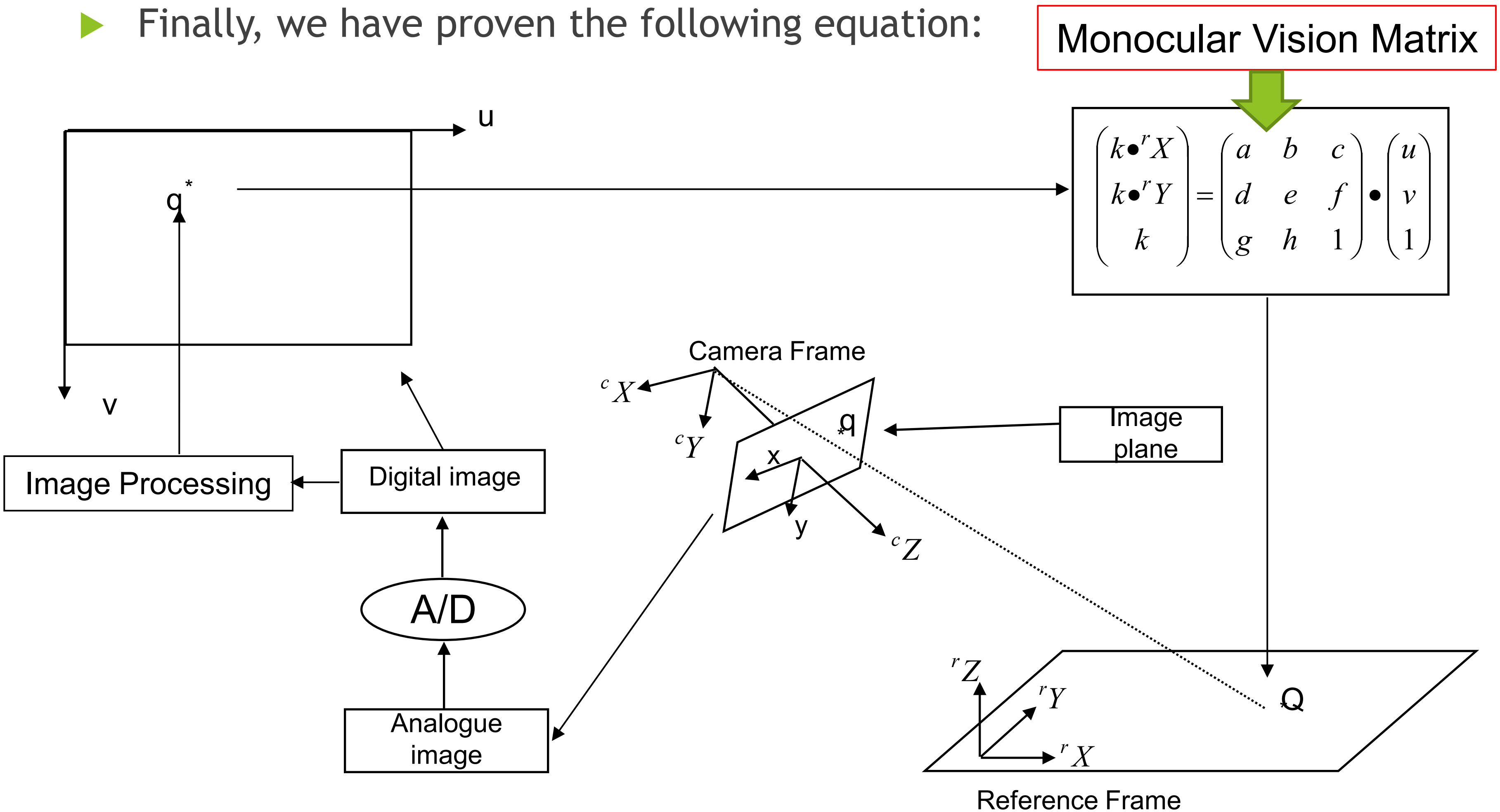
$$\begin{pmatrix} k \bullet {}^{r}X \\ k \bullet {}^{r}Y \\ k \end{pmatrix} = \mathrm{M}_{3\times3} \bullet \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} \quad \text{with} \quad M_{3\times3} = \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & 1 \end{pmatrix}$$

Equation of Monocular Vision's Inverse Projection



Summary of Proved Result:

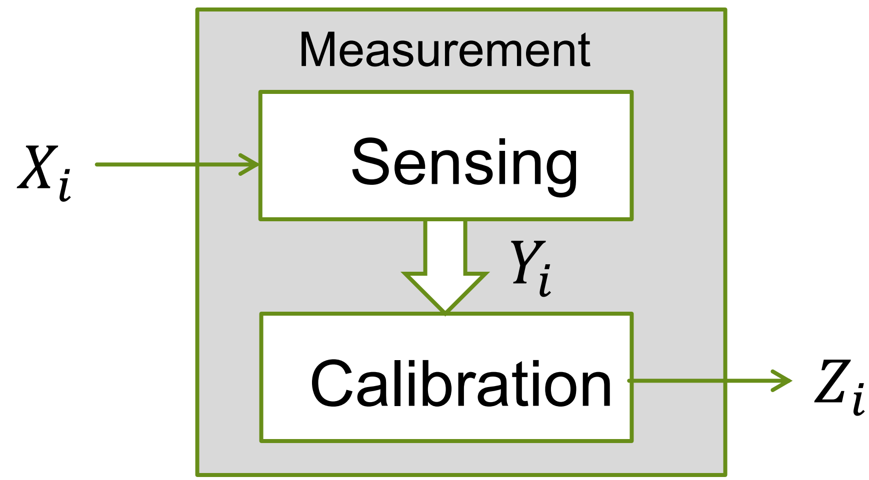
- Finally, we have proven the following equation:

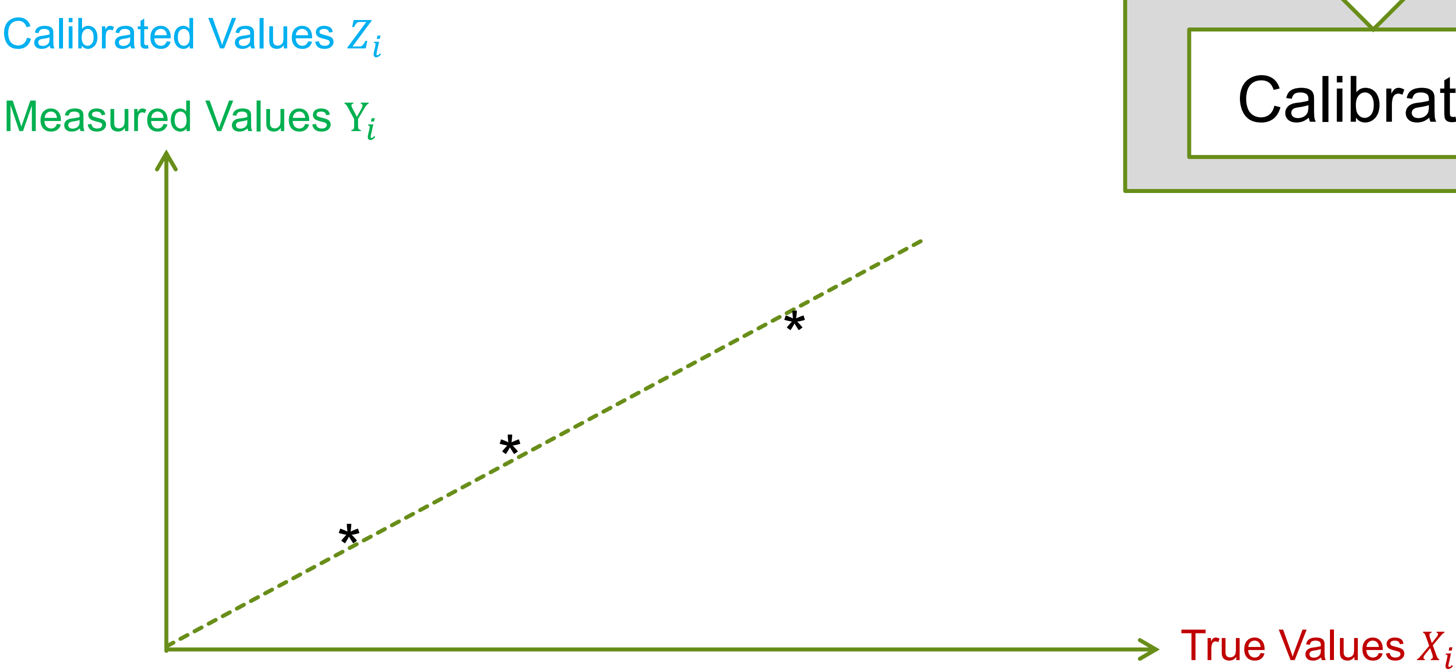


$$\begin{pmatrix} k \bullet {}^{r}X \\ k \bullet {}^{r}Y \\ k \end{pmatrix} = \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & 1 \end{pmatrix} \bullet \begin{pmatrix} u \\ v \\ 1 \end{pmatrix}$$

Remember to Do Calibration

- Curve fitting for calibration:
  - Yi is produced by Xi
  - Zi is computed from Yi
  - Zi must be equal to Xi

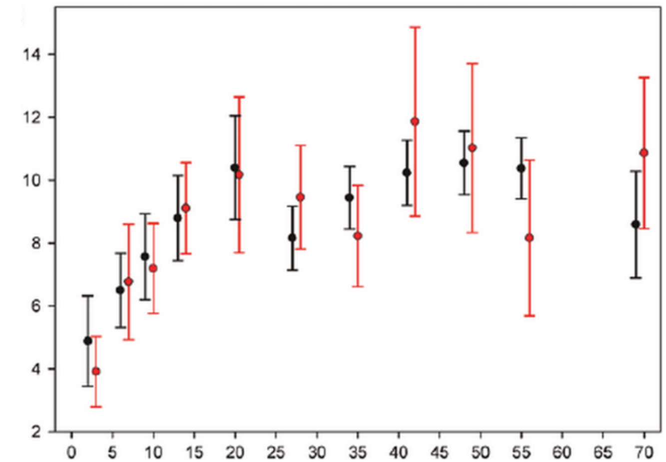


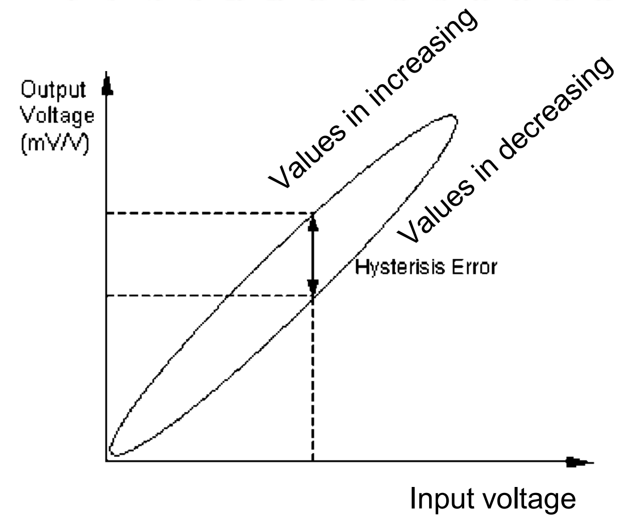


Remember to Do Error Analysis

- Systematic error = mean value – true value
- Repeatability error = value with maximum error – mean value
- Accuracy = value with minimum error – mean value
- Hysteresis error = |measured value in increasing – measured value in decreasing|

For each true value, we can do error analysis

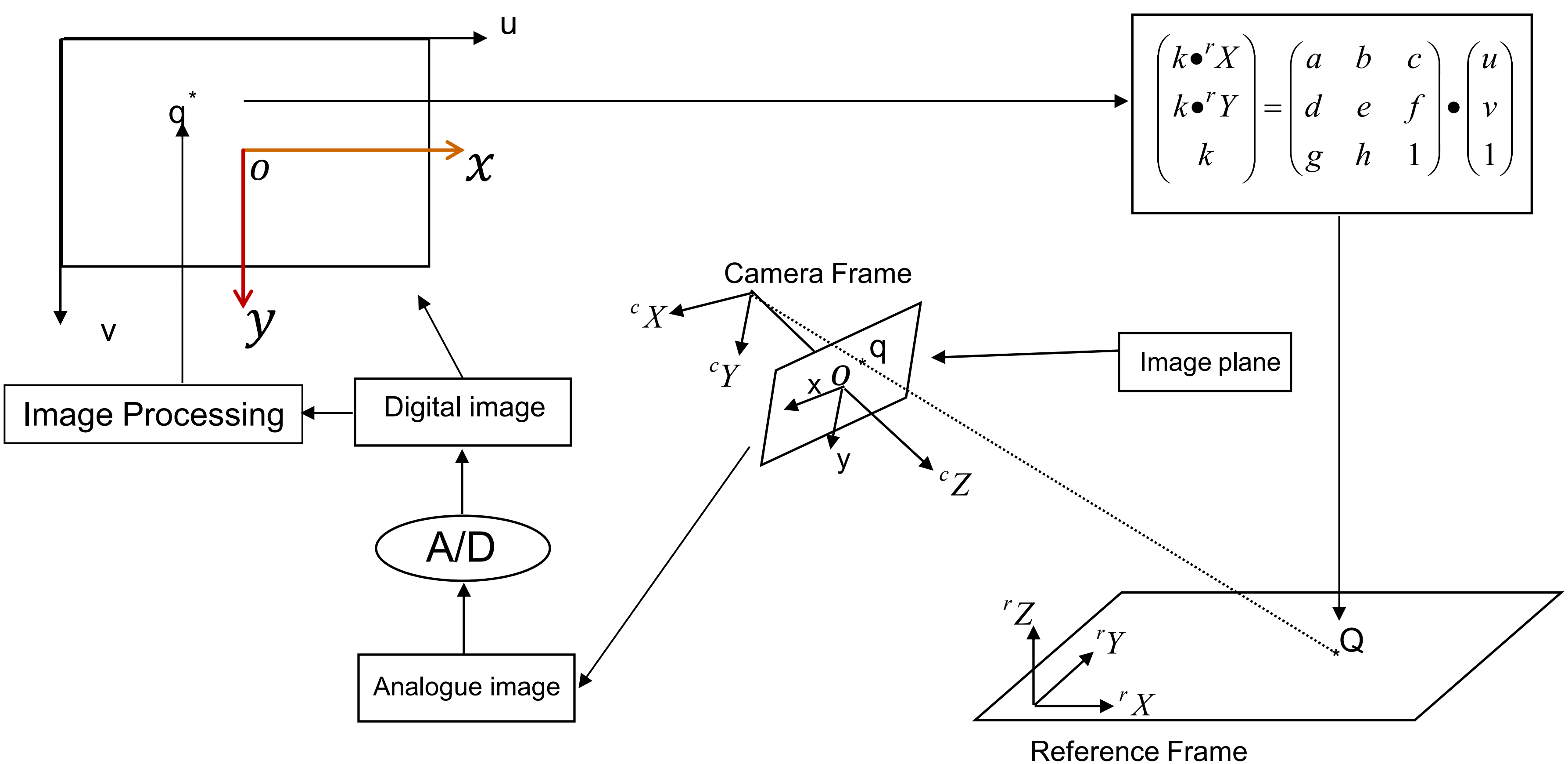




Discussion: How to calibrate monocular vision?

- How to determine the coefficients inside the monocular vision matrix?

Use of Four or More Pairs of {(u,v), (X,Y)}



$$\begin{pmatrix} k\bullet {}^rX \\ k\bullet {}^rY \\ k \end{pmatrix} = \begin{pmatrix} a & b & c \\ d & e & f \\ g & h & 1 \end{pmatrix} \bullet \begin{pmatrix} u \\ v \\ 1 \end{pmatrix}$$

Discussion: How to calibrate a camera?

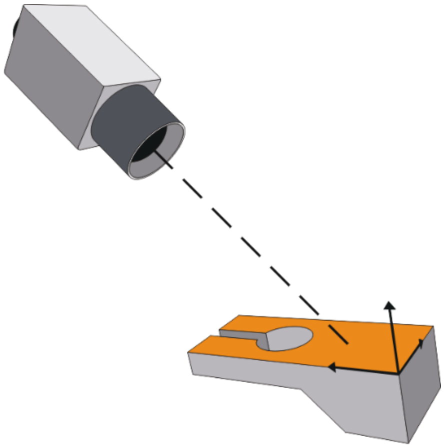
- How to obtain the intrinsic parameters $(\frac{f}{\Delta u}, \frac{f}{\Delta v}, u_0, v_0)$ of a camera?

$$\begin{pmatrix} s \bullet u \\ s \bullet v \\ s \end{pmatrix} = \begin{pmatrix} \frac{f}{\Delta u} & 0 & u_0 & 0 \\ 0 & \frac{f}{\Delta v} & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_x \\ r_{21} & r_{22} & r_{23} & t_y \\ r_{31} & r_{32} & r_{33} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{pmatrix} {}^rX \\ {}^rY \\ {}^rZ \\ 1 \end{pmatrix}$$

Camera's Forward Projection Matrix

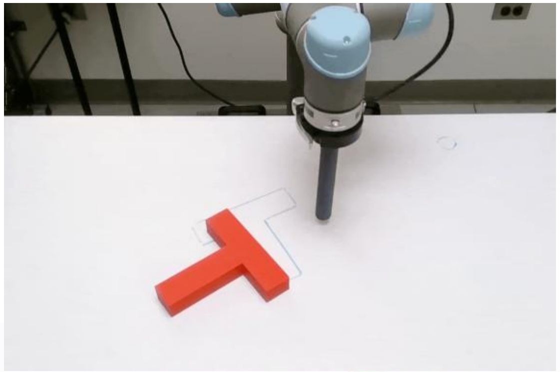
$$\begin{pmatrix} s \bullet u \\ s \bullet v \\ s \end{pmatrix} = C_{3\times 4} \bullet \begin{pmatrix} {}^rX \\ {}^rY \\ {}^rZ \\ 1 \end{pmatrix}$$

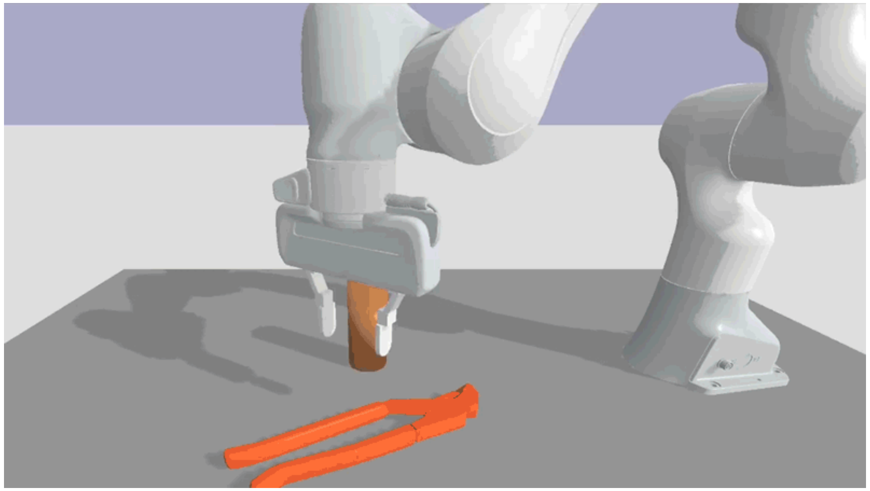
Equation of Camera's Forward Projection

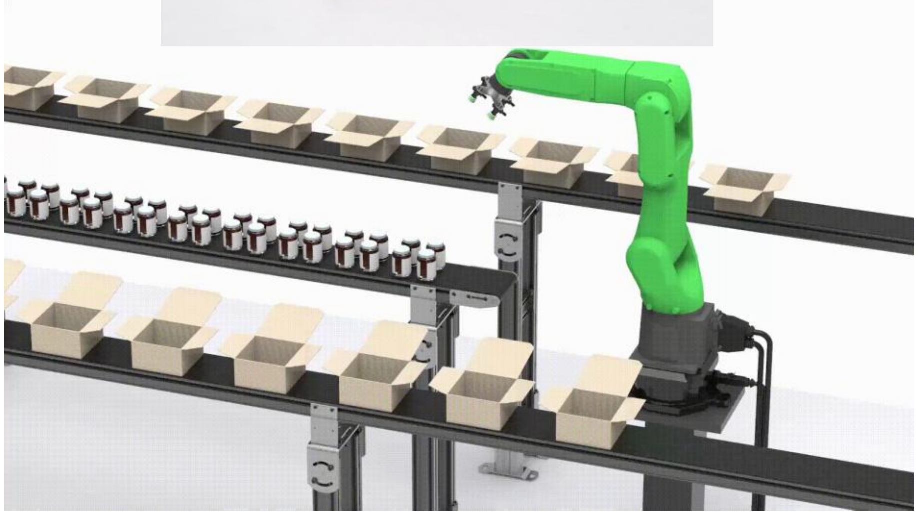


Summary

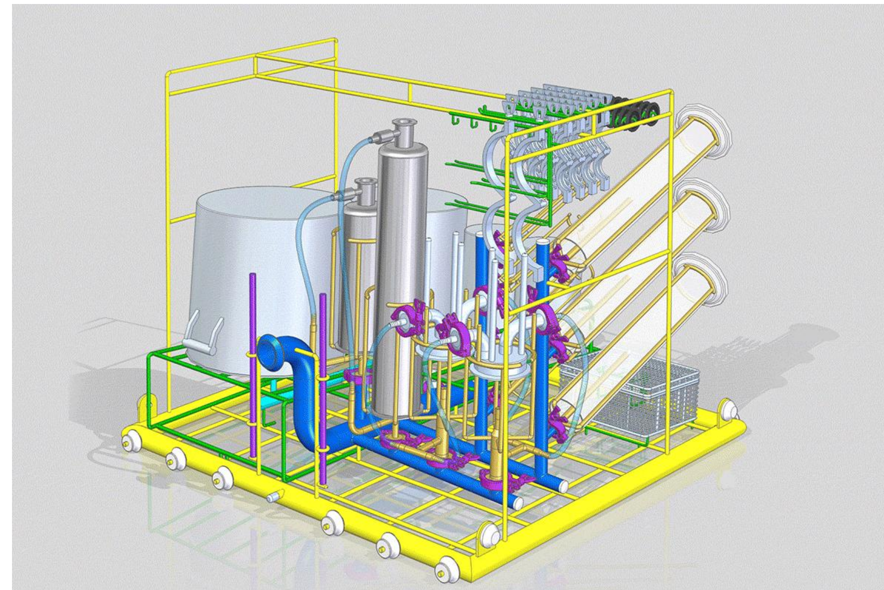
- Understanding of Geometry
- Computation of Geometry
- Measurement of Geometry







Summary of Module 5



- Lecture 1:
  - Measurement of Fluid Level
- Lecture 2:
  - Measurement of Flow Rate
- Lecture 3:
  - Measurement of Sound/Voice
- Lecture 4:
  - Measurement of Photometry
- Lecture 5:
  - Measurement of Geometry

"Ask not what your country can do for you – ask what you can do for your country," - John F. Kennedy

"Do not think that you are needy – think that you are needed in the world", - Manis Friedman

"Study will make you knowledgeable, resourceful, and hence more needed", - Xie Ming

Thank You for Listening!