LIFE
EXPERIENCE
(knowledge,
attitudes,
skills)
-
for LIFE
(cognition,
consideration,
behaviour)

University of Latvia

Prof.emer., Dr.phys.
A N D R I S B R O K S

Mobile phone: +371 26 567 120
E-mail : andris.broks@lu.lv
Blog: http://blogi.lu.lv/broks/

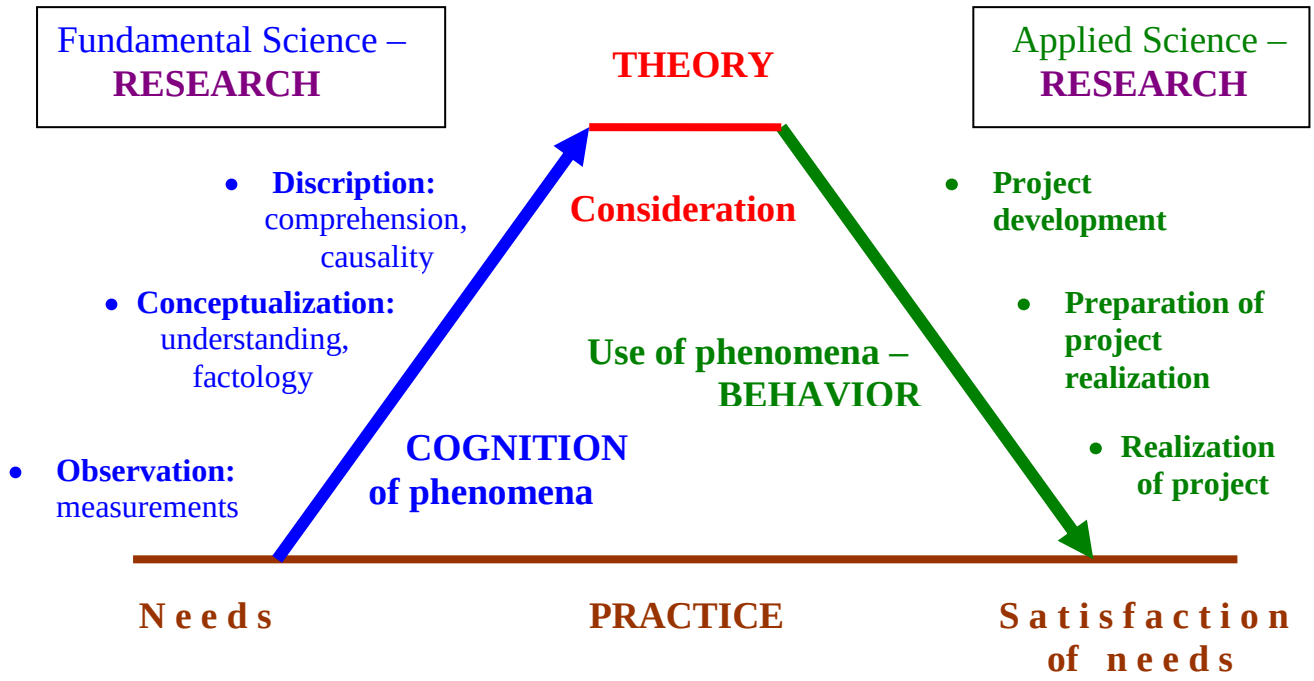
http://blogi.lu.lv/broks/category/materials-in-english/

What is EXPERIMENTAL PHYSICS ?

****

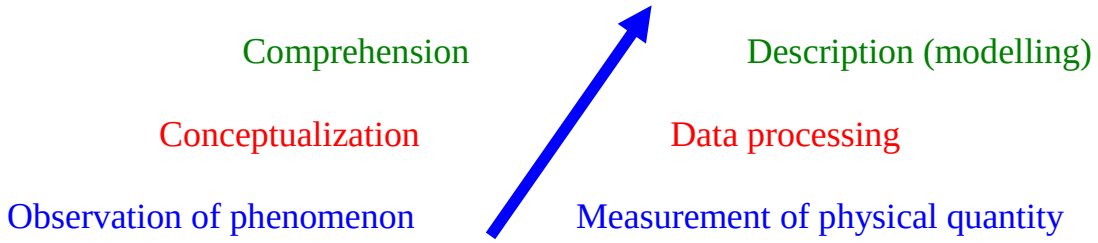
1. Let us start with general structure of scientific research

GENERAL STRUCTURE OF SCIENTIFIC RESEARCH PROCESS



Full scale research process includes both fundamental and applied research activities as creative gaining of new life experience for life to satisfy definite needs of the person or society.

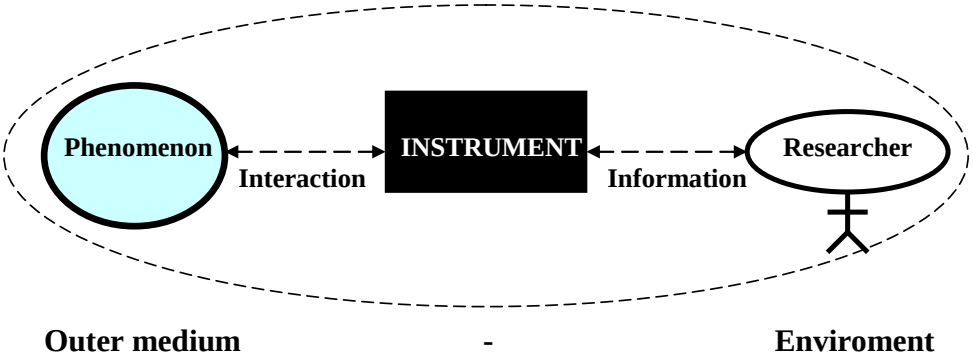
Experimental fundamental research of phenomenon



2. What does it mean "measurement of physical quantity" ?

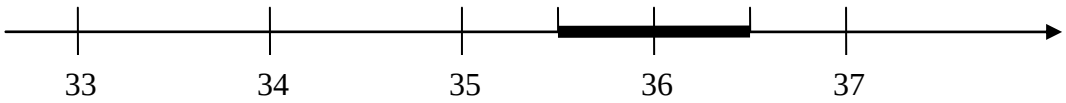
MEASUREMENT

General structure of measurement



MATHEMETICAL PRESENTATION of the results of measurements

Numbers in Mathematics and Physics



All numbers in Physics are approximate numbers and must be accompanied with corresponding units

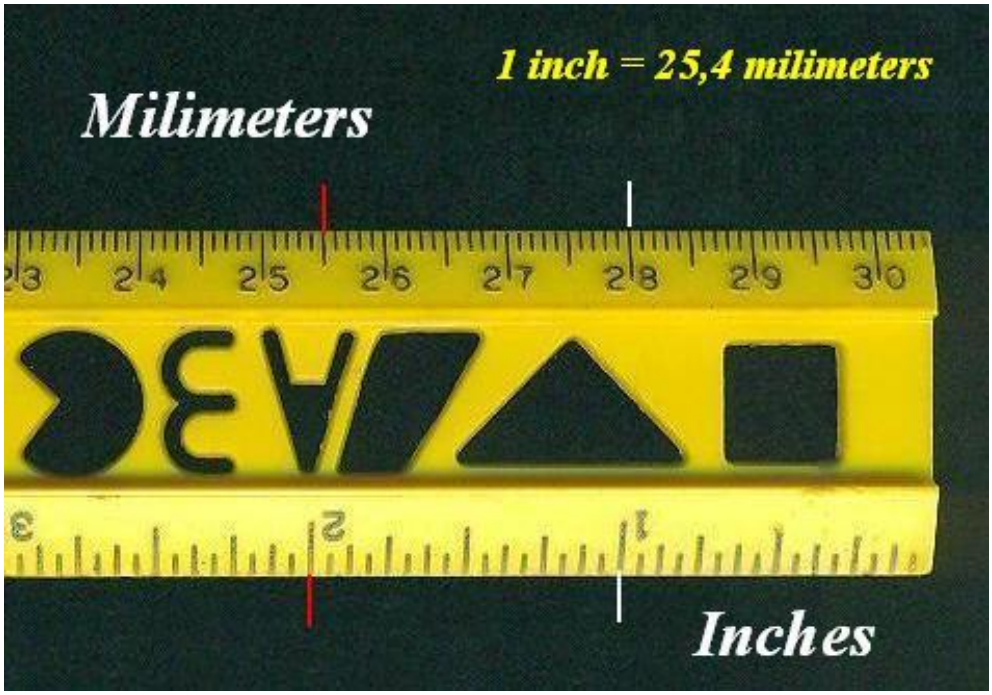
Geometric presentation of numbers:

p o i n t s in Mathematics and i n t e r v a l s in Physics

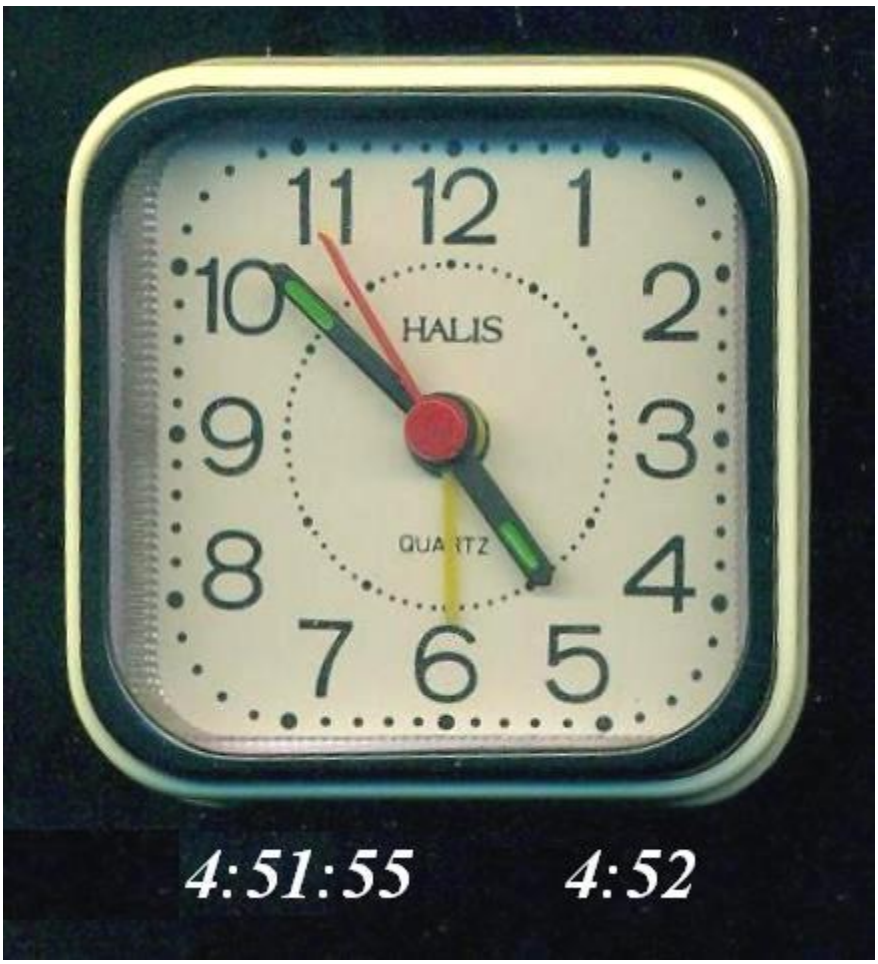
SIGNIFICANT FIGURES

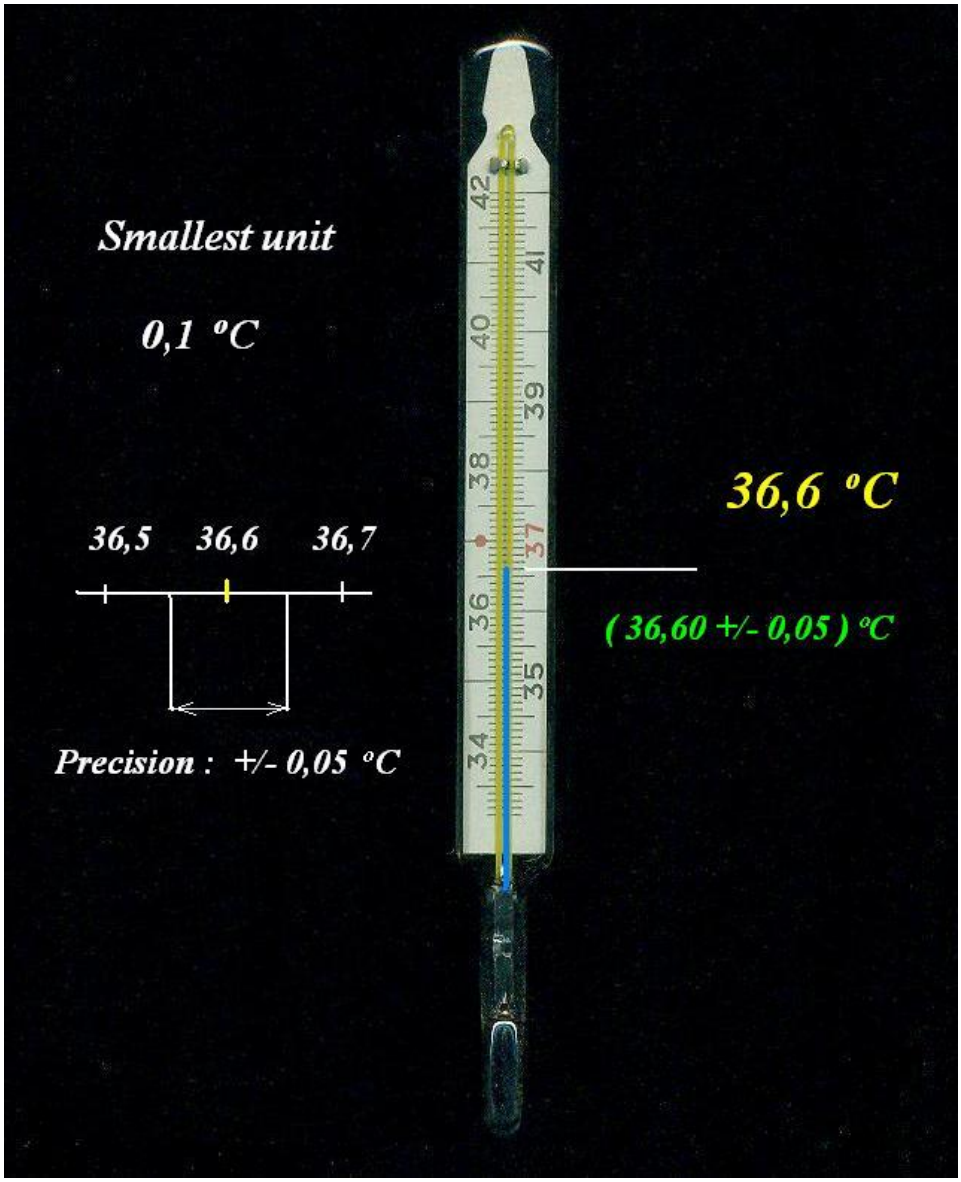
Approximate number as a result of measurement in physics must contain only significant figures. Single direct measurement made with instrument on a scale with smallest division 1 should be presented as 36 units what means interval (36,0 +/- 0,5) units.

Figures after the decimal point cannot be justified.

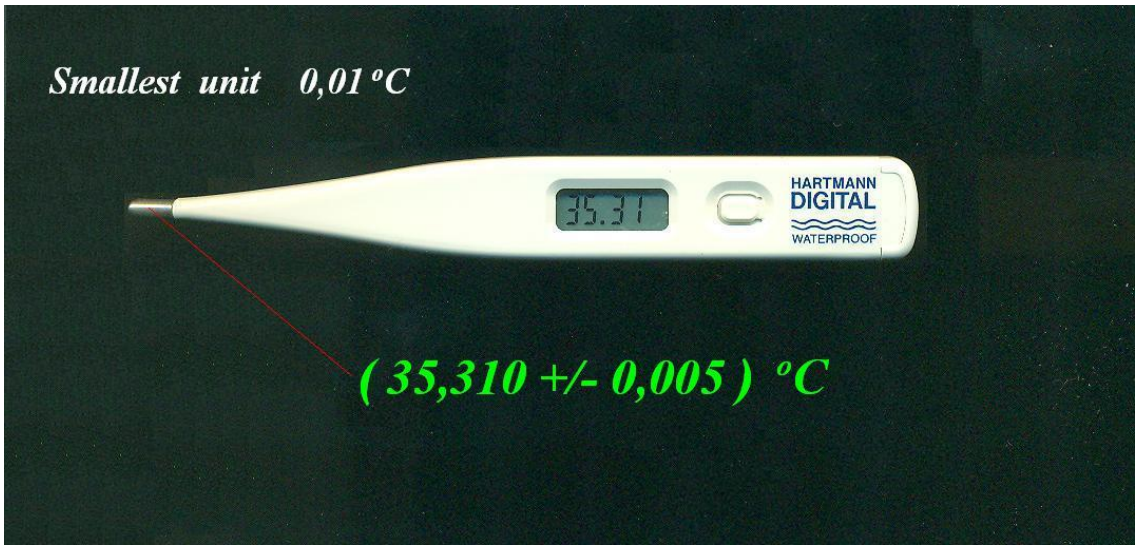


Measurements of distance and time





Measurement of temperature



Measurement of electric quantities

SINGLE and REPEATED measurements

(a , a_i)

INVESTIGATION OF RELATIONSHIPS

(changes and interrelations of properties – statics, kinetics, causal relationships)

Kinetics: $a(t) = a_0(t_0) + \Delta a\,(\Delta t)$,

$$\Delta a\,(\Delta t) = a(t) - a_0(t_0) = \sum_{i=1}^{n} \Delta a_i\,(\Delta t_i)$$

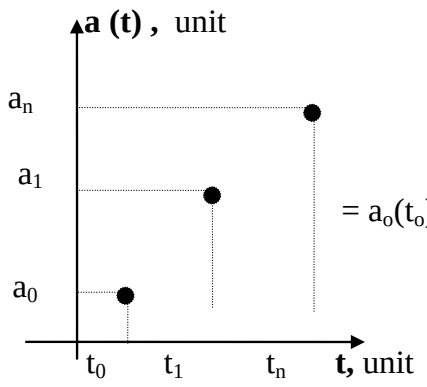
$a\,(h, g, f)$

MATHEMETICAL PRESENTATION of the experimental data

(tables, graphs)

a , unit	**t** , unit
a_0	t_0
a_1	t_1
a_2	t_2
a_3	t_3
…..	…..
a_i	t_i
…..	…..
a_n	t_n

Table



Graph

$a(t) =$
$= a_o(t_o) + b\times(t-t_o)$

Analitical functions

MATHEMATICAL MODELLING of observed relationships

Mathematical Physics

Fund.research of physical phenomena ↗ ↘ **Applied research of physical phenomena**

Experimental Physics

3. Precision (accuracy, uncertainty) of measurement result –

truth and real values of measured properties/quantities,
systematic, random and total error of measured quantities

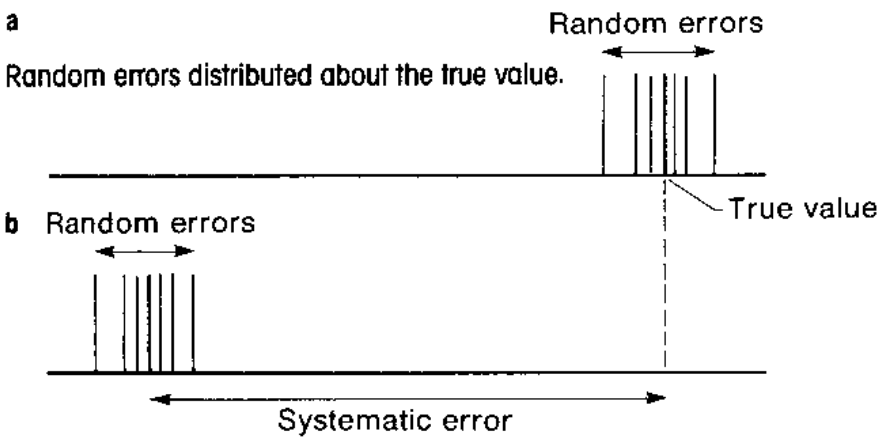
Error – characteristic of measured quantity precision

SYSTEMATIC ERRORS

A reading consistently shifted in one direction is called a systematic error. Examples include: a zero error on any scale, a calibration error, a background count in a radioactivity experiment, an end correction in a resonance tube, a stray magnetic field, backlash on screw threads. Some systematic errors can be corrected either by adjustment of the instrument or by noting the error and correcting all readings appropriately. Systematic errors are the more serious form of error since they cannot be reduced by taking repeated readings or by any other form of averaging.

Treatment of systematic errors

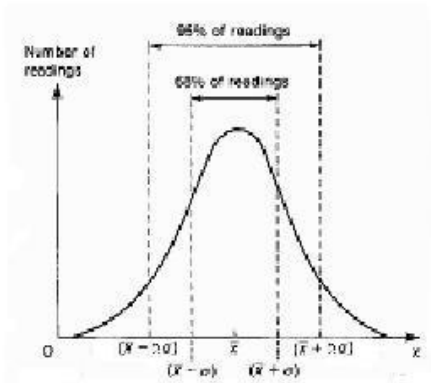
Fig. a shows a spread of readings caused by random errors; these are approximately centred about the true value. If a systematic error is also present these readings will be shifted so they are no longer centred about the true value but about some other value (Fig. b). Under these experimental conditions, no matter how many readings are taken, the final result will not approach the true value.



Random errors superimposed on a systematic error.

Treatment of random errors

When certain quantities are measured, the measured values are known only to within the limits of experimental uncertainty. The value of the uncertainty can depend on various factors, such as the quality of the apparatus, the skill of the experimenteter, and the number of measurements performed.



Gausian distribution

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-a)^2}{2\sigma^2}}$$

In general, experimental uncertainty consist on two terms: uncertainty of the apparatus Θ, and uncertainty ε caused by random variance of measured data from the real value of quantity. First parameter can be found in the apparatus user's manual or assumed to be smallest unit on the apparatus scale. The second can be estimated by analysing of statistical properties of measured data set. Under normal conditions the probability of occurances of value x coressponds to Gausian distribution

There a is real value of quantity and σ - dispersion that measures how widely measured values are dispersed from the real value of quantity. Two basic statistical parametrs of data set x_i are average value $\bar{x}$ and mean quadratic deviation S, that are defined using following mathematical expressions

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \quad S = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} = \sigma$$

As the number of performed measurements increases ($n \to \infty$), average value $\bar{x}$ tends to the real value of quantity $\bar{x} \to a$, and mean quadratic deviation S tends to the dispersion $S^2 \to \sigma^2$. The estimation of the limits of random perturbation caused uncertainty usually have been based on the property that the interval $[\bar{x}-\varepsilon, \bar{x}+\varepsilon]$ must contains 95% of all measurement results. Theoretical calculations indicated that for large number of experments $\varepsilon = 2.78\, S(\bar{x})$. There $S(\bar{x})$ is statistical quantity called mean quadratic devitation of mean arithmetic value, defined by expression

$$S(\bar{x}) = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n(n-1)}}$$

The total experimental uncertainty Δx in direct masurement is represented by expression

$$\Delta x = \sqrt{\Theta^2 + \varepsilon^2}$$

Generally the contribution of an error can be neglected if the error is less than about 1/10 of the dominant or total error. If systematic error is approximately the same value as random error, **systematic error θ and maximum random error ε** must be presented.

Maximum random error **ε** can be calculated using Student's coefficient $t_{n,\gamma}$, where n is number of repeated measurements and $\gamma = 0{,}95$

$$\varepsilon = t_{0.95,\,n} \times \sqrt{[\,\Sigma\,(d_a - d_i)^2\,] / [n \times (n-1)]}$$

n	3	4	5	6	7	8	9
$t_{0.95,\,n}$	4,303	3,182	2,776	2,571	2,447	2,365	2,306

Total error of the result of measurement means account of both - systematic and random errors

Direct measurement of property **a**

Basic types of errors	Absolute error	Relative error
Systematic error	Δa_s , unit	$\delta a_s = (\Delta a_s/a) \times 100$ %
Random error	Δa_r , unit	$\delta a_r = (\Delta a_s/a) \times 100$ %
TOTAL error	$\Delta a = \sqrt{(\Delta a_s)^2 + (\Delta a_r)^2}$, unit	$\delta a = (\Delta a/a) \times 100$ %

Result of the measurement of definite physical quantity - property **a** is presented as approximate number : **a** (units) alone or with its total absolute error (a +/- Δa) units and its relative (fractional) error $\delta a = (\Delta a/a) \times 100$ %

If there is approximate number **a** (unit) alone [**a** = 253 units], it contains only significant figures what depend on total precision (total error) of definite measurement. If total error also is presented, total error contains not more than two significant numbers [**a**= (253, 12 +/- 0,25) units, where 0,25 is calculated total absolute error of calculated quantity 253,12].

DIRECT and INDIRECT measurements

Measurements	DIRECT	INDIRECT
SINGLE	a	a (b, c, d ….)
REPEATED	$a_i\,(t_i) = \text{const}$ $a_i\,(t_i) \neq \text{const}$	a (b, c, d ….) = const $a_i\,(t_i) = a_i(b, c_i\,(t_i.) \neq \text{const}$
	Investigation of relationships	

Precision of indirect measurement depends on corresponding precision of direct measurements - every direct measurement comes with its total error what is producing corresponding uncertainty of indirect measurement. Determination of its total precision can be quite difficult task and special methods are used. The simplest method is corresponding adding of total relative errors of particular direct measurements.

Determination of density

[case study of solid state material what is formed as cylindrical body]

ρ (g/cm^3) = ?

M e a s u r e m e n t p r o c e d u r e c o n s i s t s :

1) of ***direct measurement*** of diameter **d** (cm), height **h** (cm) and mass **M** (g) of given body what include also determination of the precision of measured quantities;
2) following final ***indirect measurement*** - calculation of density ρ (g/cm^3) what again includes determination of the precision of provided indirect measurement.

1. Direct measurement of diameter **d** (cm) and determination of the total error

No of measurement	Measured values of diameter $\mathbf{d_i}$ (cm)	$d_{av} - d_i$	$(d_{av} - d_i)^2$
1 (first)	d_1 =		
2 (second)			
3	d_3 =		
4			
5	d_5 =		
6			
…. (etc.)			
Totally : **n** measurements	Calculated average value $\mathbf{d_{av}}$ **= ..**….		$\Sigma (d_{av} - d_i)^2$ = = ……..

Random absolute error

$$\Delta d_r = t_{0.95,\,n} * \sqrt{[\Sigma (d_{av} - d_i)^2] / [n * (n-1)]} = \text{.....} \text{ (cm)}$$

n - total number of measurements; $\gamma = 0{,}95$ $t_{\gamma,\,n}$ - Student's coefficient

Systematic absolute error Δd_s = ……. (cm)

T o t a l absolute error $\Delta d = \sqrt{\Delta d_s^2 + \Delta d_r^2}$ = …… (cm)

Approximate number containing two significant figures!

T o t a l relative error $\delta d = (\Delta d / d_{av}) \times 100\%$ = …….. %

R e s u l t : $(d_{av} +/- \Delta d)$ cm , δd %

……

2. Direct measurement of height **h** (cm) and determination of the total error

No of measurement	Measured values of height $\mathbf{h_i}$ (cm)	$h_{av} - h_i$	$(h_{av} - h_i)^2$
1	$h_1 =$		
2			
3	$h_3 =$		
4			
5	$h_5 =$		
…. (etc.)			
Totally : **n** measurements	Calculated average value $\mathbf{h_{av}} =$		$\Sigma (h_{av} - h_i)^2 =$ =

Random absolute error

$\Delta h_r = t_{0.95,\,n} * \sqrt{[\,\Sigma (h_{av} - h_i)^2\,] / [n \times (n-1)]} =$ …… (cm)

Systematic absolute error $\Delta h_s =$ …….. (cm)

Total absolute error $\Delta h = \sqrt{\Delta h_s^2 + \Delta h_r^2} =$ (cm)

Total relative error $\delta h = (\Delta h / h_{av}) \times 100\% =$ %

R e s u l t : $(h_{av} +/- \Delta h)$ cm , $\delta h =$ …. %

……

3. Direct measurement of mass **M** (g) and determination of the total error

Using digital mass meter we got M = (g)

Systematic absolute error of this measurement is characterized by a half of instrument's scale smallest division: $\Delta M_s =$ (g)

There was no random error effect observed when repeating mass measurements – so total error of direct measurement contains only systematic error $\Delta M = \Delta M_s$

R e s u l t : $(M +/- \Delta M)$ g , $\delta M = (\Delta M/M) \times 100$ %

……

Final i n d i r e c t measurement - calculation of density ρ (g/cm^3)

and determination of the precision of corresponding indirect measurement.

$\rho = 4\,M / (\pi \times d^2 \times h) =$ …… (g/cm^3)

Total relative error $\delta\rho\,(\%) = \delta M\,(\%) + 2 \times \delta d\,(\%) + \delta h\,(\%) =$ …… (%)

$\delta\rho =$ …… (decimal fraction)

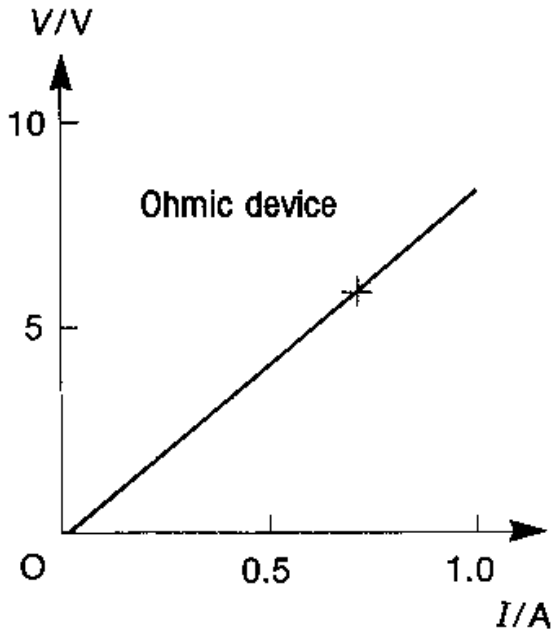
Total absolute error $\Delta\rho = \rho \times \delta\rho =$ …… g/cm^3

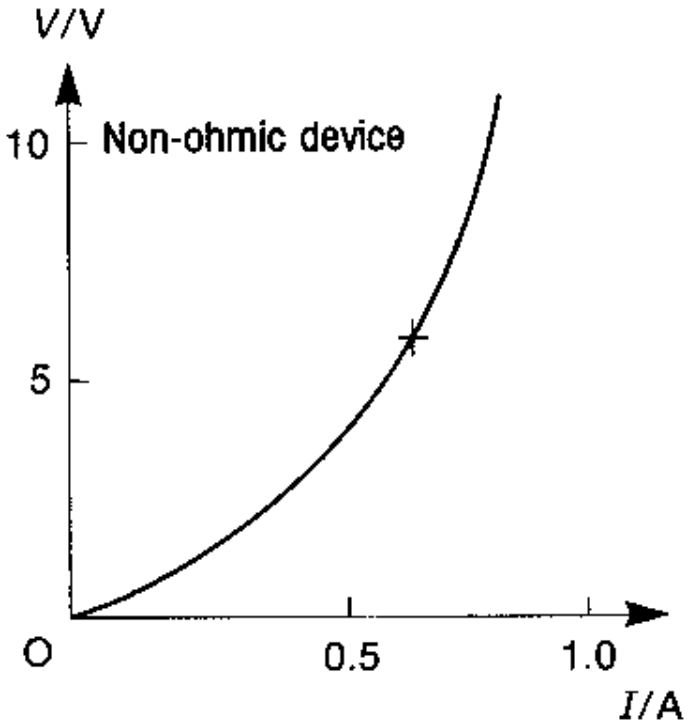
F I N A L R E S U L T : $(\rho +/- \Delta\rho)$ g/cm^3 , $\delta\rho\,(\%)$

……..……..

4. Graphical investigation of relationships

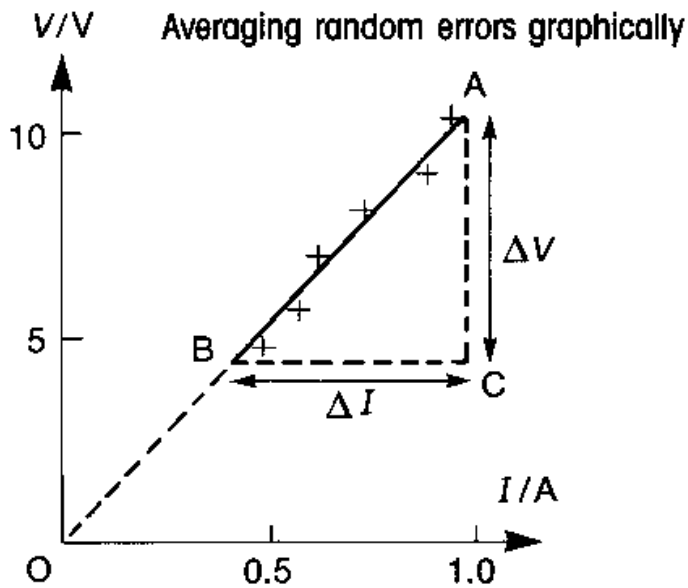
One of the most important reasons for experimental work is to investigate the relationships between two or more physical quantities. Taking a single set of readings of a physical quantity often gives very little information on the form of the relationship between the readings and the limitations of their validity. A single set of readings could





be used to calculate the physical constant involved; for example, measuring the potential difference V across and the current I through a device will give a value of the resistance R of the device for those particular values of V and I, but it would not tell you anything about the device or whether R depends on I. A single pair of values of V and I (marked as +) could be interpreted in many ways (Fig. 3.1).

Clearly several sets of readings of V and I would enable a distinction between Figs. 3.1a, b and c to be made. (A graph is easier to interpret than a table of values of V and I.) There is another important reason for using several sets of readings of V and I, namely, experimental error. There are random errors which relate to the precision with which an instrument can be read, concerning the inability of the experimenter to record an exact value. Repeated measurements of the same quantity will give different values. This type of error can be reduced by taking many readings and averaging them; but a graph can also be used to achieve the same end (Fig. 3.2). There will always be a deviation of experimental points from the straight line. The straight line should pass symmetrically between the points. The slope or gradient of the line $\Delta V/\Delta I$ = AC/BC gives an average value of R.



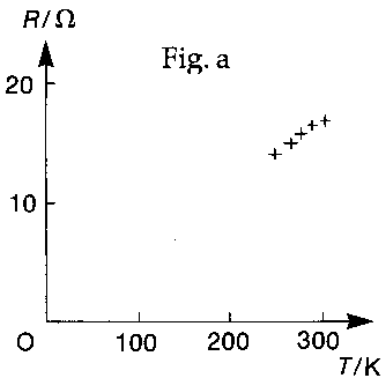
Plotting a graph

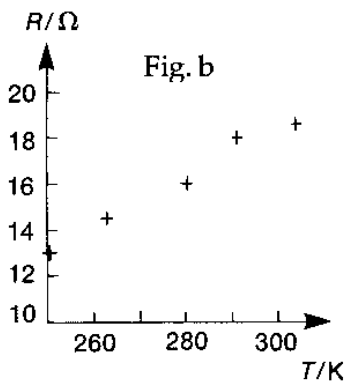
a) Always plot a graph as the experiment proceeds. This will help to detect errors and deviations.

b) Decide on the range of values of each variable which will occur in the experiment. This may sometimes involve doing a quick preliminary experiment to find maximum and minimum values.

c) If an intercept (point where the graph cuts an axis) is not required, the origin need not be included. This is often useful if the values of one quantity cover only a small range.

d) It is usually a good thing to spread the points to fill the graph. For example, in Fig. a it would be difficult to decide whether R were linearly related to T but it should be evident from Fig. b.

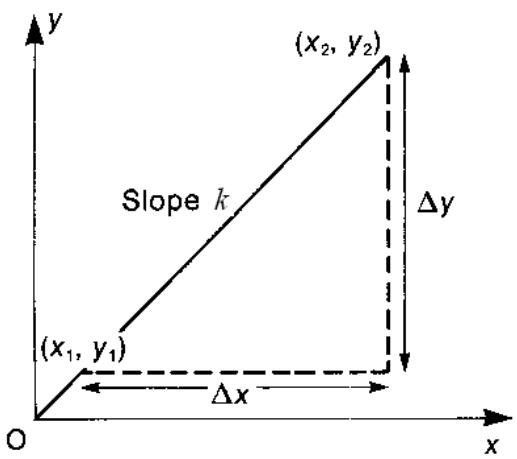




Proportional / linear relationships

A proportional relationship takes the form $y = kx$. If we plot y against x the graph will be a straight line through the origin.

$$\text{slope} = k = \frac{\text{change in } y}{\text{change in } x} = \frac{\Delta y}{\Delta x} = \frac{(y_2 - y_1)}{(x_2 - x_1)}$$

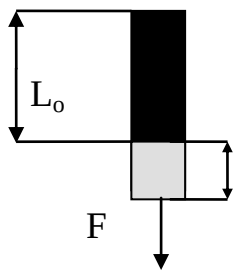


Elastic deformation of metallic string

[case study of elastic deformation (stretching, compression) of solid bodies - determination of Young modulus]

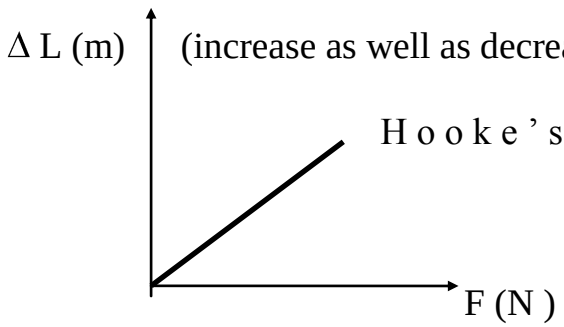
Y (N/m^2) = ?

The absolute increase of string's length **ΔL** when stretching force **F** is applied depends on the amount of force applied to stretch a rod **F**, cross-sectional area of the rod **A** and the nature of rod's material.



A - cross-sectional area of the string
D - diameter of given cylindrical string
L_o - initial length of the string
ΔL - absolute increase of length when stretching force F is applied

Mathematical model of the elastic behaviour - deformation for a given string can be expressed by the linear relation, if the amount of stretching is small compared to the original length of the string :



(increase as well as decrease of length in meters)

H o o k e ' s l a w : deformation (as change of string's length) and force are directly proportional to one another

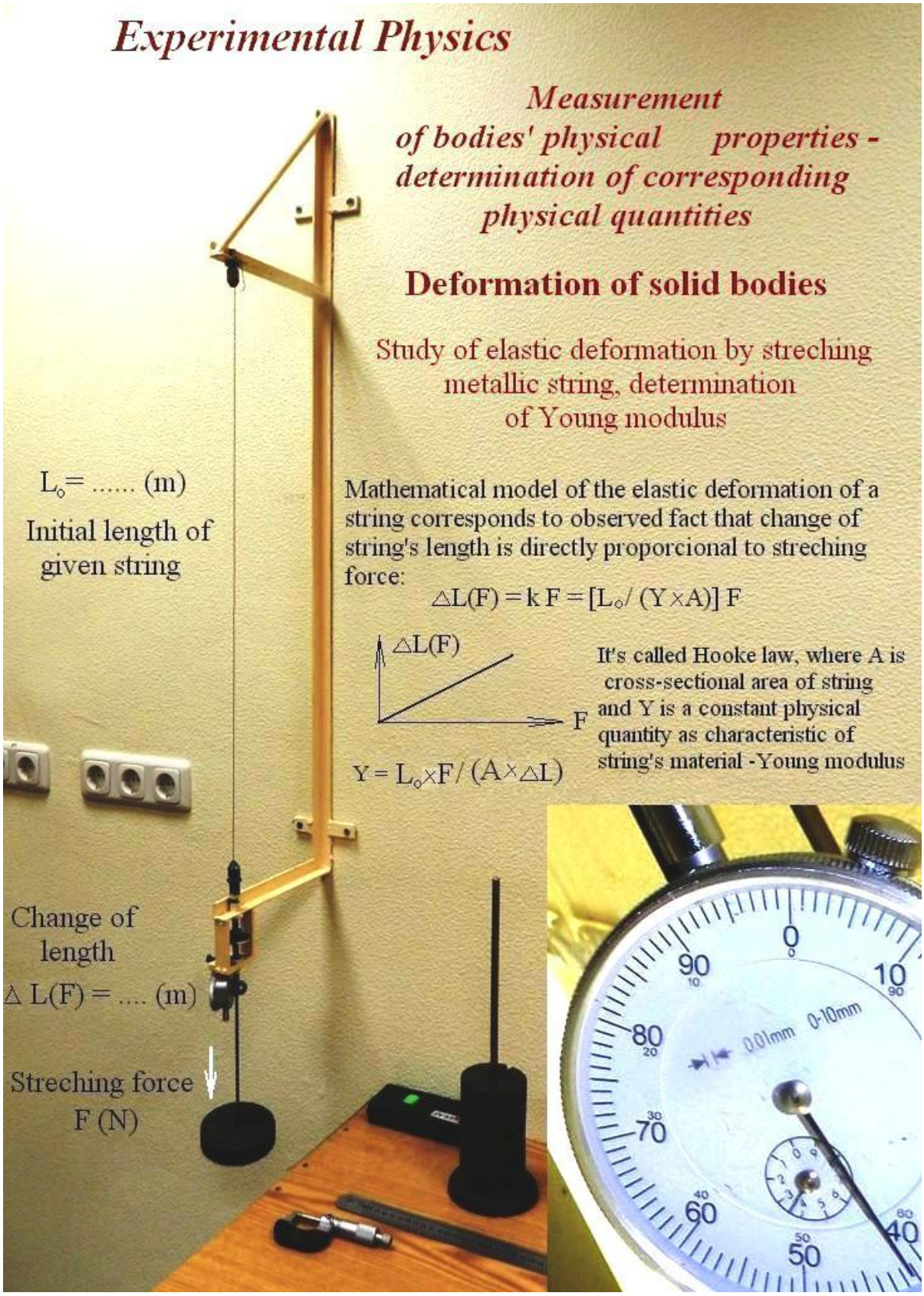
(magnitude of the stretching force in newtons)

$\Delta L = k \times F$

where $k = L_o / (\mathbf{Y} \times A)$ means the slope of function's graph and **Y is a constant, called Young modulus**, what value depends on the nature of the string's material

$$\Delta L = k \times F = L_o / (\mathbf{Y} \times A)$$

$$\mathbf{Y} = L_o / (k \times A)$$


Experimental Physics
Measurement of bodies' physical properties - determination of corresponding physical quantities
Deformation of solid bodies
Study of elastic deformation by streching metallic string, determination of Young modulus
L₀= ..... (m)
Initial length of given string
Mathematical model of the elastic deformation of a string corresponds to observed fact that change of string's length is directly proporcional to streching force:
△L(F) = k F = [L₀/ (Y×A)] F
△L(F)
F
Y = L₀×F/ (A×△L)
It's called Hooke law, where A is cross-sectional area of string and Y is a constant physical quantity as characteristic of string's material -Young modulus
Change of length
△ L(F) = ... (m)
Streching force
F (N)
0.01mm 0-10mm

Direct measurements of metallic string

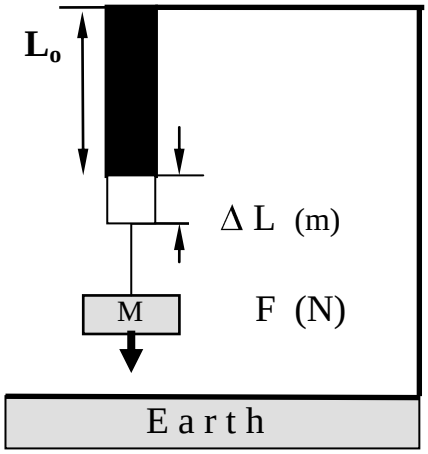
L_o = …… (mm) = …… 10^{-3} m

D = ……(mm) = …… 10^{-3} m

E x p e r i m e n t : stretching of metallic string

$A = \pi D^2 / 4 =$
$= 0.785\ D^2 =$
$=$ $=$
$=$ (m^2)

F (N) $= F_{gravitational} =$
$= M\ (kg) \cdot 10\ (m/s^2)$



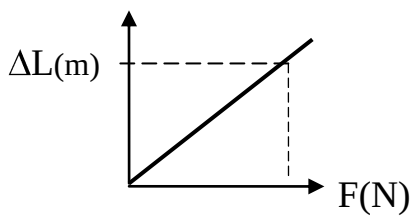
M (kg)	**Δ L** (m)	**F** (N)	**Δ L** (m)
$M_o = 0$	$\Delta L_0 = 0$	$F_0 = 0$	ΔL_{18} = … $\times 10^{-3}$
$M_1 = 0{,}5$	ΔL_1 = …… $\times 10^{-3}$	$F_1 = 5$	
1,0			
1,5			
2,0			
2,5			
3,0			
3,5			
4,0			
4,5	ΔL_9 =… $\times 10^{-3}$		ΔL_9 = …….$\times 10^{-3}$

Determination of Young's modulus using data from graph $\Delta L(F) = k \times F$

k = ΔL (m) / F (N) = ……

Y = $L_o / (k \times A)$ = …… =

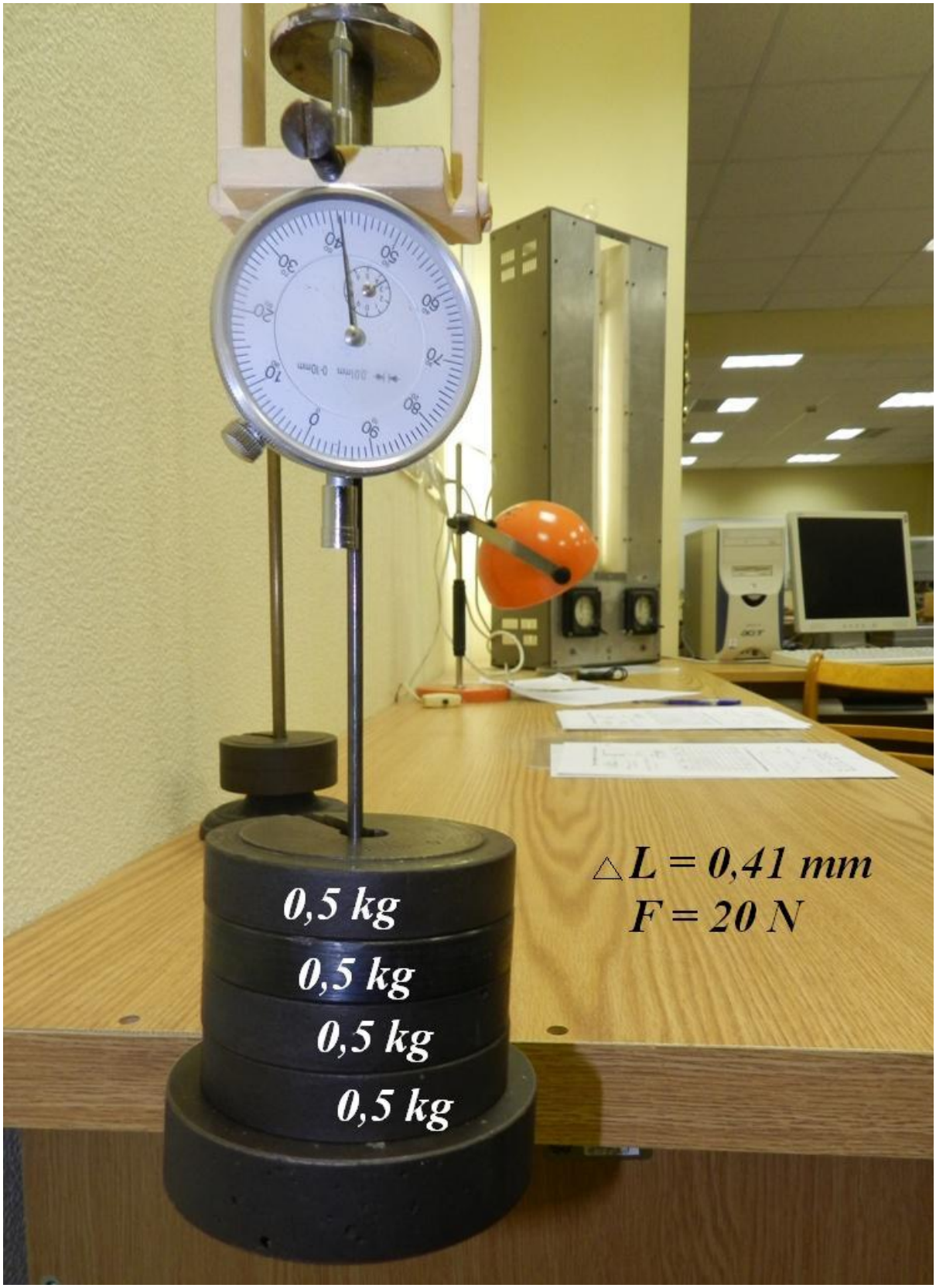
= …… (N/m^2)



Random experimental quantities of linear function's slope are averaged graphically

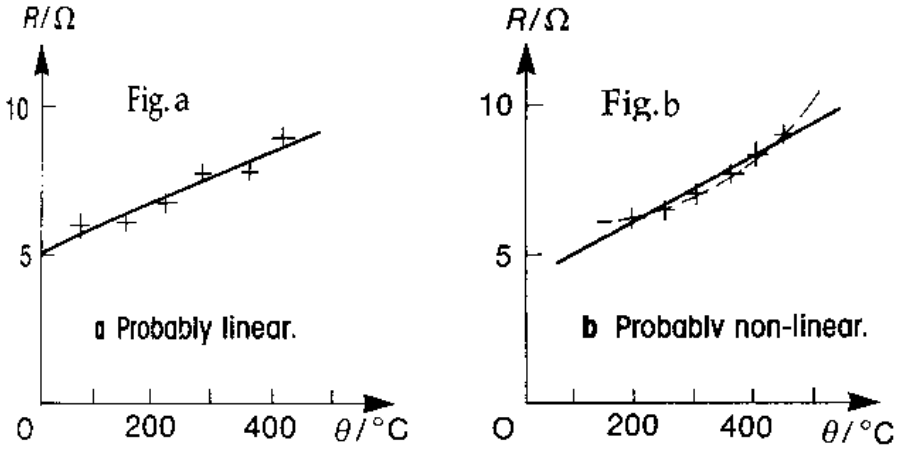
Teflon - 3.7×10^8 N/m^2
Nylon - 3.7×10^9 N/m^2
Aluminium - $0{,}69 \times 10^{11}$ N/m^2
Copper - 1.1×10^{11} N/m^2

Bo**ne (stretching)** - $1{,}6 \times 10^{10}$ N/m^2
Bone (compression) - $0{,}94 \times 10^{10}$ N/m^2


0,5 kg
0,5 kg
0,5 kg
0,5 kg
△L = 0,41 mm
F = 20 N

Non-linear relationships

Fig.a probably represents a linear relationship – the points are spaced either side of the line drawn. In Fig.b this is not so – remember the main reason for the



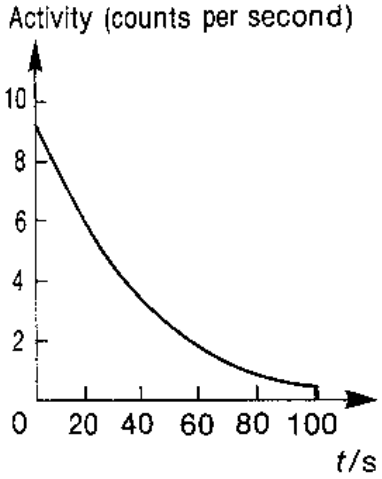
a Probably linear.

b Probably non-linear.

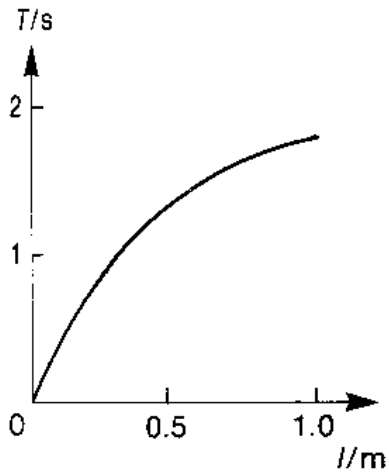
spread of points is random errors. Fig.b shows systematic deviations from the straight line drawn and a curve is probably a more accurate way of relating R and θ for the device.

The purpose of this section is to look at particular relationships and decide what form the final graph should take if it is to be a straight line. This will enable us to see whether the relationship is valid for our experiment and, more importantly, find the constants of the equation from the slope and the intercept.

The radioactive decay of a nucleus (activity) with time t



Variation of the period T of a simple pendulum with its length l

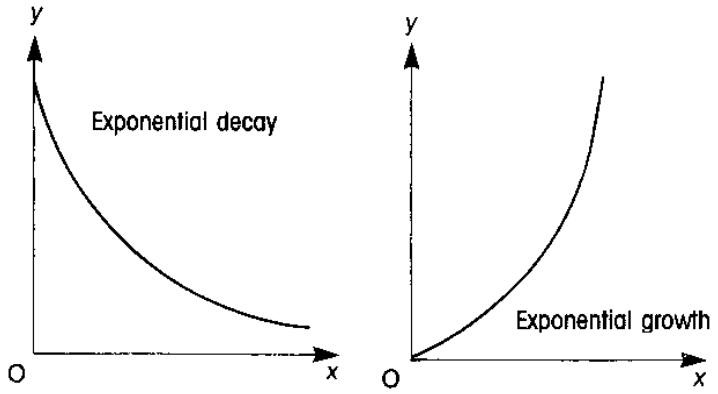


Many experimental relationships are not linear, that is a graph of y against x will be a curve.

Clearly the exact relationship could be worked out from the experimental curve, but it is difficult to distinguish between different types of curve over a small range of values and it is not easy to determine the constants from a curve. When plotting a graph during an experiment always plot the variables as measured and then decide whether the graph should be a curve or a straight line.

Exponential relationships

These have the form $y = a \exp(kx)$ or $y = ae^{kx}$. Usually in physics this type of relationship is met in decay, when k is negative.

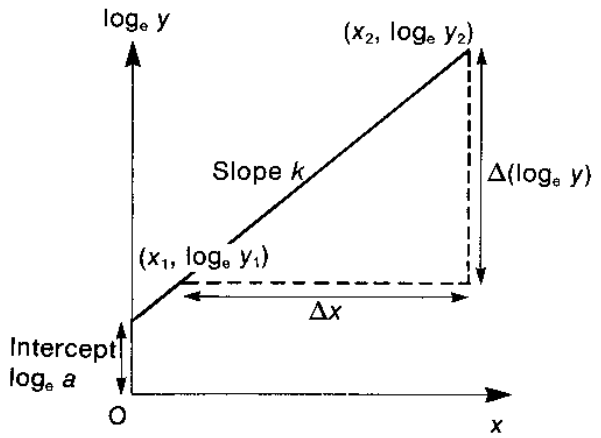


To produce a linear relationship for plotting we have to take logarithms to base e, (see footnote on page 23) which gives: $\log_e y = \log_e a + kx$

or: $\ln y = \ln a + kx$

Comparison with $y = mx + c$ shows that a graph of $\log_e y$ against x should give a straight line of slope k and with intercept on the $(\log_e y)$-axis of $\log_e a$.

Obtaining a linear relationship for $y = a \exp(kx)$



Exponential relationships

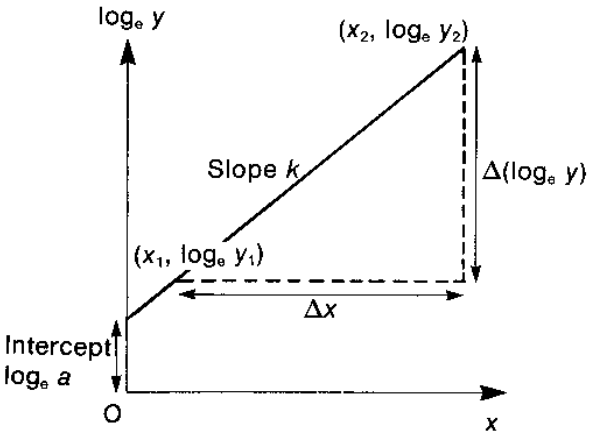
These have the form $y = a \exp(kx)$ or $y = ae^{kx}$. Usually in physics this type of relationship is met in decay, when k is negative.

To produce a linear relationship for plotting we have to take logarithms to base e, (see footnote on page 23) which gives: $\log_e y = \log_e a + kx$

or: $\ln y = \ln a + kx$

Comparison with $y = mx + c$ shows that a graph of $\log_e y$ against x should give a straight line of slope k and with intercept on the $(\log_e y)$-axis of $\log_e a$.

Obtaining a linear relationship for $y = a \exp(kx)$

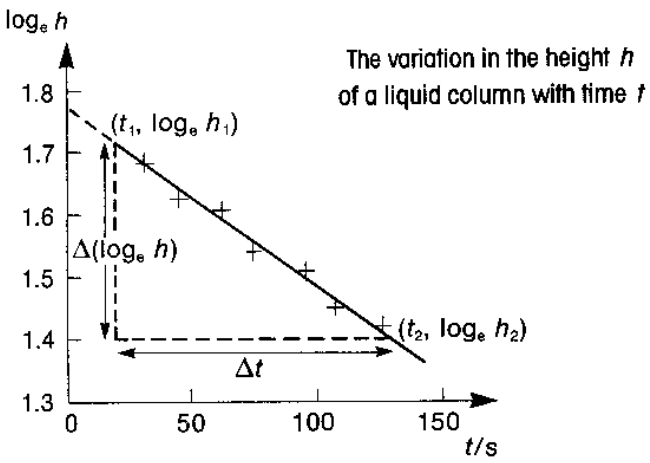


An example of this kind of relationship is the variation of the height of water flowing down a burette with time: $h = h_0 \exp(-\lambda t)$. This can be written as:

$$\log_e h = -\lambda t + \log_e h_0$$

hence the slope of the graph is $-\lambda$:

$$-\lambda = \frac{(\log_e h_2 - \log_e h_1)}{(t_2 - t_1)}$$

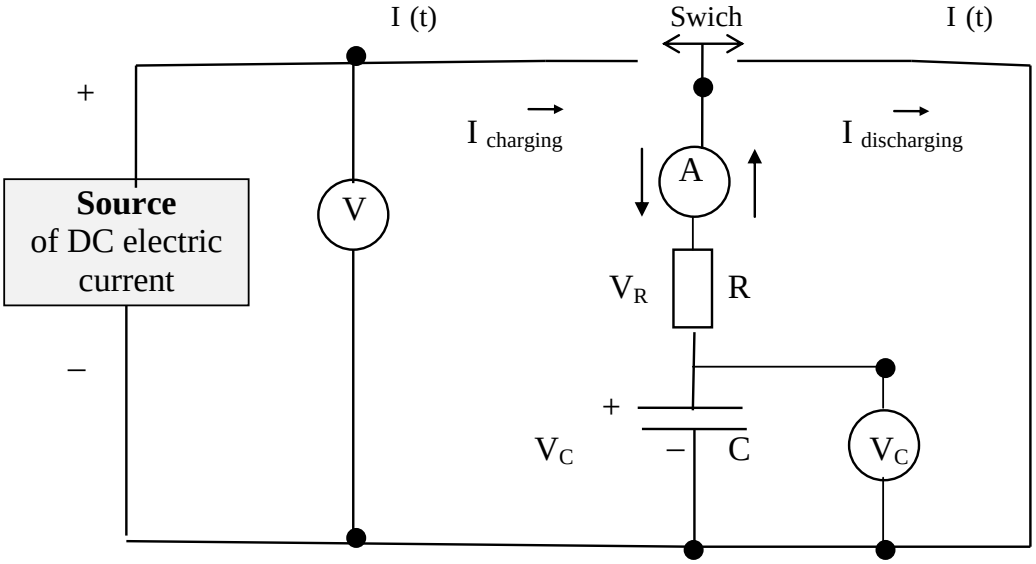


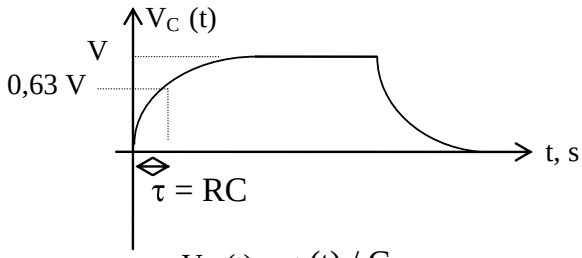
The time taken for the water to reach half of its original height is:

$$t_{\frac{1}{2}} = \frac{\log_e 2}{\lambda} = \frac{0.693}{\lambda}$$

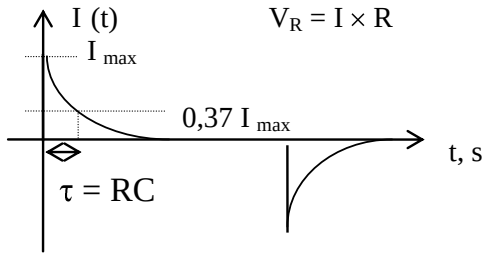
Another example is the variation of DC electric current and voltage when charging / discharging capacitor.

Direct (DC) electrical current I (t) when charging/discharging capacitor





$V_C(t) = q(t) / C$



$I_{ch}(t) = V / R \exp(-t / RC)$

$I_{disch}(t) = -V / R \exp(-t / RC)$

If R=50kΩ, C=100μF, then $\tau = 500s \approx 8min$

If V =5V, then $I_{max} = 100\ \mu A$

$$\mathbf{q(t) = C \times V_C(t)}$$

This is mathematical model of directly invisible physical – electric phenomena. We can directly observe only formal characteristics of the flow of electric charge : electric current and corresponding voltages.

5. Organization and realization of scientific experimental research

Introduction (what and why we are going to investigate?)

Theoretical background of research

Practical activities (organization and providing of measurements, data processing – getting final results)

Discussion of results

Conclusions (do we have reached the goal of provided research?)

Report / written and/or oral presentation of results