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Terminology

Transducer – A device that converts a nonelectrical quantity into an electrical signal and vice versa

- **Sensor** – A device that converts a nonelectrical quantity into an electrical signal
    - An input transducer
    - Examples: pressure sensor, accelerometer

- **Actuator** – A device that converts an electrical signal into a nonelectrical quantity
    - An output transducer
    - Examples: motor, light bulb, electric heater

Measurand – the quantity being measured by the sensor (such as pressure or temperature)

Size

Macro – 2mm and larger (us: 6' = 1.8288m) – our world

Meso – 2mm down to 500μm (small fire ant is 2mm long) – her world

Micro – 500μm down to 0.5μm (paramecium is 100μm to 300μm long, human red blood cell has a 6μm to 8μm diameter)

Nano – 0.5μm down to 1nm (spherical influenza virus: 50nm to 120nm diameter with 10nm to 14nm spikes on surface)

Human Hair: ~100μm diameter

Modern Transistor: <100nm dimensions (TSMC has a 5 nm process)

MEMS: acronym for "Microelectromechanical Systems"

Definition: Any device or system partially or fully manufactured using microfabrication techniques

Microsensor: a sensor with at least one sub-mm physical dimension

MEMS Characteristics

(1) Typically based around a silicon substrate

(2) Typically use batch fabrication processing borrowed from microelectronics fabrication technology

Batch Fabrication: many devices fabricated in parallel

- Reduces Cost per Device

(3) Sometimes compatible with microelectronics fabrication

(4) But often not compatible with microelectronics fabrication

Sensor and Sensing Characteristics

(1) Accuracy – how correct the sensor readings are

(2) Precision – the resolution of the sensor

(3) Range – defines the minimum and maximum measurand levels that can be sensed

(4) Minimum sampling rate – must be at least twice the highest frequency present in the data to avoid aliasing

(5) Minimum sample collection period – must be long enough to capture any trends present in the data (see example on next page)

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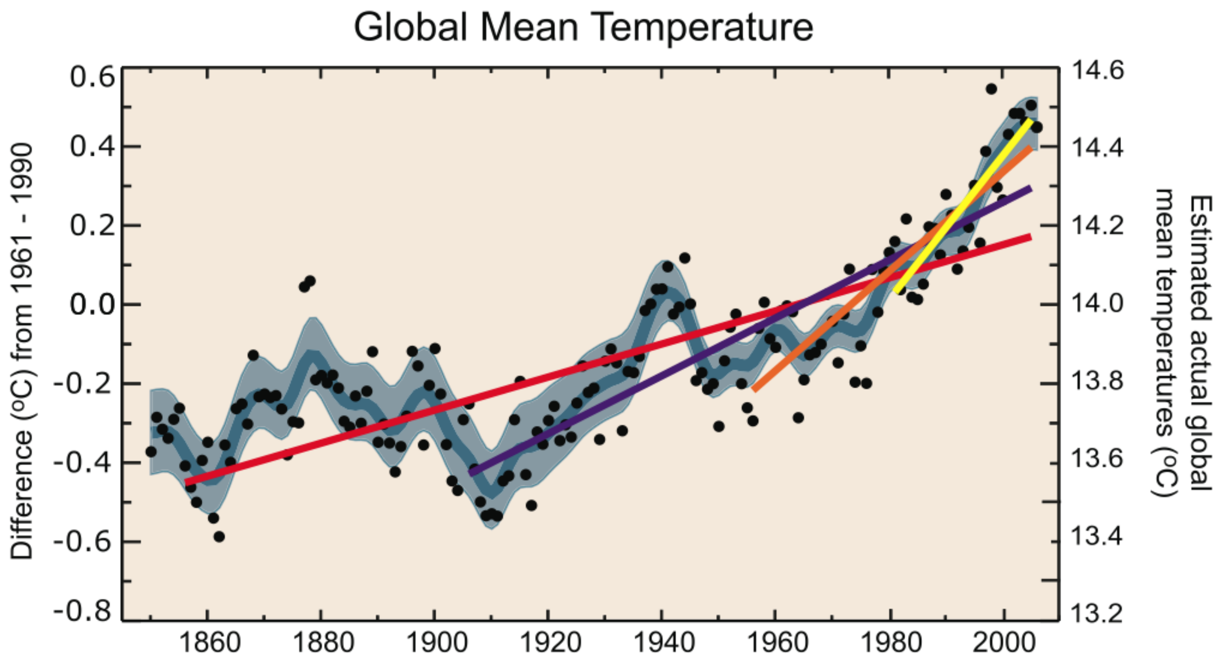
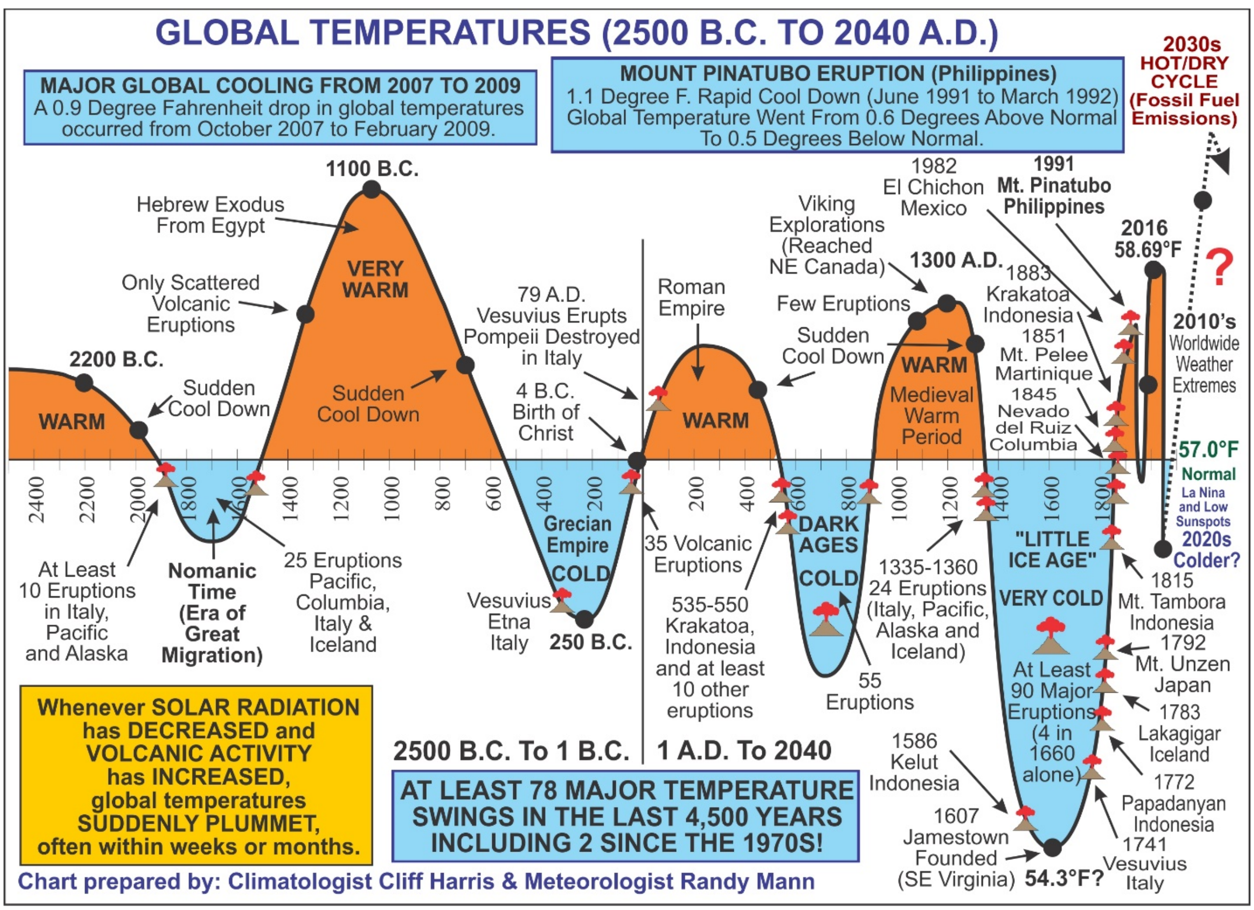


https://wg1.ipcc.ch/publications/wg1-ar4/faq/wg1_faq-3.1.html



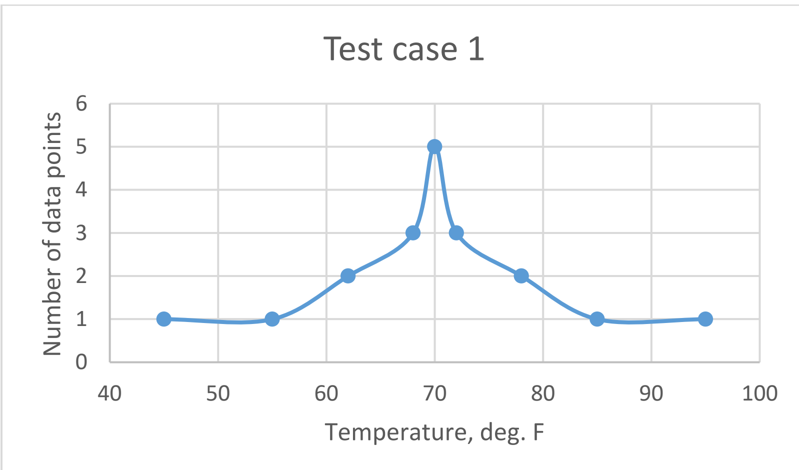
http://www.longrangeweather.com/global_temperatures.htm

Statistics of Sensor Data

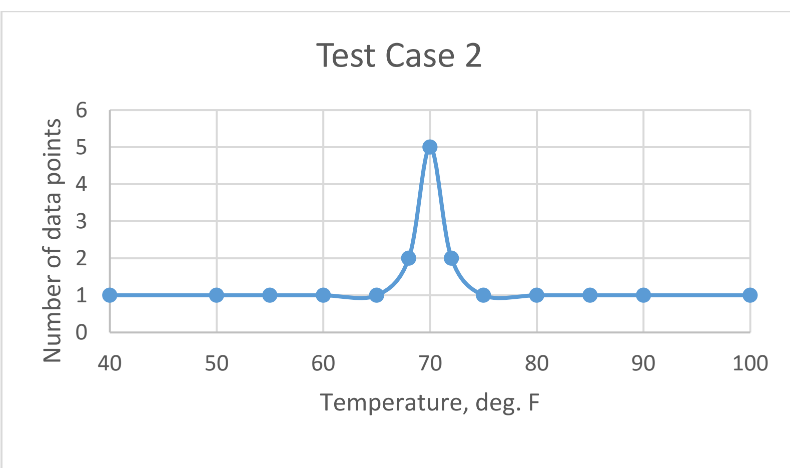
(1) Average (mean) – sum total of the values divided by the number of values of the data set

(2) Median – the middle value of the data set. Same number of data points above and below the median.

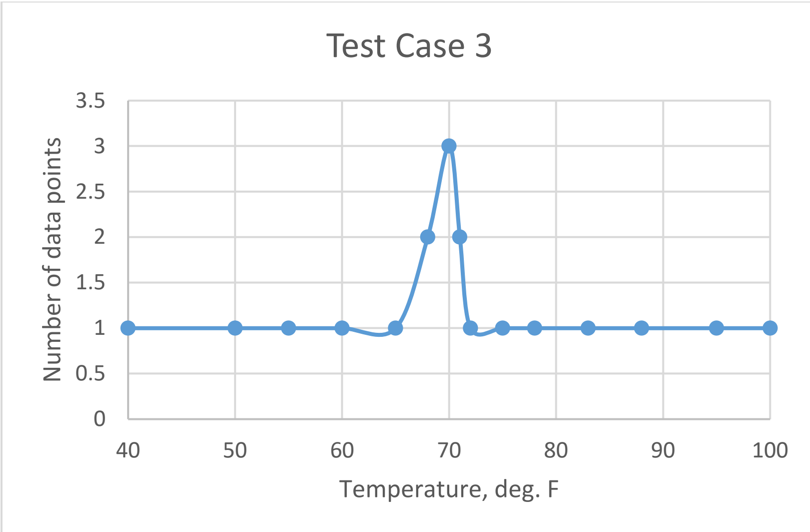
(3) Standard Deviation (σ) – a measure of the amount of variation in a set of data values. 68.27% of the data set lies within ± 1 σ. 95.4% within ± 2 σ.



Symmetrical Distribution
Average = 70 F
Median = 70 F
σ = 10.2 F



Average = 70 F
Median = 70 F
σ = 13.2 F



Skewed Distribution (most data points are below the average)
Average = 71 F
Median = 70 F
σ = 14.1 F

Note: in the case above, you are more likely to have data points below the average: this is then the "normal" case. But you wouldn't know that from just comparing data to the average value…

Scaling

The relative importance of physical quantities and forces varies with size

Dimensions:

- Length: $L \propto L$
- Surface area: $A \propto L^2$
- Volume: $V \propto L^3$

Therefore physical quantities proportional to volume decrease faster than quantities proportional to length as size is reduced

Example: a 50% reduction in x, y, z: $L_{new} = 1/2\ L_{old}$

$V_{new} = 1/8\ V_{old}$

Comparison of Macro and Micro Worlds:

Macro World
- Inertial forces important
- Electromagnetic actuators more efficient
- Responds slowly to environmental temp change
- Fluidic forces less important

Micro World
- Inertial forces less important
- Electrostatic actuators more efficient
- Responds quickly to environmental temp change
- Fluidic forces important
- Friction, Van der Waals forces, capillary action important

Examples of Microsensors:

Mechanical
- flow rate
- proximity
- stress/strain
- pressure
- acceleration
- angular rate (gyroscope)

Thermal
- PTAT
- thermistor
- thermocouple

Chemical
- humidity
- gas detection
- moisture content

Acoustic
- microphone

Radiation
- micro-antenna
- photodetectors
- photovoltaic
- x-ray
- magnetic field
- electric field

Biological
- DNA analysis
- contagion (E. coli, anthrax, Covid…)

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Introduction to Microfabrication

Fabrication processes used to fabricate integrated circuits and most MEMS devices

For a more detailed study of microfabrication:

(1) ELEC 5730/6730 Microelectronic Fabrication

(2) ELEC 5820/6820 MEMS

Micromachining: A term used to describe the process of fabricating MEMS or micromachined devices

Silicon (Si)

The base material for microfabrication: Substrate

Si is the most common substrate material

Si: hard, brittle semiconductor material

Single crystal Si is grown into ingots and sawn/polished to produce thin wafers – used as substrates

(1) Example Si wafer: 100mm diameter and 500µm thick
(2) Diamond crystal structure, different crystalline planes: (100), (110), (111): with different properties
(3) Can be doped n- or p-type: can be high or low resistivity

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Other Materials in Si Based MEMS:

(1) **SiO_2**: grown onto exposed Si though a process called <u>oxidation</u>
Typically less than 1μm thick

(2) **Polysilicon**: polycrystalline Si deposited onto a substrate
Up to a few μm thick

(3) **Metallization**: deposited layers or "films" of metal (Al, Ti, Au, Cr…)
<u>Thin films</u>: up to few μm thick
<u>Thick films</u>: greater thicknesses (up to 100s of μm thick)

(4) **Non-metallic layers:**
Silicon nitride (SiN)
Various polymers
Diamond coatings
Epoxies

Materials in Non-Si Based MEMS:

(1) SiC (silicon carbide)
(2) Diamond
(3) Glasses
(4) Ceramics
(5) Polymers / plastics
(6) PCB laminates
(7) Metals
(8) 3D printed materials

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2 Basic Processing Types:

(1) **<u>Additive Process</u>:** The deposition of a layer or volume of a material

(2) **<u>Subtractive Process</u>:** The removal of some amount of a material

Basic Microfabrication Processing Terms

Patterning: The process of transferring a designed pattern into a physical layer

Photolithography: A process of patterning a light-sensitive organic layer called photoresist (PR)

Photolithography mask: a transparent glass plate with an opaque pattern (plated Cr) on one side that the designer desires to transfer to the substrate or thin layer

Photolithography Process

(1) Clean wafer
(2) Spin coat on a uniform layer of PR
(3) "Soft bake" to dry the PR
(4) Align the photolithography mask to the wafer and place it in contact with the PR layer – using a mask aligner
(5) Expose it to UV light for a set time (only areas not covered by the Cr pattern are exposed
(6) Develop the PR in a liquid developer
    Exposed PR removed – "positive PR"
    Unexposed PR removed – "negative PR"
(7) "Hard Bake" to harden the remaining PR

After Photolithography

(1) Affect the exposed layer beneath the PR
(2) Remove the remaining PR (solvents, O_2 plasma "ashing")

Etching: the selective removal of a material

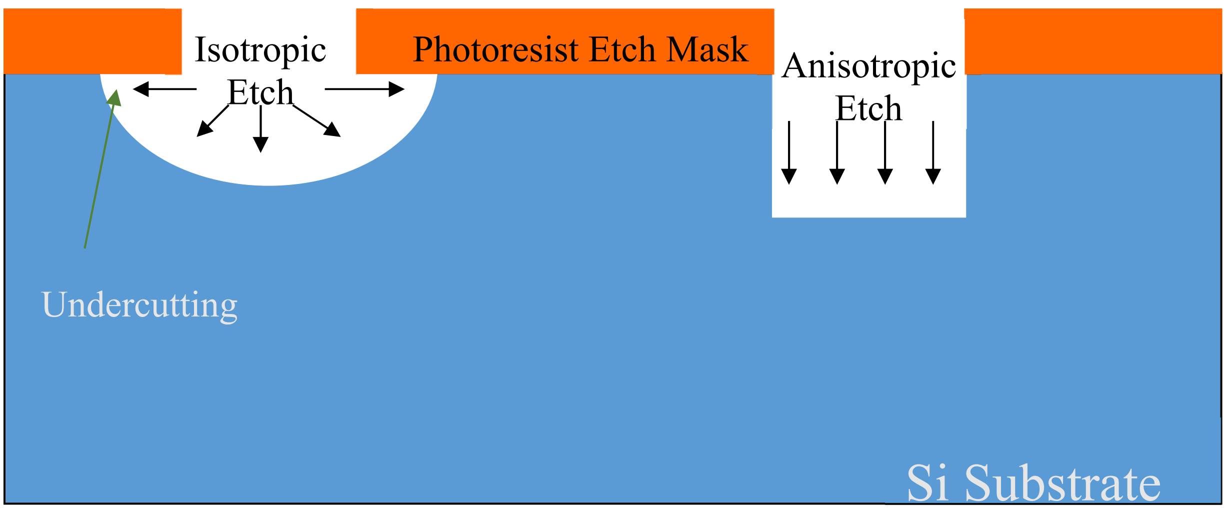
Selectivity: The properties of an etchant with regard to what it will and will not etch. Typically want a high selectivity.

<u>PR Etch Mask</u>: A patterned layer of PR used to only expose some areas for etching

<u>Isotropic Etch</u>: Equal etching effect in all directions

<u>Anisotropic Etch</u>: Unequal etching effect in different directions

<u>Undercutting</u>: Where the etch process undercuts the PR or other etch mask



There are <u>no</u> purely anisotropic etch processes.

Aspect Ratio: Ratio of depth to width of an etched feature.
Example: 10:1 - 10µm down, 1µm over