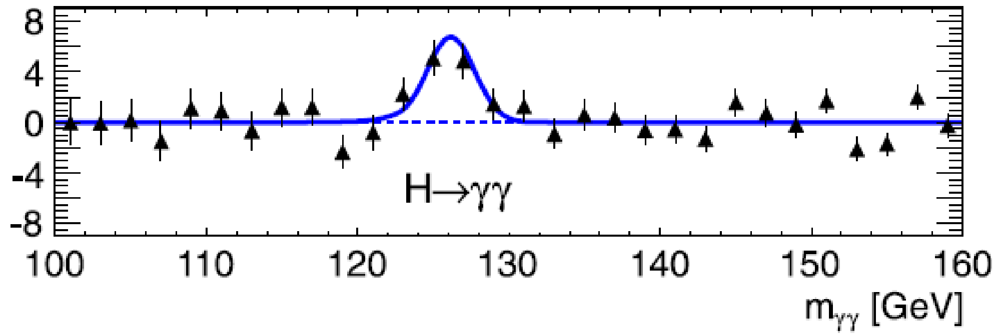
EP122
Measurement Techniques and Calibration

Topic 1

Basic Concepts



http://www.gantep.edu.tr/~bingul/ep122

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Measurement (ölçme)

Measurement is the assignment of numbers to objects or events.

All measurements consist of three parts:

- magnitude,
- dimensions (units) and
- Uncertainty

For example electronic charge:

$$e = (-1.602176565 \pm 0.000000035) \times 10^{-19}\ C$$

$$= -1.602176565(35) \times 10^{-19}\ C$$

System of Units

- Physics is an experimental science.
- Measurments must be expressed in units.

- There are several systems of units in use today.

1. **International System (SI) or MKS units (we'll use this)**
2. **CGS units**
3. **British Gravitational (BG)**
4. **U.S. Customary units**

e.g: Length can be measured in

meters, centimeters, yards, inches, etc.

SI Name	Symbol	Definition
Meter	m	*The length* of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second.
Kilogram	kg	*The mass* of the international prototype of the kilogram
Second	s	*The duration* of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom.
Ampere	A	The constant *electric current* which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.
Kelvin	K	The fraction 1/273.16 of the *thermodynamic temperature* of the triple point of water.
Mole	mol	*The amount of substance* of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12 atom.
Candela	cd	*The luminous intensity* in a given direction, of a light source that emits monochromatic radiation of frequency 540×10^{12} Hz and that has a radiant intensity in that direction of 1/683 watt per steradian.

Derived SI Units

- Relying on the base units, all other units of measurement can be formed.

Quantity	Symbol	SI	Derived SI
Force	*F*	$kg.m/s^2$	Newton, N
Energy	*E*	$kg.m^2/s^2$	Joule, J
Pressure	*P*	$kg/m.s^2$	Pascal, Pa

Scaling Prefixes of SI Units

Multiplication Factor	Prefix	SI sysmbol
1,000,000,000,000,000,000,000,000 = 10^{24}	yotta	Y
1,000,000,000,000,000,000,000 = 10^{21}	zetta	Z
1,000,000,000,000,000,000 = 10^{18}	exa	E
1,000,000,000,000,000 = 10^{15}	peta	P
1,000,000,000,000 = 10^{12}	tera	T
1,000,000,000 = 10^{9}	giga	G
1,000,000 = 10^{6}	mega	M
1000 = 10^{3}	kilo	k
100 = 10^{2}	hecto	h
10 = 10^{1}	deka	da
0.1 = 10^{-1}	deci	d
0.01 = 10^{-2}	centi	c
0.001 = 10^{-3}	milli	m
0.000,001 = 10^{-6}	micro	μ
0.000,000,001 = 10^{-9}	nano	n
0.000,000,000,001 = 10^{-12}	pico	p
0.000,000,000,000,001 = 10^{-15}	femto	f
0.000,000,000,000,000,001 = 10^{-18}	atto	a
0.000,000,000,000,000,000,001 = 10^{-21}	zepto	z
0.000,000,000,000,000,000,000,001 = 10^{-24}	yocto	y

Examples:

1 GHz = 10^{9} Hz

1 MW = 10^{6} W

1 kPa = 10^{3} Pa

1 mm = 10^{-3} m

1 μF = 10^{-6} F

Significant Figures (s.f.)

Number of digits used to express a number carries information about how precisely the number is known.

E.g: A stopwatch reading of 5.3 s (2 s.f.) is less precise than a reading of 5.32 s (3 s.f.)

The rules for significant figures:

Number	Number of s.f.	Reason	Scientific notation
504	3	in an integer all digits count (if last digit is not zero)	5.04×10^2
608 000	3	zeros at the end of an integer do not count	6.08×10^5
200	1	zeros at the end of an integer do not count	2×10^2
0.000 305	3	zeros in front do not count	3.05×10^{-4}
0.005 900	4	zeros at the end of a decimal count, those in front do not	5.900×10^{-3}

In addition, subtraction, multiplication and division, the result must have as many s.f. as the **least** precisely known number entering the calculations.

$$3.21 + 4.1 = 7.32 \approx 7.3$$

$$12.367 - 3.15 = 9.217 \approx 9.22$$

$$23 \times 578 = 13294 \approx 1.3 \times 10^4$$

$$6.244 / 1.25 = 4.9952 \approx 5.00$$

Rounding the number 542.48 = 5.4248×10^2

$5.4248 \times 10^2 \approx 5.4 \times 10^2$ (rounded to 2 s.f.)

$5.4248 \times 10^2 \approx 5.42 \times 10^2$ (rounded to 3 s.f.)

$5.4248 \times 10^2 \approx 5.425 \times 10^2$ (rounded to 4 s.f.)

Calibration

Calibration is a comparison between measurements (best and unknown).

The device with the known or assigned correctness is called the *standard*.

The second device is the unit under test is called the *test instrument*.

Experiment (deney)

An experiment is a methodical procedure carried out with the goal of verifying, the validity of a hypothesis.

In general, experiments are performed

- to test a theory
- to compare with other independent experiments measuring the same quantity.

- When performing experiments,we should be concern not only with the measured value but also with its accuracy.

- The accuracy is derived from an *experimental error* for the measured quantity.

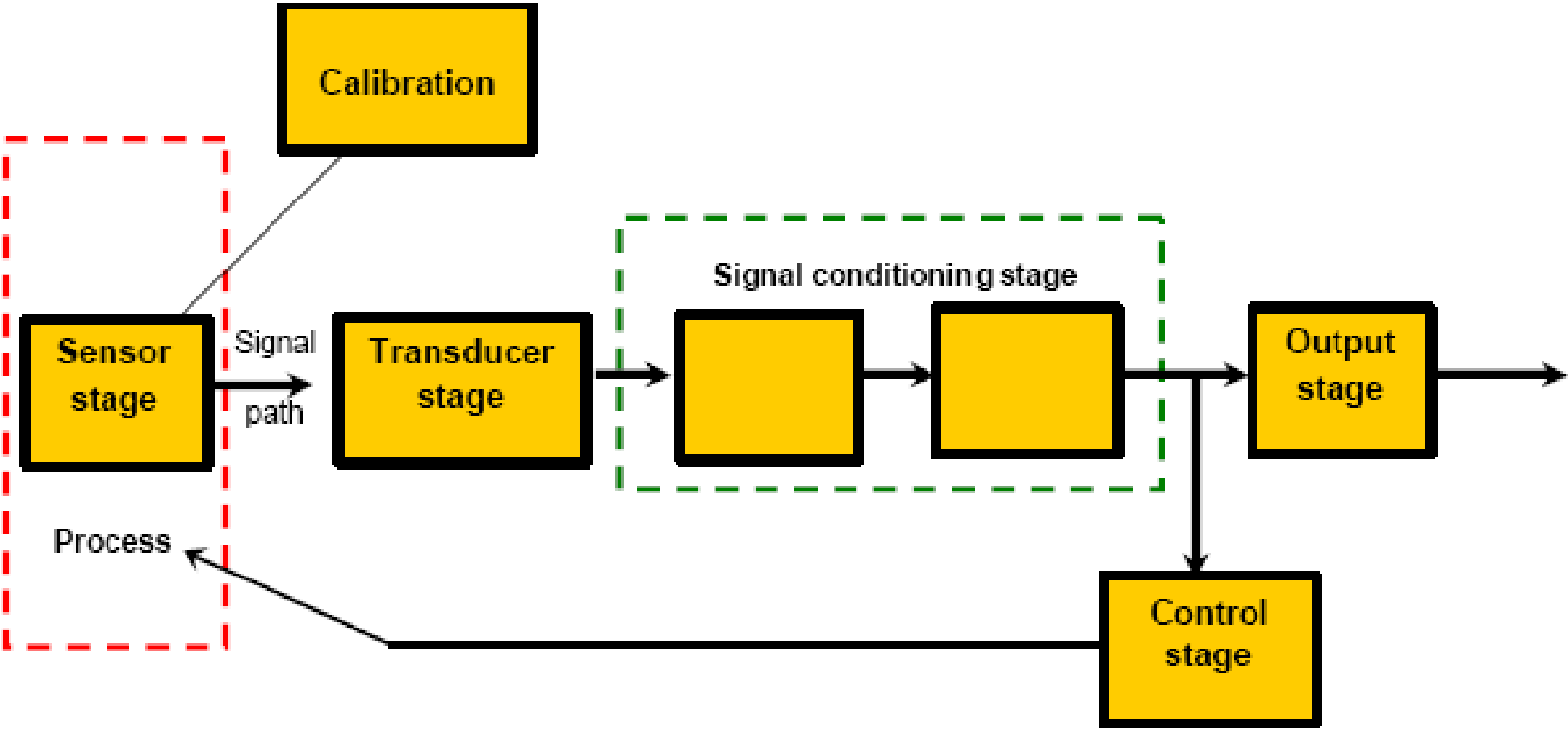
- For example, consider a measurement of the gravitational acceleration due to the gravity is obtained as:

$$g = 9.77 \pm 0.14 \text{ m/s}^2$$

- We will see later what we mean by the error ± 0.14

The more accurate the experiment the smaller the error.

Measurement System



Components of a general measurement system

Error & Uncertainty

Error (=hata)

is the difference between
<u>true value</u> and <u>measured value</u> of a quantity.

Uncertainty (=belirsizlik)

is the <u>estimated error for a measurement</u>.

- Since a true value for a physical quantity may be unknown, it is sometimes not possible to determine the true error of the measurement.
- *So, the term uncertainty is more sensible for the error computations although the terms error and uncertainty are used instead of each other in literature*.

Combined Definition:

Error is an estimate of the inherent uncertainty associated with our experimental procedure.

For example:

Suppose we are asked to measure the length of a block of glass. Our experimental error depends on the method of measurement.

Method	Typical error
Cheap ruler	0.5 mm
Calipers	0.05 mm
Travelling microscope	0.005 mm
Interferometer	0.00001 mm

Since we can never measure anything absolutely accurately, it follows that

any measured quantity has an associated error.

The associated error is an important part of the measurement, since it allows an outsider to assess the significance of the quoted value in case of any discrepancy with earlier measurements or theoretical predictions.

Example

We measure two glass blocks to be 19.0 mm and 19.5 mm long. Are they really different?

Answer

if we used a cheap ruler

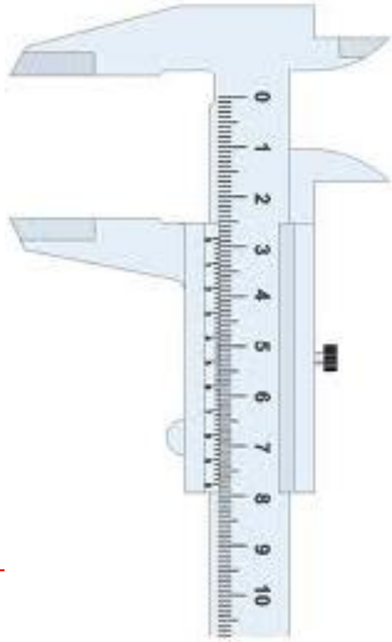
$$19.0 \pm 0.5\,\text{mm} \;\; \textit{and} \;\; 19.5 \pm 0.5\,\text{mm}$$

we have no reason to believe so.

if we used a caliper

$$19.00 \pm 0.05\,\text{mm} \quad \textit{and} \quad 19.50 \pm 0.05\,\text{mm}$$

they certainly are different!



Sources of Errors

There are two fundamentally different types of experimental error.

- **Statistical (or Random) errors**
- **Systematic errors**

Statistical errors are random in nature.

Repeated measurements will differ from each other and from the true value by amounts which are not individually predictable, although the average behaviour over many repetitions can be predicted.

- *Scale reading errors belong to this class:*
  if we get 50 people to measure our glass block, we expect to get a range of (slightly) different values.
- *Intrinsically random processes like radioactive decay also belong in this category.*

Statistical errors may be reduced by repeating the same experiment many times

Statistical errors are random in nature.

Repeated measurements will differ from each other and from the true value by amounts which are not individually predictable.

Random errors are unbiased.

* Suppose you ask ten people to use stopwatches to measure the time it takes an athlete to run a distance of 100 m.
  You will get 10 different result (Why?).
  If you calculate average of them you will get a better estimate for the time.

* Using a digital calipper try to measure length of an object.
  10 students will get 10 diiferent results!

Systematic errors arise from problems in the design of the experiment.

They are not random, and affect all measurements in some well-defined way.

Sometimes, it is not easy to predict the systematical errors.

The systematic errors may be reduced by calibration of the device.

Systematic errors biases measurements in the same direction.

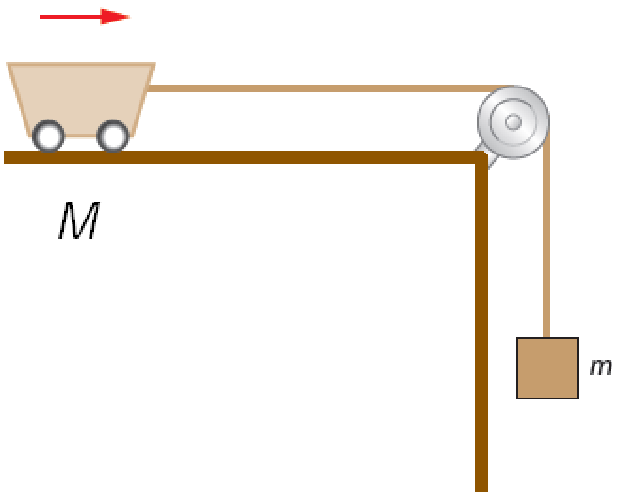
The results are too high or too low

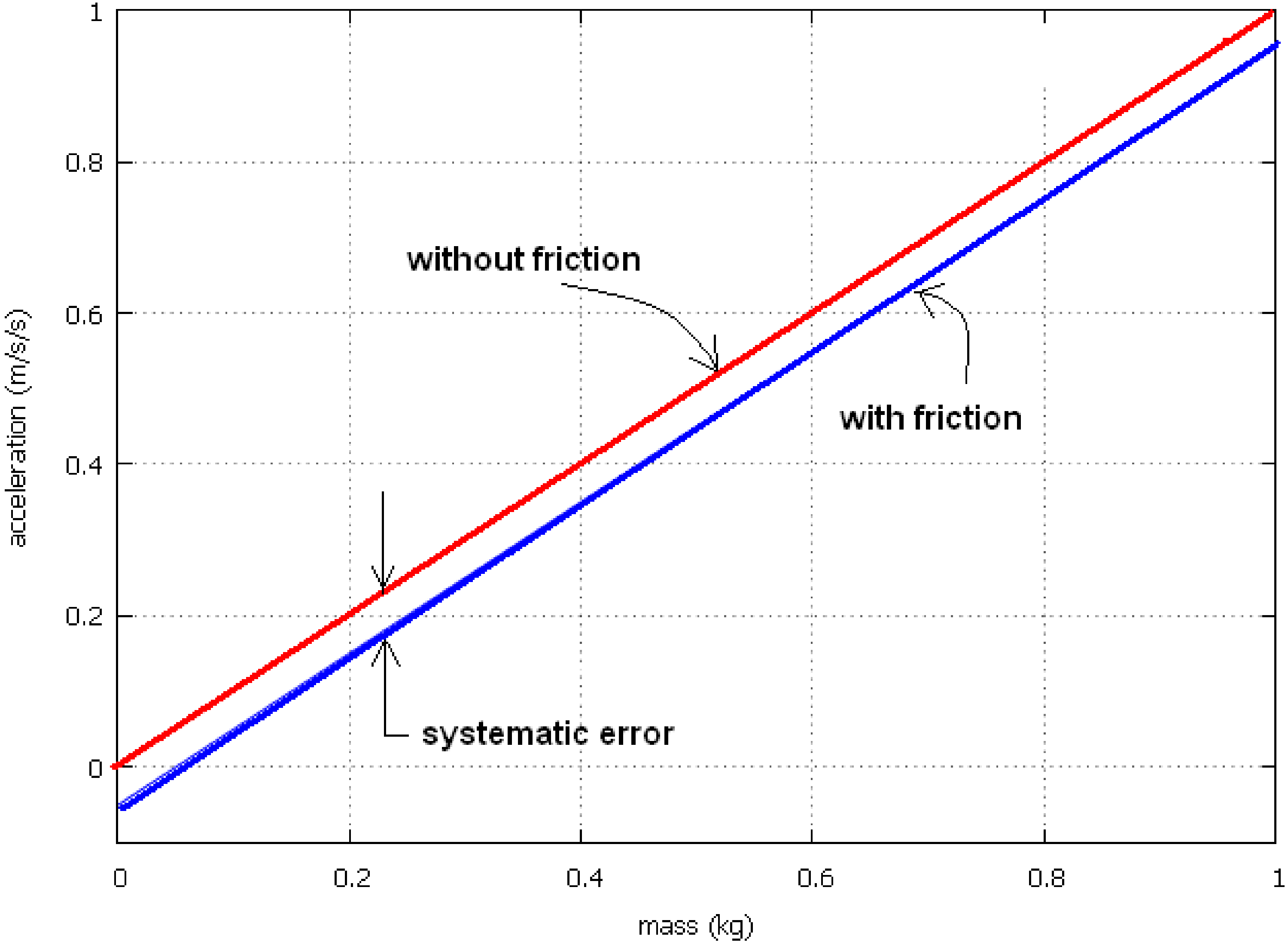
* If you use an ampermeter that shows a current 0.1 A even before connected to a circuit, every measument of current will be larger than the true value by 0.1 A.

* Suppose you want to test Newton's 2nd law.
The accelation of mass m is

$a = mg/(m+M)$ if you ignore friction

$a = mg/(m+M) - f/(m+M)$ if you dont ignore friction

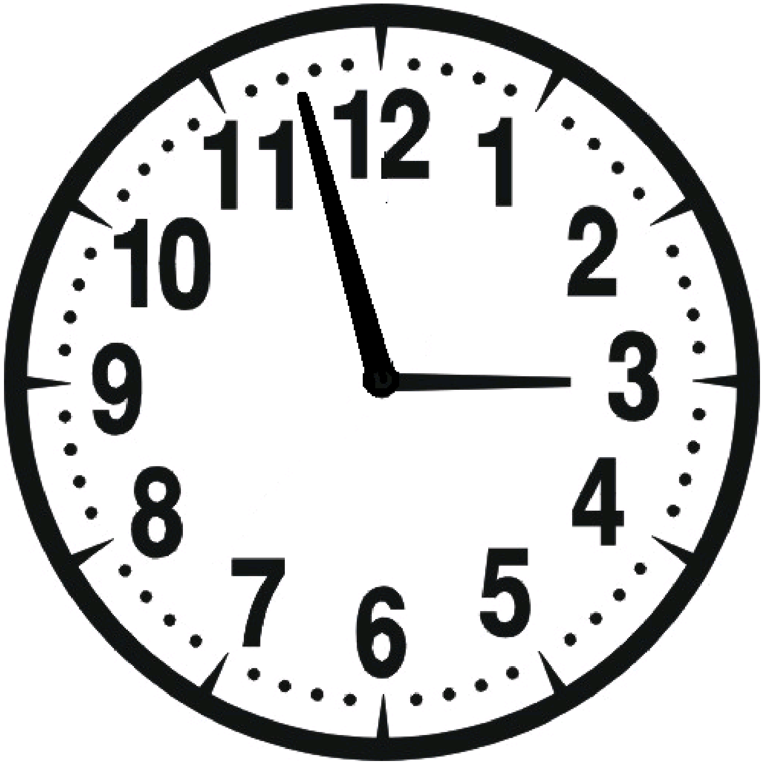




without friction
with friction
systematic error
acceleration (m/s/s)
mass (kg)
0
0.2
0.4
0.6
0.8
1

Example

Suppose a watch has only hour and minute hands, but no second hand. What is the time?



When you try to estimate the time, you will have <u>random error</u> of maximum one minute.

If the watch is running slow so that it is wrong by an amount that you are not aware of (say 10 min),
the reading will have a 10 min the <u>systematic error</u> too.

Measurement Errors for Some Devices (Instrumental Limitations)

- The values of experimental measurements have uncertainties due to *measurement limitations*.

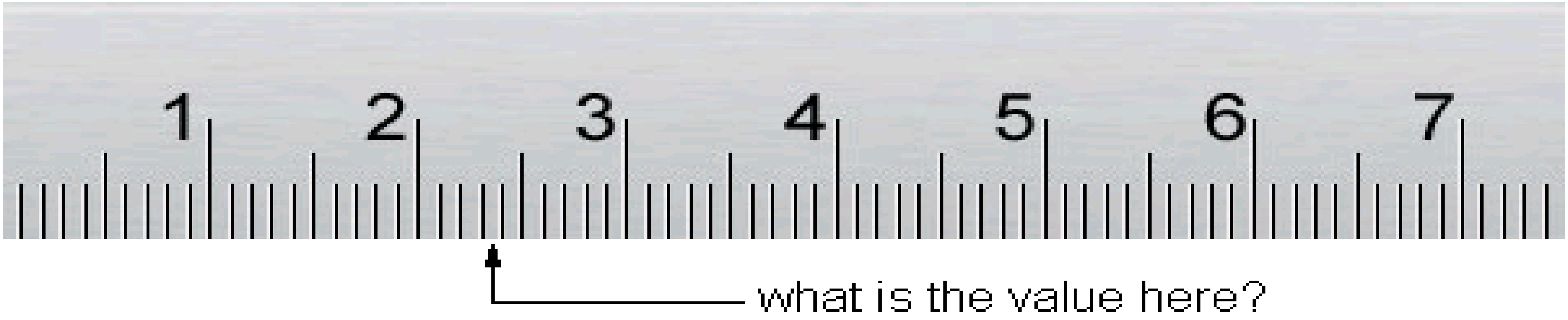
- Here we will show the uncertainty for two mostly used devices in the labs.

Ruler

In Fig, the pointer indicates a value between 23 and 24 mm. With this millimeter scale one strategy is to take the center of the bin as the estimate of the value, the maximum error is then half the width of the bin. So in this case our measurement is

$$23.5 \pm 0.5\,\text{mm}$$

The value of 0.5 mm is the estimate of the random error.



Digital Measuring Devices

All digital measuring devices has a maximum uncertainty of the order of half its last digit. For example, in Fig, for the reading from a digital voltmeter, the uncertainty is $\pm 0.01/2$ Volts.

Thus, assuming the voltmeter is calibrated accurately, the measured voltage is

$$9.160 \pm 0.005\,\mathrm{V}$$

- The measurement readings fall between the smallest scale division of each instrument:

35.5 ± 0.5 mm

12.880 ± 0.005 V

10.55 ± 0.25 m/s

$70.5 \pm 0.5\ ^{o}C$

Definitions

In this section, we will give some fundamental terms used in the measurement systems.

Sensitivity (=hassasiyet)

The sensitivity of an instrument (such as microphone) is the minimum magnitude of input signal required to produce a specified output signal having a specified criteria.

Accuracy (=doğruluk)

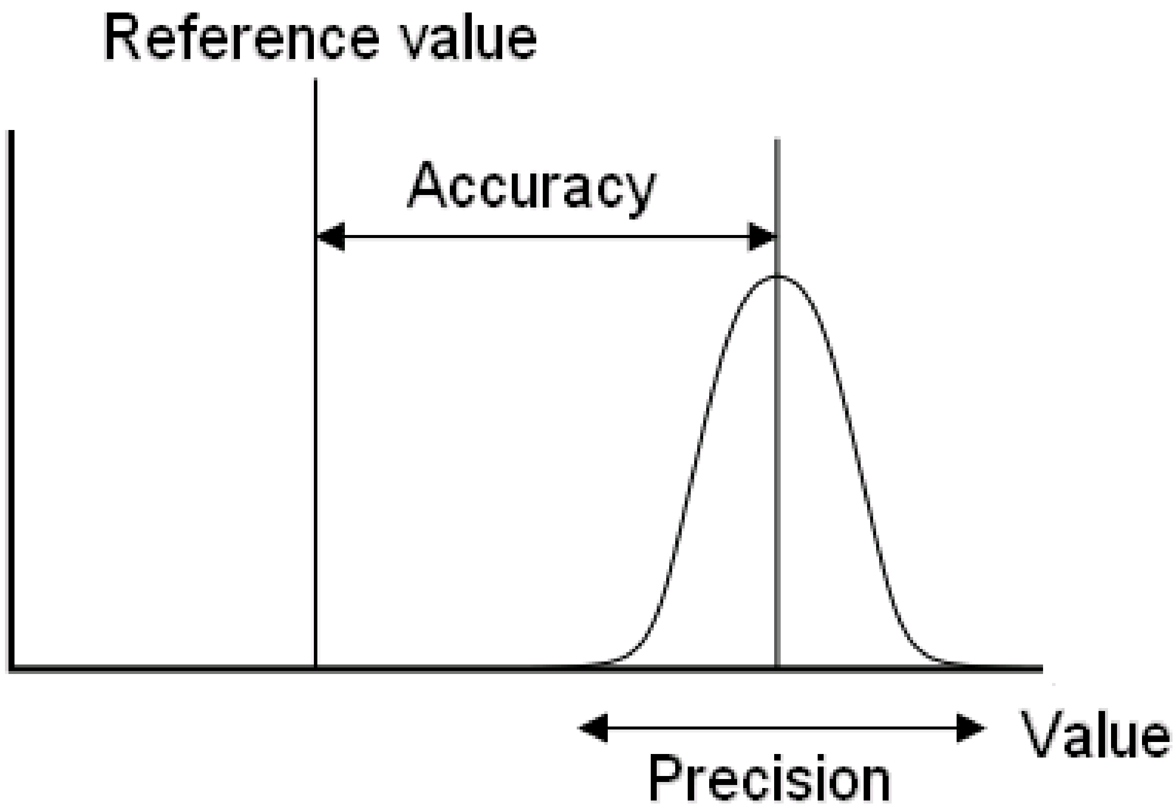
The accuracy of a measurement system is the degree of closeness of measurements of a quantity to its true (actual) value.

Precision (=kesinlik)

The precision of a measurement system, also called reproducibility or repeatability, is the degree to which repeated measurements under unchanged conditions show the same results.

A measurement system can be accurate but not precise, precise but not accurate. This can be represented by an analogy to the grouping of arrows in a target.

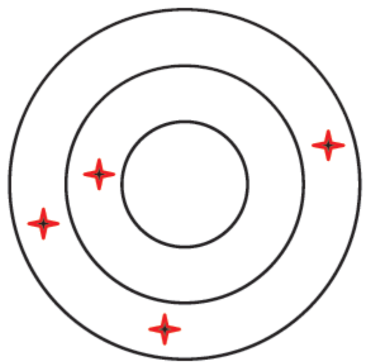
Accuracy indicates proximity of measurement results to the true value, precision to the repeatability or reproducibility of the measurement



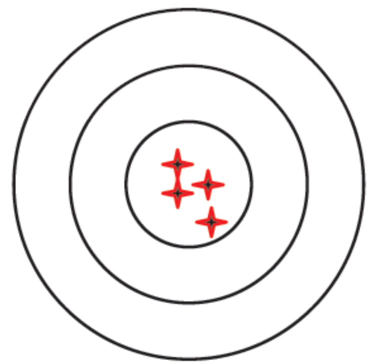
Accuracy & Precision (Doğruluk & Kesinlik)

A measurement is said to be accurate is the systematic error is small.
The measured value is close to accepted value.

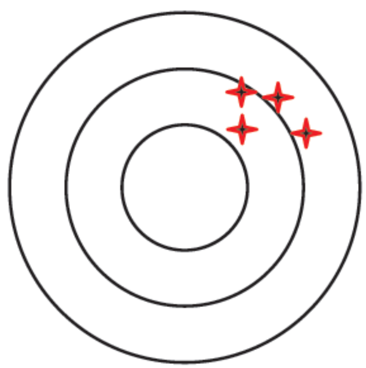
A measurement is said to be precise is the statistical error is small.
Individual measurement results are close to each other



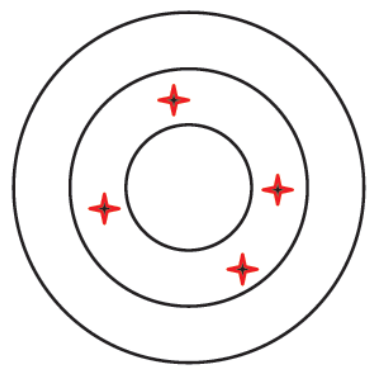
not accurate and not precise



accurate and precise



not accurate but precise



accurate but not precise

Percentage Error

measures the accuracy of a measurement by the difference between a measured or experimental value E and a true or accepted value A.

Percentage error is calculated by:

$$PE = \frac{|E - A|}{A} \times 100\,\%$$

Percentage Difference

measures precision of two measurements by the difference between the measured or experimental values E_1 and E_2 expressed as a fraction the average of the two values.

The equation to use to calculate the percent difference is:

$$PD = \frac{|E_1 - E_2|}{(E_1 + E_2)/2} \times 100\,\%$$

Questions

1. What is a random error? Give an example for it.
2. What is a systematic error? Give an example for it.
3. How can we reduce random and systematic errors in an experiment?
4. How does the limited accuracy of the measuring apparatus result in a random error?
5. How do uncontrolled changes in the environment result in a systematic error?
6. What is the difference between error and uncertainty?
7. What is meant by sensitivity, accuracy, precision?
8. Why instrument calibration is necessary?
9. What is the difference between percentage error and percentage difference?

10. Two measurements of body temperature before and after a drug is administered: 38.2 oC and 38.4 oC. Is temperature rise significant for errors (a) +- 0.01 oC and (b) 0.5 oC.

11. Sensitivity of a microphone is 2 mV/Pa. What is the value of output signal in mV for 1.2 atm pressure? (1 atm = 1.01325 x10^5 Pa)?

12. For a measurement of gravitational acceleration g = 9.811 m/s^2, calculate the percentage error with respect to best measured value (having very small uncertainty) of 9.80665 m/s^2.

13. Two measurement of gravitational acceleration are given by:

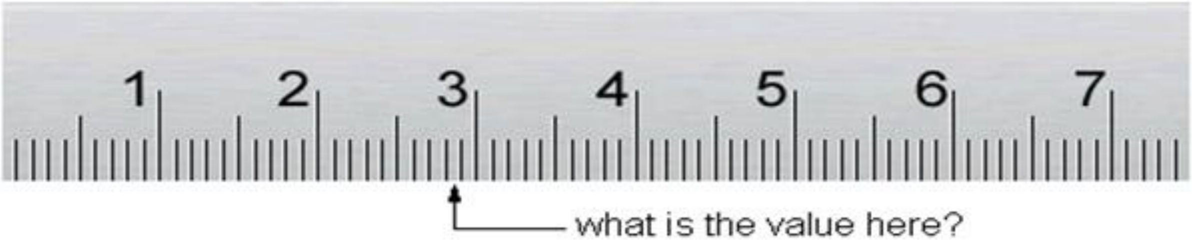
$$g_1 = 9.77 \pm 0.14 \, \mathrm{m/s^2} \quad \text{and} \quad g_2 = 9.82 \pm 0.10 \, \mathrm{m/s^2}$$

(a) Which one is the better measurement?

(b) Calculate the percentage difference between the measurements.

14. What is the value of reading given below?

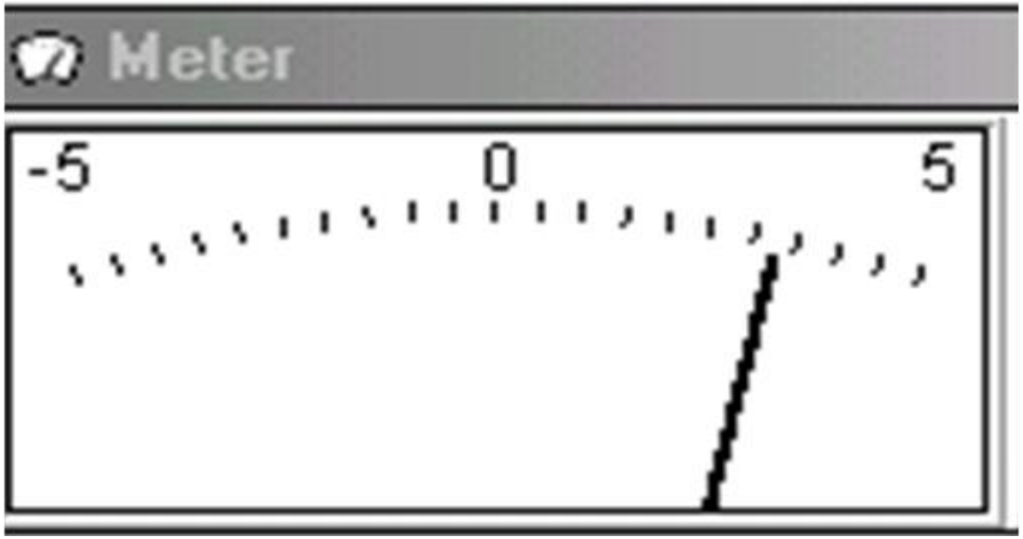
(a) 28.5 +- 0.5 mm
(b) 28.0 +- 0.5 mm
(c) 29.0 +- 0.5 mm
(d) 27.5 +- 0.5 mm



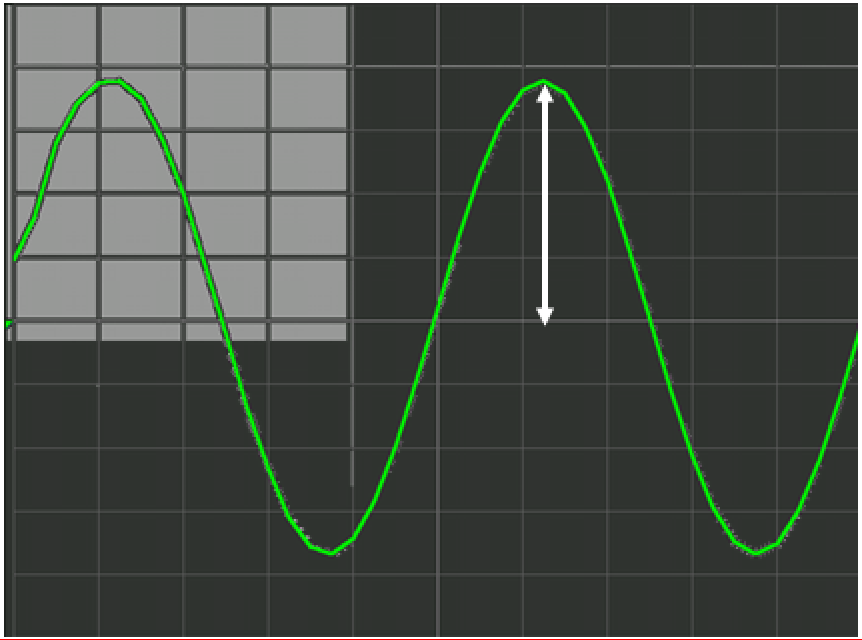
15. The last digit of the following electronic ballance can be 0, 2, 4, 6, 8. What is the value of reading on display?

(a) 12.58 +- 0.10 g
(b) 12.58 +- 0.20 g
(c) 12.58 +- 0.01 g
(d) 12.58 +- 0.02 g

16. What is the value of reading given below?



17. What is the maximum value of voltage reading from osiloscpe given right for 1V/division?



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