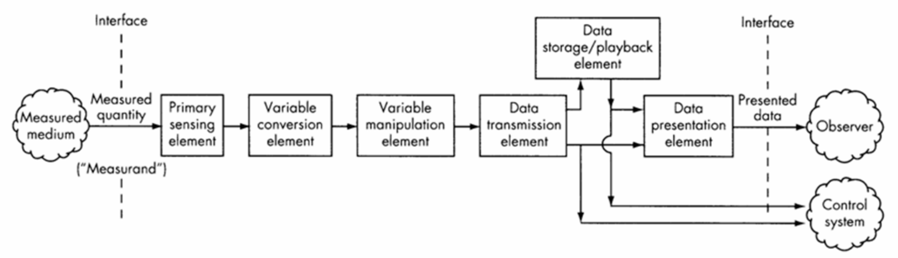
General Concepts of Measurement Systems

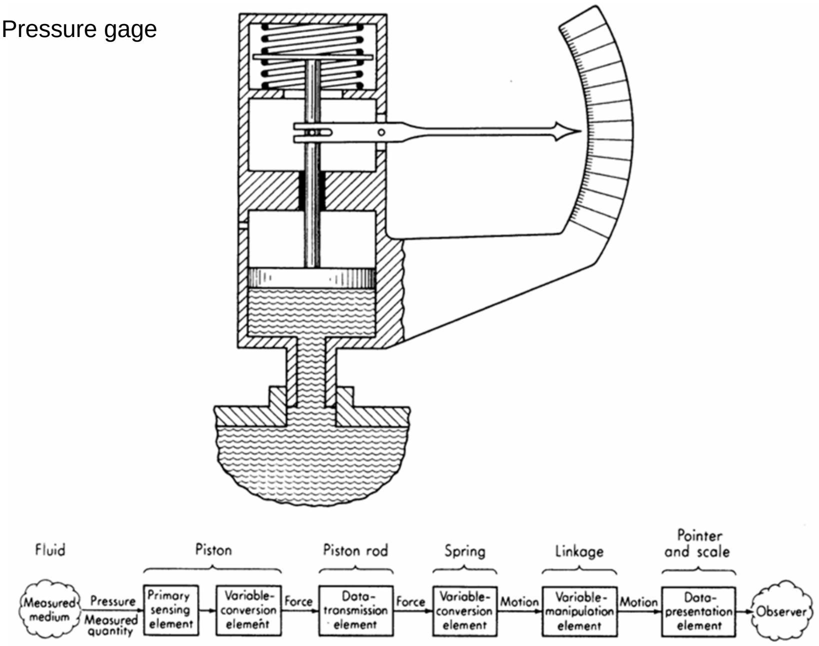
Functional Elements of an Instrument

- An instrument always extracts some energy from the measured medium
- The measured quantity is always disturbed
- It is impossible to make a perfect measurement
- Good instruments are designed to minimize this effect

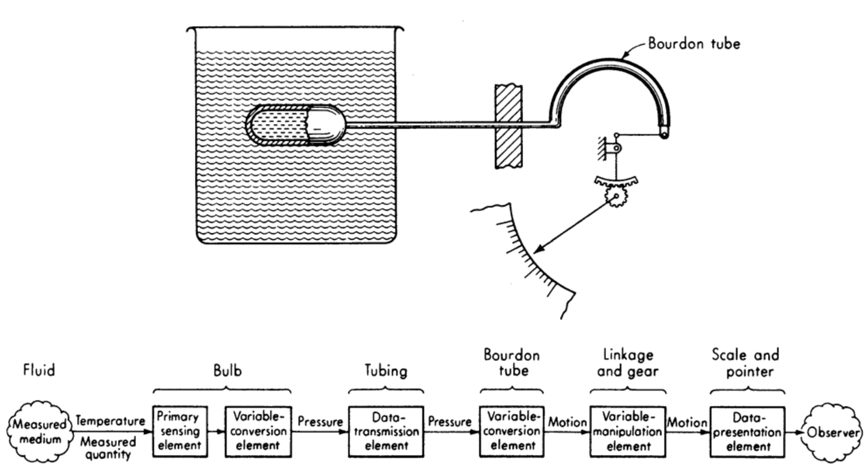
Functional elements of an instrument



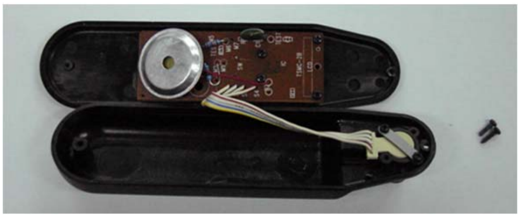
Pressure gage



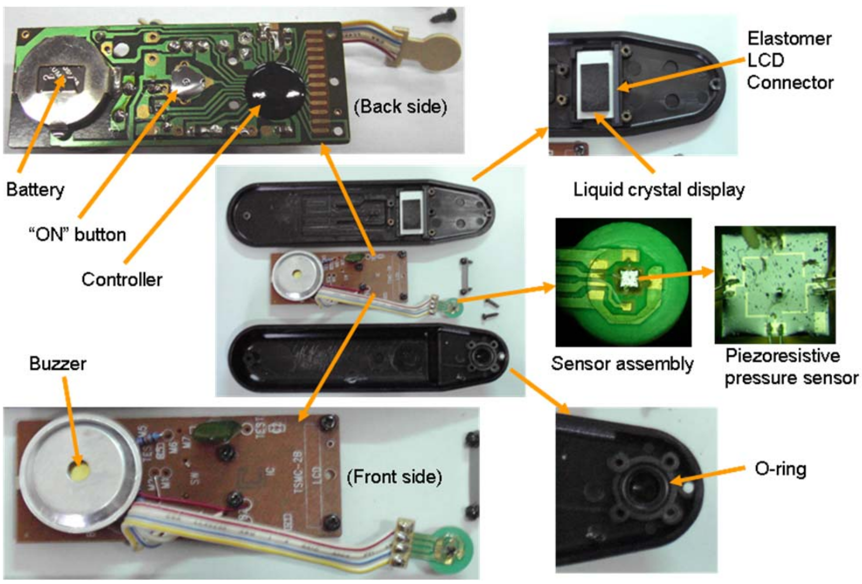
Pressure thermometer



Example: A tire pressure gage



- Primary sensing element: Silicon diaphragm
- Variable-conversion element: Wheatstone bridge circuit
- Variable-manipulation element: Electronic amplifier and Field Programmable Gate Array (FPGA)
- Data-transmission element: Printed circuit board (PCB)
- Data presentation element: Liquid crystal display (LCD)
- Data storage/playback element: (Not applicable)



Active and passive transducers

- Transducer: A device that converts one type of energy to another.
  A device that converts a signal from one form to another.

  轉換器；換能器 ；轉能器；傳感器

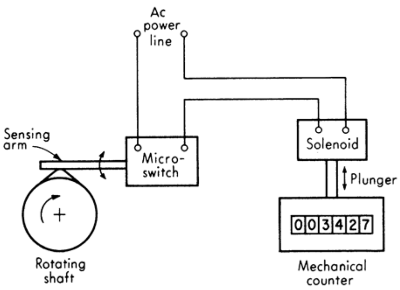
- Passive transducer: A transducer operates without the need for an external power source other than the input signal.

  被動轉換器 (換能器 ；轉能器)

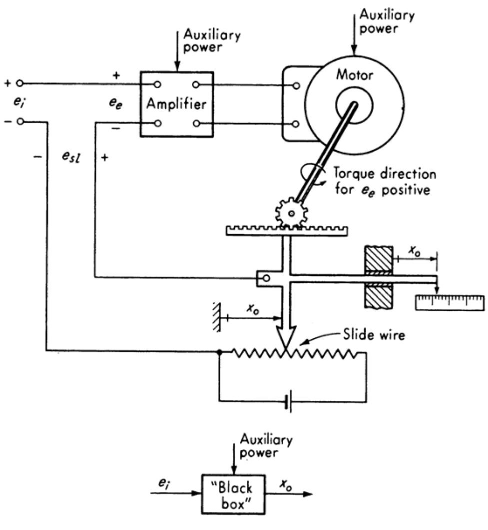
- Active transducer: A transducer that needs additional power sources to convert the input signal into the output information.

  台灣： 主動轉換器
  大陸： 有效換能器，有源換能器

Digital revolution counter



Instrument servomechanism



Analog and digital modes of operation

- Analog (analogue) signal: Any (time) continuous signal where some (time varying) feature of the signal is a representation of some other (time varying) quantity.

  台灣： 類比信號，大陸：模擬信號

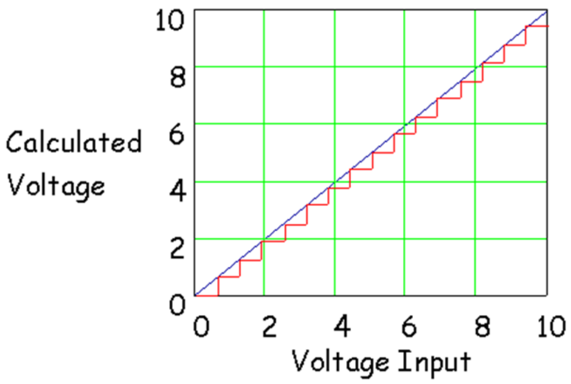
- Analog is usually thought of in an electrical context, however mechanical and other systems may also convey analog signals.
- Analog signal differs from a digital signal in that small fluctuations in the signal are meaningful.
- Digital signal: Digital representations of discrete(-time) signals, which are often derived from analog signals.

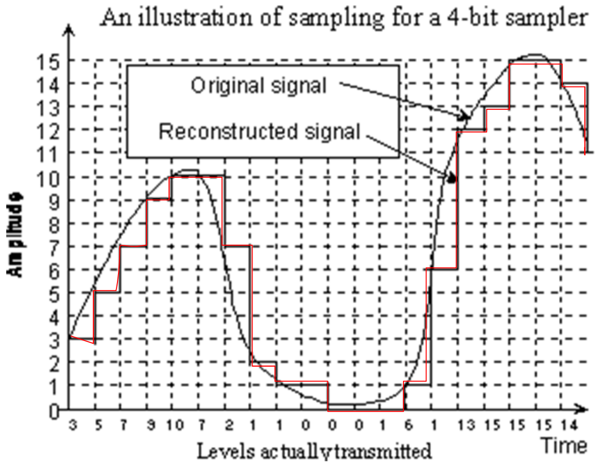
  台灣： 數位信號，大陸：數字信號

- Analog-to-digital converter (ADC, A/D or A to D): A device which converts continuous signals to discrete digital numbers. The reverse operation is performed by a digital-to analog converter (DAC).

  台灣： 類比數位轉換器，大陸：模數轉換器

A 4-bits A/D converter





Null and deflection methods

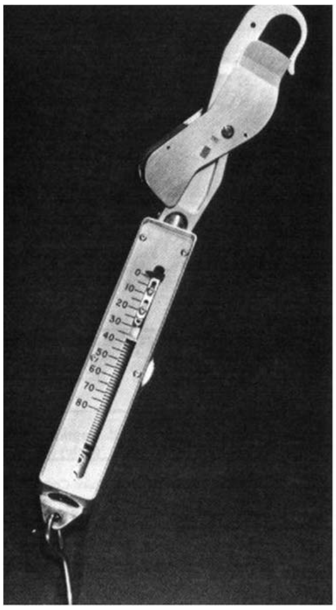
Deflection-type device

- The measured quantity produces some physical effect that engenders a similar but opposing effect related to some variable that can be directly observed by some human sense.
- The opposing effect increases until a balance is achieved, at which point the deflection is measured.

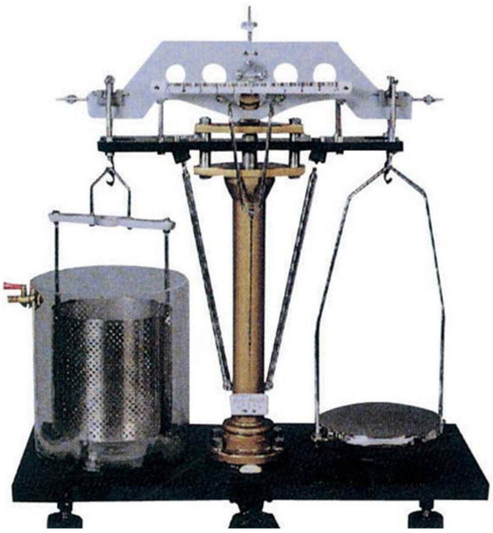
Null-type device

- The device attempts to maintain zero deflection by suitable application of an effect opposing that generated by the measured quantity.
- A detector of unbalance and a means of restoring balance are necessary.
- The unknown quantity is compared with the standard directly.
- The detector need not be calibrated since it must detect only the presence and direction of unbalance, but not the amount.
- The dynamic measurement can be achieved by use of automatic balancing devices.

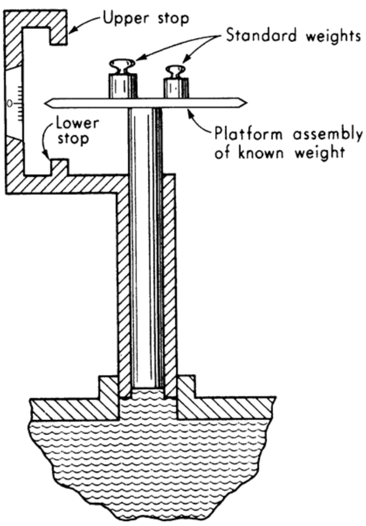
Spring balance



Mechanical hydrostatic balance



Deadweight pressure gage



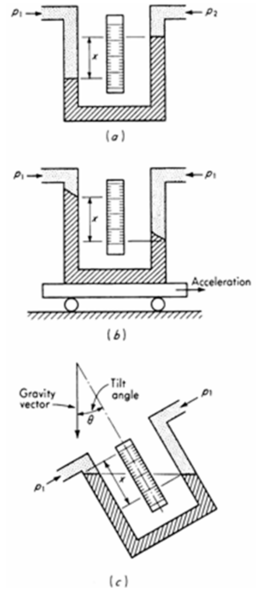
Input-output configuration

Example: A manometer

The desired input:
Pressure difference to be measured

The interfering input:
Acceleration and tilt effect cause an output even though the differential pressure might be zero.

The modifying input:
Ambient temperature and gravitational force lead to the modification in the scale factor.



Correction for interfering and modifying inputs

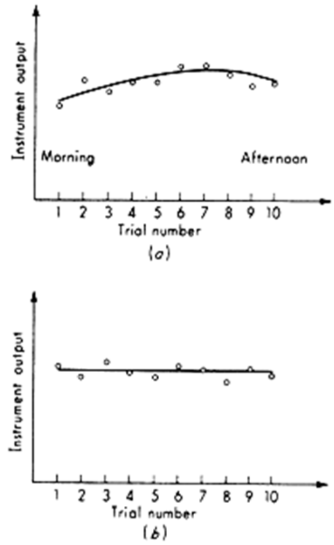
- Method of inherent insensitivity
- Method of high-gain feedback
- Method of calculated output corrections
- Method of signal filtering
- Method of opposing inputs

Static characteristics

Static calibration

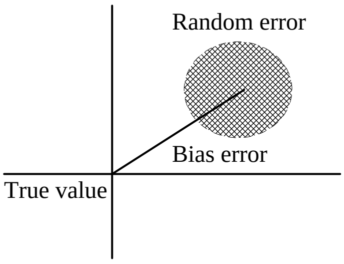
Necessary steps for calibration:

- Examine the construction of the instrument, and identify and list all the possible inputs.
- Decide which of the inputs will be significant in the application for which the instrument is to be calibrated.
- Procure apparatus that will allow you to vary all significant inputs over the ranges considered necessary.
- By holding some inputs constant, varying others, and recording the output, develop the desired static input-output relations.



Accuracy, precision, and bias

- Error: the difference between the measurement and the corresponding true value, which is taken to be positive if the measurement is greater than the true value.
- Accuracy: the degree of conformity of a measured quantity to its true value.
- Precision: the degree to which further measurements show the same or similar results. Also called reproducibility or repeatability.
- Bias error: a systematic error that offsets the average estimate from the true value. Bias error can be corrected for if known.
- Random error: the spread of the estimates around the average.



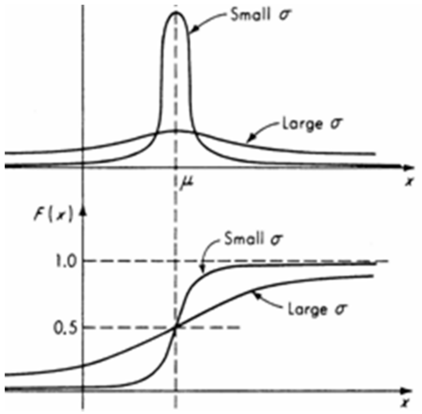
Examples:

High **accuracy**, but low **precision**

High **precision**, but low **accuracy**

Random error

Gaussian distribution



μ = Mean value

σ = Standard deviation

68% of the readings lie within $\pm 1\sigma$ of μ

95% of the readings lie within $\pm 2\sigma$ of μ

99.7% of the readings lie within $\pm 3\sigma$ of μ

Least square calibration curves

$\overline{X}$ = Sampled mean value

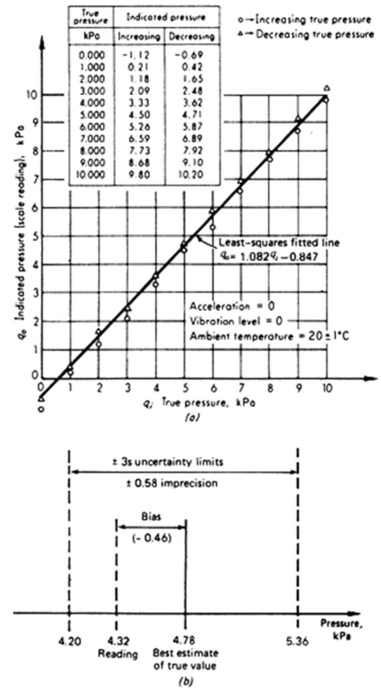
s = Sampled standard deviation

$$\overline{X} \equiv \frac{\sum_{i=1}^{N} X_i}{N}$$

$$s \equiv \left[\frac{\sum_{i=1}^{N} (X_i - \overline{X})^2}{N-1} \right]^{1/2}$$

X_i = individual reading

N = total number of readings



True pressure	Indicated pressure	
kPa	Increasing	Decreasing
0.000	-1.12	-0.69
1.000	0.21	0.42
2.000	1.18	1.65
3.000	2.09	2.48
4.000	3.33	3.62
5.000	4.50	4.71
6.000	5.26	5.87
7.000	6.59	6.89
8.000	7.73	7.92
9.000	8.68	9.10
10.000	9.80	10.20

Least square method

Example: Straight line curve fit

The equation for an ideal straight line

$$q_o = mq_i + b$$
$$q_o = \text{output quantity (dependent variable)}$$
$$q_i = \text{input quantity (independent variable)}$$
$$m = \text{slope of line}$$
$$b = \text{intercept of line on vertical axis}$$

The measured input and output data

$$q_{i,1}\ ,\ q_{i,2}\ ,\ q_{i,3}\ ,\ \cdots\ ,\ q_{i,n}\ ,\ \cdots\ ,\ q_{i,N}$$
$$q_{o,1}\ ,\ q_{o,2}\ ,\ q_{o,3}\ ,\ \cdots\ ,\ q_{o,n}\ ,\ \cdots\ ,\ q_{o,N}$$

For measured case, the difference e_n between the nth measured output $q_{o,n}$ and its ideal straight line prediction is

$$e_n = q_{o,n} - (mq_{i,n} + b)$$

The total *error square* E is

$$E = \sum_{n=1}^{N} e_n^2$$
$$N = \text{total number of data points}$$

Find m and b such that E is minimum

$$\frac{\partial E}{\partial m} = 0 \quad \text{and} \quad \frac{\partial E}{\partial b} = 0$$

The fitted results are

$$m = \frac{N\sum q_{i,n}q_{o,n} - (\sum q_{i,n})(\sum q_{o,n})}{N\sum q_{i,n}^2 - (\sum q_{i,n})^2}$$
$$b = \frac{(\sum q_{o,n})(\sum q_{i,n}^2) - (\sum q_{i,n}q_{o,n})(\sum q_{i,n})}{N\sum q_{i,n}^2 - (\sum q_{i,n})^2}$$

The standard deviation of q_o

$$s_{q_o}^2 = \frac{1}{N-2}\sum(mq_{i,n} + b - q_{o,n})^2$$

The standard deviation of q_i

$$s_{q_i}^2 = \frac{1}{N-2}\sum(\frac{q_{o,n} - b}{m} - q_{i,n})^2$$

Bias and imprecision

bias = systematic error
Imprecision = random error

The calibration is the process of removing bias and defining imprecision numerically.

t distribution

For limited sample number, the uncertainty band is sensitive to sample size.

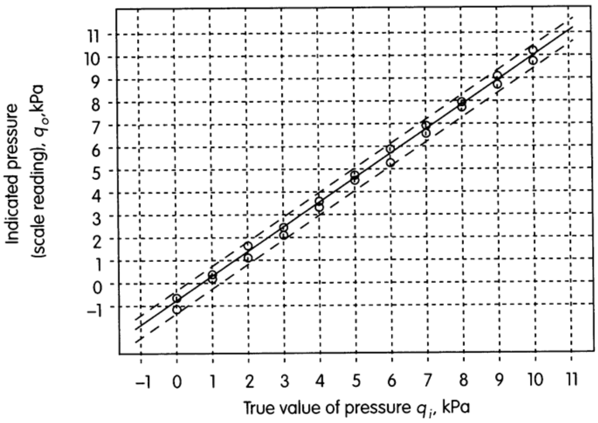
95% level of confidence

Degrees of freedom $(N-2)$	t_{95} value	Degrees of freedom $(N-2)$	t_{95} value
1	12.706	14	2.145
2	4.303	15	2.131
3	3.182	16	2.120
4	2.776	17	2.110
5	2.571	18	2.101
6	2.447	19	2.093
7	2.365	20	2.086
8	2.306	25	2.060
9	2.262	30	2.042
10	2.228	40	2.02
11	2.201	60	1.980
12	2.179	infinity	1.960
13	2.160		

$$\Delta q_0 = \pm t_{95,N-2} s_{q_o} \left[\frac{1}{n} + \frac{1}{N} + \frac{\sum(q_{i,n} - \bar{q}_i)^2}{N\sum q_{i,n}^2 - (\sum q_{i,n})^2}\right]^{1/2}$$

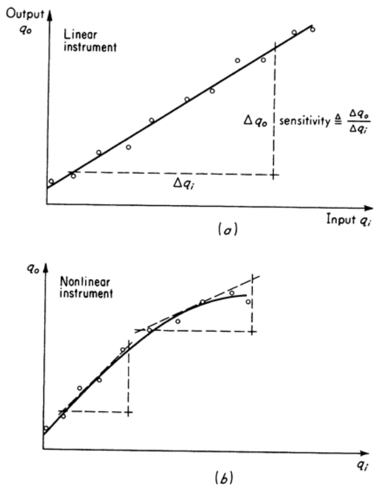
$n =$ number of repeated measurements

N=22, *n*=2

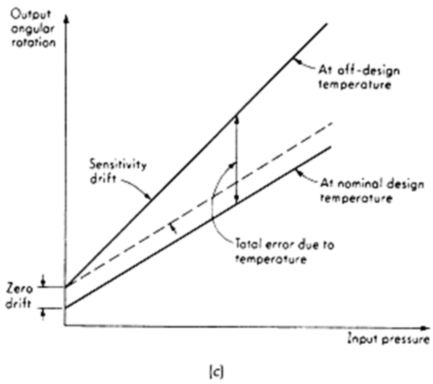


Calibration curve with 95% level of confidence

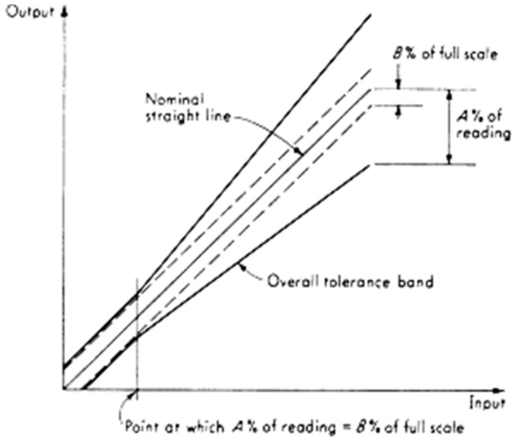
Static sensitivity



Zero and sensitivity drift due to temperature



Linearity specification



Threshold

Noise floor

Resolution

NTU50235100

Hysteresis

周元昉

NTU50235100

Dead Space

周元昉

Span

Dynamic range

Loading effect