LABORATORY MANUAL

FOR EXPERIMENTS

IN

PHYSICS (20147)

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Experiment no. 1: Introduction to Errors and Graphs

Purpose of the laboratory:

In the study of physics there are several resources available to students. These include textbooks, lectures, and problem solving and laboratory exercises. The laboratory provides a unique opportunity to validate physical theories in a quantitative manner. Laboratory experience teaches students the limitations inherent in the application of physical theories to real physical measurements, and introduces ways to minimize experimental uncertainty. In general, the purpose of this laboratory exercise is to demonstrate some physical principles, and to give the student the chance to learn and appreciate the techniques of careful measurement.

Errors:

All measurements are subject to errors. There are three types of errors classified as personal, systematic and random errors. Random errors are sometimes called statistical errors. We shall deal with these errors in detail in this section.

Personal errors:

In fact, personal errors are not really errors in the same sense as the other two types of errors. Instead they are merely mistakes made by the experimenter. Sometimes they are called illegitimate errors. Mistakes are fundamentally different from the other two types of errors because mistakes can be completely eliminated if the experimenter is careful. These mistakes can be made either whilst taking data or later in calculations done with the original data. Both types of mistakes are bad, but mistakes made in data-taking processes are probably worse because often they are not discovered until it is too late to correct them. Mistakes made in data-taking processes include misreading of scales and recording data incorrectly.

Care must be taken to avoid mistakes in calculations of other quantities from the measured quantity. There are at least two kinds of mistakes that can be made in these calculations. The first kind of mistakes is to incorrectly state the equation for some derived quantity in terms of the measured quantities. For example, suppose that the distance an object travels, and the time it takes that object to travel that distance, are both

measured. The task is to calculate the average velocity of the object. The velocity can only be calculated correctly by dividing the distance by the time. Any other calculations using that data will not lead to velocity. A typical mistake might be to divide the time by the distance or perhaps multiply the distance by the time. Mistakes of this kind are difficult to detect when the first calculated quantity, in this case the velocity, is then used to calculate another quantity. For example, if an incorrectly calculated value for velocity is then used to calculate the acceleration, the results obtained for the value of the acceleration will obviously be incorrect.
The second kind of common mistakes occur when incorrect arithmetic operations are performed on a correct equation. Considering the fact that most students do all their calculations with hand-held calculators, these only amounts to pushing the wrong button, but it is a very common mistake. Again the best defense against such a mistake is to cultivate the proper habit of continually checking the calculations. If all performers do their own independent calculations, mistakes will often be found that would not be discovered if one person's calculations were unquestionably accepted by the group.

A first point to be made about calculations is, if possible, all calculations should be completed before leaving the laboratory. Not only are calculation mistakes more likely to be detected and corrected, but sometimes attempts to perform calculations with the data that have just been taken make it clear that mistakes were made in the data-taking process. If time permits, the original mistake made in taking the data can be corrected by performing the experiment again.

Systematic errors:
Systematic errors are errors that tend to be in the same direction for repeated measurements, giving results that are either above the true value or below it. In many cases some flaw in the experimental apparatus causes such errors.

It is difficult to deal with systematic errors caused by equipment problems in the laboratory. One cannot afford to spend a great deal of time each week assuming that all of the equipment has little or no error, A few quick measurements made by two groups on the same object will often serve to at least prove that both groups' equipment seems to perform the same or nearly the same. Although it may not be possible to eliminate a systematic error in this case, the experiment can be performed in such a way that any systematic error is minimized.

In this lab, we will deal with the systematic error in two ways:

1. Eliminating any obvious systematic error if possible.

2. Identifying any data that shows systematic error and suggesting possible reasonable cause for such errors.

Random Error:

The final class of errors is those that are produced by unpredictable and unknown variations in the total experimental process. The variations caused even when one does the experiment as carefully as possible. The variations caused by an observer's inability to estimate the last digit the same way every time definitely

be one contribution. Other variations can be caused by the fluctuations in line voltage, temperature changes, mechanical variations or any of the many physical variations inherent in the equipment. It is important to realize the following differences between random errors and personal and systematic errors. In principle all personal and systematic errors can be eliminated, but there will always remain some random errors in any measurement. We have two methods to measure any quantity experimentally, one can make several measurements for the same quantity and then took the final result, and the other is to make one reading only for this quantity. Random error can be calculated for each method in different way which will be described in the following section.

Calculation of Random errors

(I) For method of several reading.

In this method, random error can be determined by the following steps:

Step one: Calculation of the mean (average) value of the measured quantity. Assume a series of repeated measurements are made in which there are no systematic or personal errors, and thus only random errors are present. Assume there are N measurement made of some quantity X, and the i-th value obtained

is X_i, where i varies from 1 to N. The mean (average) value of the quantity X (whose symbol is X) is given by :

$$\bar{X} = \frac{\sum_i^N X_i}{N} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The symbol $\sum$ stands for a summation or in other words addition process in which the sum is taken from i = 1to i = N.

Step two: Calculation of standard deviation.

Statistical theory states that the precision of the measurement can be determined by calculation ofa quantity called the standard deviation from the mean of the measurement. The symbol for standard deviation is S, and it is defined by the following relation:

$$S = \sqrt{\left\{\frac{1}{N-1}\right\} \sum_i^N (X_i - \bar{X})^2} \quad \ldots\ldots\ldots\ldots (2)$$

Step Three: Calculation of random error. The precision of the mean is indicated by the quantity called random error. The random error whose symbol is σ is defined by

$$\sigma = \frac{S}{\sqrt{N}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Example: Assume four measurements are made of the same quantity X, the four results are 18.60,19.30,17.70,20.40. Find the mean value of X, the standard deviation S and the random error in the mean value then write the final result of the value of the quantity X .

Solution: From equation (1) the mean value of X is

$$\bar{X} = \frac{18.60+19.30+17.70+20.40}{4} = 19.00$$

The standard deviation S given by equation (2) is

$$S = \sqrt{\left\{\frac{1}{4-1}\right\}(18.60-19.00)^2 + (19.30-19.00)^2 + (17.70-19.00)^2 + (20.40-19.00)^2}$$

$$S = 1.14$$

The random error in the mean value σ is

$$\sigma = \frac{1.14}{\sqrt{4}} = 0.57$$

Then we can write the final result of the value of the quantity X as

$X = 19.00 \pm 0.57$

In our lab, the student will be often asked to make measurements of the same quantity and to calculate the mean value and the random error in the mean value.

(II) For method of one reading only.

If we made one measurement only to obtain the value of a certain quantity, then the rand m error in this value is given by the general form as

σ= 0.5 x least count of the instrument used the least count of the instrument means the minimum value that the instrument can read. The least count o any instrument can be obtained by means of the graduated marks on the instrument. For the simple ruler, as an example, the minimum mark graduated on it is 1 mm or 0.1 cm, so the least count of the simple ruler is 0.05 cm.

Now if we used the simple ruler to measure the dimension of a body or a distance between two points, then the random error in the obtained value is

$\sigma = 0.5 \times 0.1 = 0.05$ cm. As an example, if we measure the length of a body by the simple ruler for one reading only and give us the result equal to 23.6 cm, the error in this value according to the rule is 0.05 cm, then we write the final result as : length of the body

$L = (23.6 \pm 0.05)$ cm.

Each instrument used in our lab has its own least count which can be obtained for each

Errors in calculated quantities.

To obtain the random error for a quantity derived by calculation from other quantities, whose random errors are known, certain rules must be followed. Suppose variables X and Y are measured, the means X and Y and random errors of the means σ_x and σ_y are determined. Some quantity Z is calculated from the mean values X and Y. The question is: What is the random error σ_z of the calculated quantity Z in terms of σ_x and σ_y?

Here we deal with the following cases:

1. FOR $Z = \bar{X} + \bar{Y}$ or $Z = \bar{X} - \bar{Y}$

The error σ_Z is given by $\sigma_Z = \sigma_X + \sigma_Y$

2. For $Z = \frac{\bar{X}}{\bar{Y}}$ or $Z = \bar{X} * \bar{Y}$

The random error σ_Z is given by $\sigma_Z = \left(\frac{\sigma_X}{\bar{X}} + \frac{\sigma_Y}{\bar{Y}}\right) Z$

3. For $Z = \bar{X}^n * \bar{Y}^m$

The random error in this case σ_Z is given by :

$$\sigma_z = \left(\frac{n\sigma_x}{X} + \frac{m\sigma_y}{Y}\right)Z$$

Percentage error and percentage difference

In several of the laboratory experiments, the true value of the quantity being measured is considered to be known. In those cases the accuracy of the experiment will be determined by comparing the experimental result with the known value. Normally this is done by calculating the percentage error of the measurement compared to the given known value. If E stands for the experimental value, and K stands for the theoretical known value, then the percentage error is given by:

$$\text{percentage error} = \frac{|E - K|}{K} \times 100\%$$

In other cases a given quantity is measured by two different experimental methods. There will then be two different values, E_1 and E_2, but the true value may not be known. For this case the percent-age difference between the two experimental values is calculated. This will be a measure of the precision. The percentage difference between the two measurements is defined as:

$$\text{percentage difference} = \frac{|E_1 - E_2|}{(E_1 + E_2)/2} \times 100\%$$

Here the absolute difference between the two measurements has been compared to the average of the two measurements.

Graphs:

It is helpful to present data in the form of a graph as an aid to interpreting the overall trend of data. Most graphs in our laboratory will be drawn on Cartesian (rectangular) coordinates. The horizontal axis (x-axis) is called the abscissa, and the vertical axis (y-axis) is the ordinate. Any two variables can be plotted against each other in a graph.

The first thing to do in preparing a graph is to choose a scale for each one of the axes, not necessarily the same for both axes. Choose a scale that extends the graph over as much as possible of the sheet. Choose

scales that have the smallest divisions of the graph paper equal to multiples of 2, 5 or 10 units. This makes it much easier to connect the individual data points.

The scale should range from zero to greater than the largest value for any given set of data points. For example, if the largest value of a variable is 25.49 the scale must be chosen to range from 0 to 30 units. If a set of data contains ordinates that range from 60 to 90, do not choose a scale that shows only the range. Instead a scale from 0 to 100 should be chosen.

The axes should always be labeled with the names and units of he variables they represent. Major scale divisions should be labeled with the appropriate numbers defining the scale. Always include a title for each graph.

Case # 1

The relation between the coordinates (x, y) of any point on the straight line that passes through the origin is in the form y=mx

where x is the independent variable, y is the dependent one, and m is a constant. In general, the values of x and y are determined experimentally while the constant m is determined from the graph of y versus x. The graph of the above relation should look like the one in Fig. 1. It passes through the origin, since when x = 0 we get y = 0.

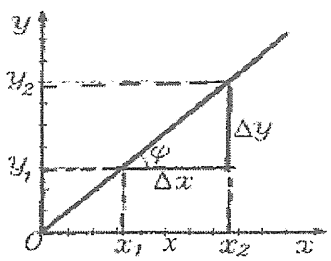


Fig. 1

The tangent of the angle Φ that the straight line makes with the positive x-axis is called the slope of the line .

$$\text{i.e. } \tan\varphi = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}$$

From the relation $y = m\,x$, $\frac{\Delta y}{\Delta x} = m$. We conclude that the constant m is given by the slope of the straight line of y against x.

Case # 2

The relation between the coordinates of any point (x, y) on the straight line is in the form y=m x+b

Here again, x and y are variables obtained experimentally, while m and b are constants to be determined from the graph. Note .when x = 0, we have y = b. The line does not pass through the origin, but intersects the y-axis at point b as shown in Fig. 2.

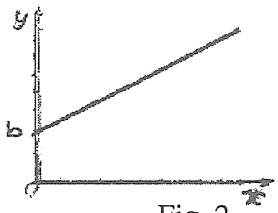


Fig. 2

The constant b is called y-intercept. It can be determined easily from the y-axis scale. The constant m is the slope of the straight line as mentioned in case # 1.

Now, if b is negative, the graph of y = f(x) will be as shown in Fig.3

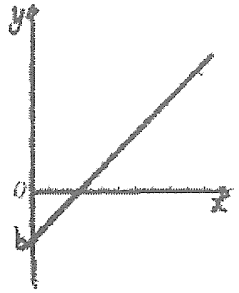


Fig. 3

The SI system of units:

The international system of units (SI) was approved in 1960 by the conference of weights and measures. It is coming into increasing use throughout the world because of its many advantages over other systems of units.

The SI system of units is based on seven basic units:

Physical quantity	Unit	Symbol
length	meter	m
mass	kilogram	kg
time	second	s
electric current	Ampere	A
temperature	Kelvin	K
luminous intensity	candela	cd
amount of substance	mole	mole

All other units are derived from these units. The more important derivative units, which all have special names, are as follows:

Physical quantity	Name of unit	Symbol & derivation
Energy Force	Joule Newton	J =kg.m^{2} s-2 N=J.m-^{1}
Power	Watt	W = 1.s-^{I}
Electric charge Electric	Coulomb	C=A.s
potential difference Electric	Volt	Y=W.A-I
capacitance	Farad	F = cv-!
Magnetic flux	Weber	Wb=Y.s H
Inductance Magnetic	Henry	= Y.s.A-^{I}
flux density	Tesla	T=wb.m-^{2}
Luminous flux	Lumen	lm = cd.sr "
lllumination	Lux	lx = Im.m-^{2}
Frequency	Hertz	Hz=s-I .

* Note: The abbreviation for the unit of solid angle, steradian, is Sf.

Any other units are made of combinations of these and the basic units. e.g. kilogram per cubic meter (kg.m-$^{3)}$ for density, Newton per square meter (N.m-$^{2)}$ for pressure, and ohm-meter (Ω.m) for resistivity.

Table 1: Some prefixes for powers of ten.

Power	Prefix	Abbreviation
10^{-18}	atta	a
10^{-15}	femto	f
10^{-12}	pico	b
10^{-9}	nano	n
10^{-6}	micro	μ
10^{-3}	milli	m
10^{-2}	centi	c
10^{-1}	deci	d
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{15}	peta	P
10^{18}	exa	E

Table 2: The Greek Alphabet.

Name	Capital	Lower case	Name	Capital	Lower case
Alpha	Α	α	Nu	Ν	ν
Beta	Β	β	Xi	Ξ	ξ
Gamma	Γ	γ	Omicron	Ο	ο
Delta	Δ	δ	Pi	Π	π
Epsilon	Ε	ε	Rho	Ρ	ρ
Zeta	Ζ	ζ	Sigma	Σ	σ
Eta	Η	η	Upsilon	Υ	υ
Theta	θ	ϑ	Phi	Φ	φ
Iota	Ι	ι	Chi	Χ	χ
Kappa	Κ	κ	Psi	Ψ	ψ
Lambda	Λ	λ	Tau	Τ	τ
Mu	Μ	μ	Omega	Ω	ω

Experiment no. 2 Basic Measurements I

A) The Vernier caliper
B) The micrometer caliper

Objectives:

1. Using a Vernier caliper and a micrometer caliper to demonstrate the concept of experimental uncertainty in simple measurements.

2. Applying the statistical concepts of mean, standard deviation from the mean, and the standard error to simple measurements.

3. Demonstrating the propagation of errors by the determination of the uncertainty in the volume calculated from the measured length and radius.

Apparatus:

Vernier caliper, micrometer caliper, cylindrical cups, and wires of different radii.

Theory:

Physics is an experimental science, and as such, it is a science of measurements. The measurement of the dimensions is of fundamental importance in scientific work; hence it is fitting to begin experimental work with this type of measurement. In this experiment repeated measurements of the dimensions of different objects will be used to accomplish the objectives of the experiment.

Measurement of length

The measurement of length is the simplest exercise required from a student of science, and the use of scales of length should be familiar to every one before dealing with any precise scientific work. The accuracy required in various kinds of length measurement is, however, widely different, and we will consider the methods of obtaining these various degrees of accuracy in typical cases.

It should be noted here that in all measurements of length two observations must be made, one at each end of the length measured, and that therefore the possible error of the value of the length obtained is double the error of each observation.
The accuracy of observations made with an ordinary scale is limited, because the dividing lines have a finite thickness, and because the eye can not estimate fractions of divisions in the order of 0.1 mm. In any estimation of length made with ordinary scale, therefore the accuracy is not greater than 0.5 mm. If accuracy of a higher order is needed, it is essential that apparatus should be used to assist eye, and the divisions of the scale should be marked with fine regular lines.

The proper use of the meter stick might seem to need little explanation--one simply holds it against the object being measured and computes the difference between the readings at the extremes of the object. Yet, even during such a simple operation, a couple of errors are commonly made. Both involve the manner in which the meter stick is held

The parallax (line-of-sight) error can occur when the actual measuring scale is not up against the object being measured. When such is the case, the reading will depend upon the line-of-sight of the experimenter. (See Figure 1) The resulting reading will be of questionable value. This error is considered a blunder and should be avoided.

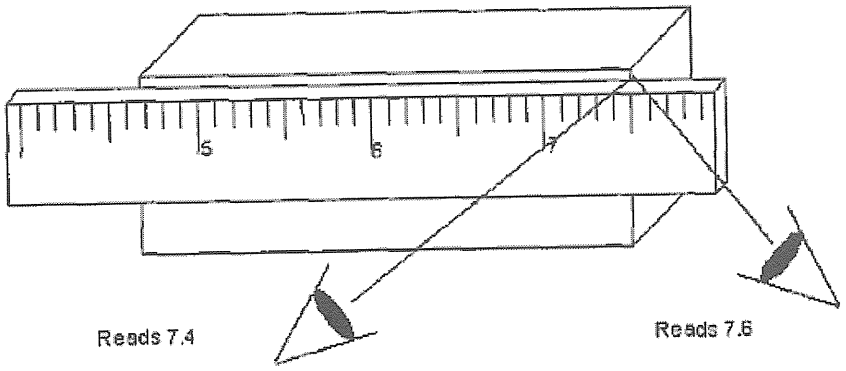


Fig.1 The Parallax error

By holding the measuring scale directly against the object, a good reading can be taken irrespective of the line of sight of the experimenter. (See fig. 2).

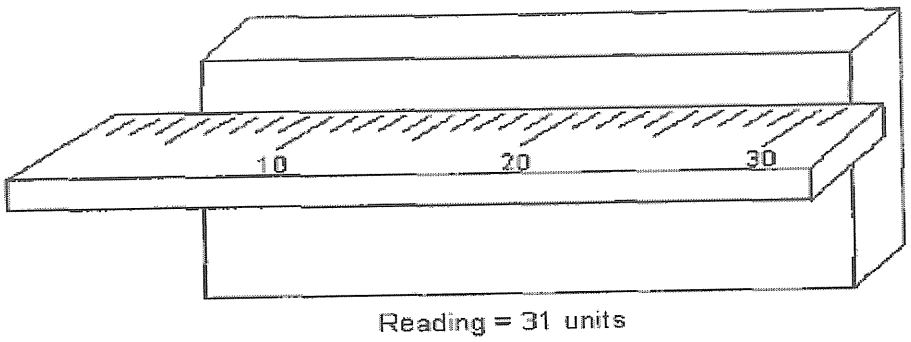
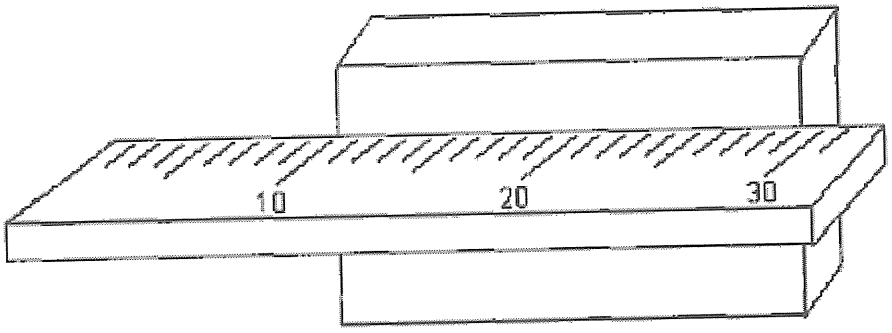


Fig. 2 Better positioning of a meter stick

A "zero-error" is also common because the end of the meter stick is often assumed to correspond to a reading of "zero". For real meter sticks, such is usually not the case. The discrepancy might be due to the manufacturing process or to the wearing-down of the meter stick with use. In Figure 3, a technique that avoids the zero-error is illustrated. (Notice that a couple of units are worn off the left end of the stick.) The end of the meter stick is not used. Rather some convenient reference is chosen such as the 10 unit mark. The length is then the difference between the extremes.



Measured length = 29-10units = 19units

Fig. 3 avoiding the zero error

The Vernier Caliper:

A typical Vernier caliper is pictured in Figure 4. It consists primarily of two parts: the main frame and the movable frame. Often the frame will include both English and metric scales and the number of lines on the Vernier can be more than the number shown here.

The outside caliper jaws are used to measure the outside dimensions of an object while the inside caliper jaws are used to measure inside dimensions (such as the inner diameter of a tube). The depth gauge can measure the depth of holes.

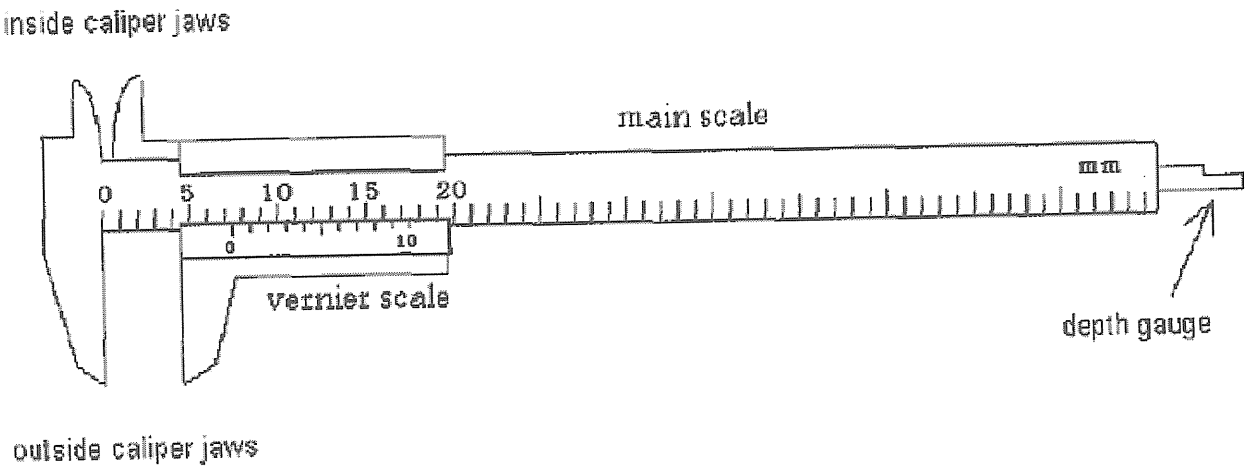


Fig. 4 A Vernier Caliper

In using the Vernier Caliper, therefore, the least count must be first determined according to the following general rule

Least count of Vernier Caliper = The value of the smallest division on the main scale divided by the number of divisions on the vernier scale.

In our lab, the Vernier Caliper has a smallest value on its main scale equal to 1 mm, and the vernier scale divided into 20 divisions, thus according to the general rule, the least count our Vernier Caliper is equal to 1/20 = 0.05 mm

This means that the space between each line on the vernier scale equal to 0.05 mm.

It should be noted that the least count of the Vernier Caliper shown in fig 4 has a least count according to the general rule equal to 1/10 = 0.1 mm.
Consider the following examples of the way in which Vernier Caliper shown in fig 4 should be used.

Example:
To read the Vernier caliper, one first looks to see where, on the main scale, the zero line of the movable scale (the "index line") lies. In general it will not line up exactly with any line on the main scale but will exceed some line by some fraction of the least count. (See Figure 5.) The purpose of the movable or "Vernier" scale is to indicate that fraction to the nearest tenth. One counts the lines of the Vernier scale from the left (starting with zero) until one comes to a line that is best aligned with a main-scale line. The number of that Vernier line indicates the number of tenths by which the reading exceeds the number just to the left of the index line.

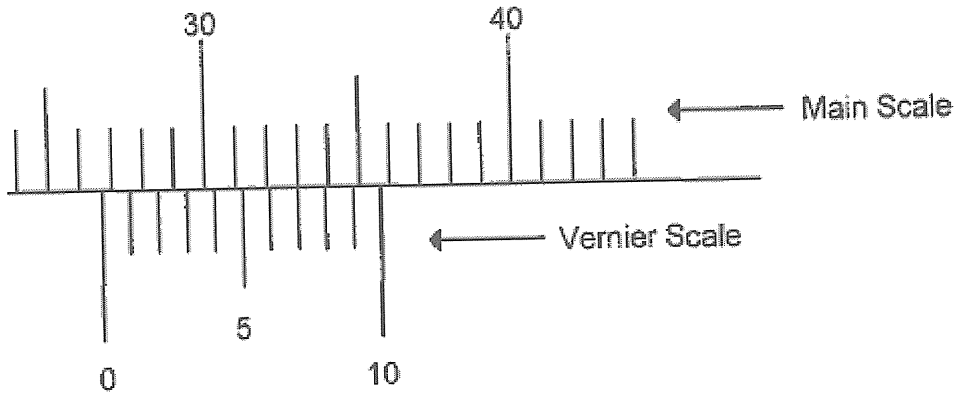


Fig. 5 A basic Vernier scale

The index line indicates 26 mm + some fraction. Since the 7th line of the Vernier scale is aligned with a main-scale line, that fraction is .7 mm and the reading is 26.7 mm. Since the alignment of the seventh line was clear, we assign an uncertainty of one-half the least count, namely .05 mm. The measurement value is then 26.7 ± .05 mm.

Example:

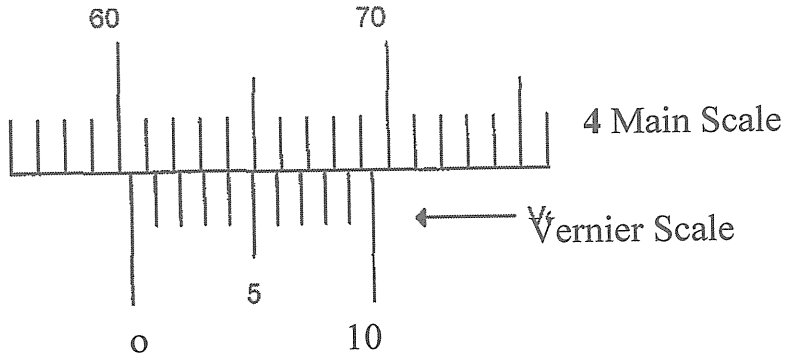


Fig. 6

The index line indicates 60. + a fraction. Since the 4th line of the Vernier scale is aligned, the fraction is .4 mm. Thus the reading is 60.4 mm. If the alignment was clear, we assign an uncertainty of one-half the least count, namely .05 mm. Then the recorded value should be 60.4 ± .05 mm.

Example:

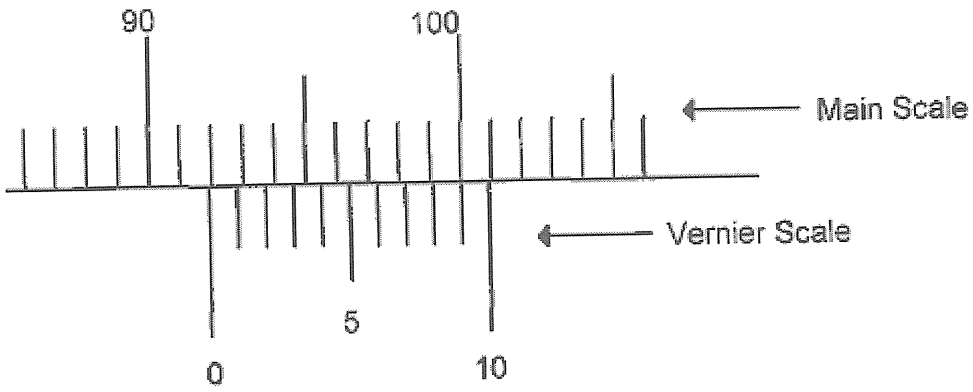


Fig. 7

The proper reading here is 91.9 ± .05 mm.

The micrometer Caliper:

A typical micrometer caliper is shown in Figure 8

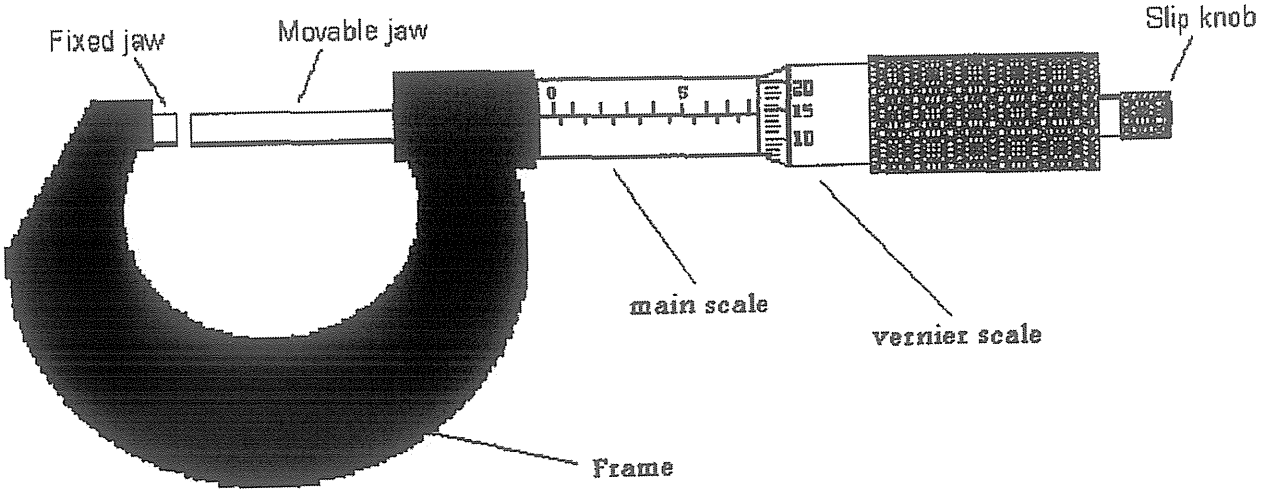


Fig. 8 The micrometer caliper

The movable jaw advances or recedes when the thimble is rotated due to screw threads inside the sleeve. (Important: when closing the jaws, do not turn the thimble directly but rather tum the slip knob. This will prevent damage to the instrument and guarantee a consistent exertion of pressure on the jaws.)Because one revolution of the screw advances the jaw exactly .5 mm, the fifty equally spaced markings around the circumference of the thimble each correspond to 0.5/50th of.5 mm or .01 mm. Furthermore, as the thimble turns it reveals more of the sleeve scale. Between these two scales, very accurate readings are possible. An experimenter with a sharp eye can even make estimates of readings that lie between lines on the thimble scale.

Example:

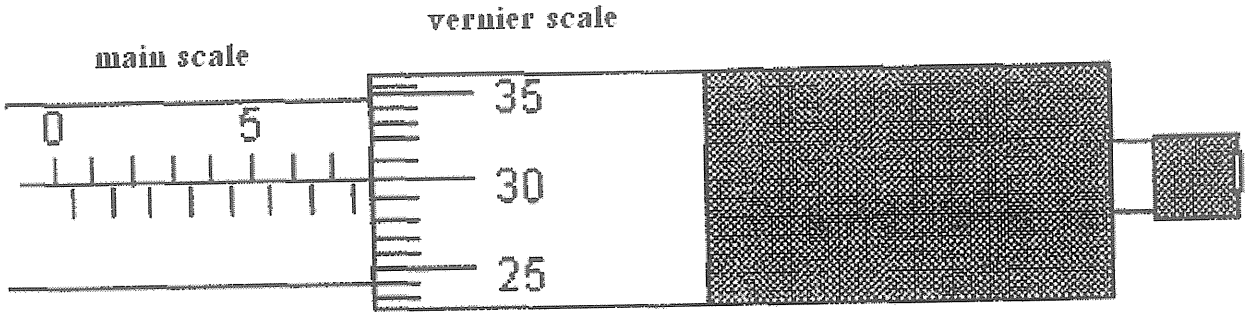


Fig. 9

From the location of the thimble edge on the sleeve scale, one reads 7.5 mm + a fraction. From the location of the index line (the horizontal line on the sleeve) on the thimble scale one reads 0.30 mm, Thus: reading = 7.80 mm. Actually, because the index line was so well lined up with the 30, one might dare to say the reading is 7.800 ±. 005 mm.

Example:

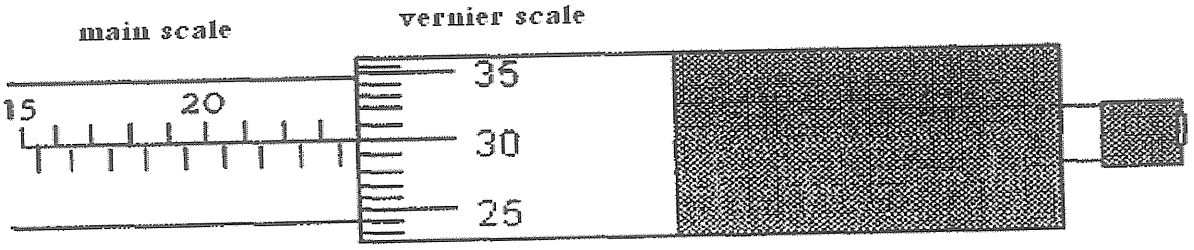


Fig. 10

From the sleeve scale, the reading is 23.5 mm + fraction. From the thimble scale, the fraction is 0.30.Then the total reading is 23.8 mm. was an estimate, its. Then the reading should be recorded as 23.8 ± .005 mm.

Example:

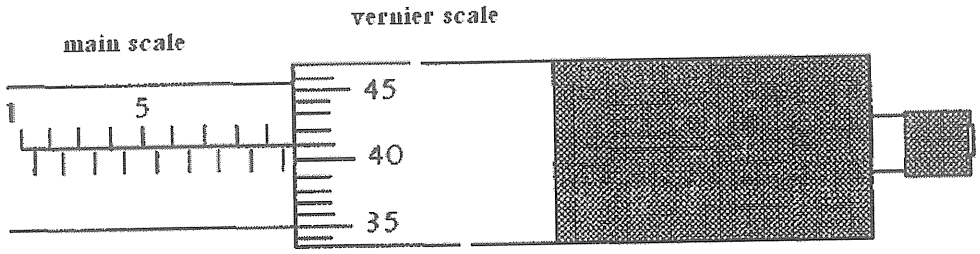


Fig. **11**

From the sleeve one reads 9.5 mm plus a fraction. From the thimble: fraction = 0.41mm
Then the reading is 9.91 ± .005mm.

The possibility of a zero-error also occurs with the micrometer caliper. To check the calibration, simply close the jaws completely, using the slip knob, and take the reading. If the reading is non-zero, ask your teacher to adjust it.

Procedure:

A. The Vernier caliper

1. Use the Vernier caliper to measure the diameter ofa thin wire. Repeat the measurement five times at different positions. Record the results in data table I in the laboratory report.
2. Use the Vernier caliper to measure tile outside diameter, the inside diameter and the depth of the cylindrical cup (figure 7). Record tile results in data table 2.

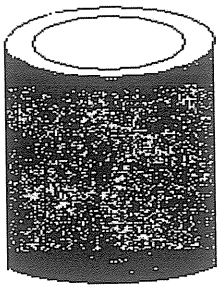


Figure 7: Cylindrical cup.

B. The Micrometer Caliper

1 Take the zero reading of the micrometer caliper, closing the jaws each time with the ratchet.

2. Take three measurements for the diameter of the copper wire. These readings should not all be taken at the same position, but should be so distributed over the body that good average values are obtained. Record the results in data table 3.

3. Repeat the above steps for the other two wires.

Experiment no. 3 Basic Measurement II

The Spherometer

Objectives:

To determine with a spherometer the radii of curvature of spherical surfaces, and the thickness of the microscopic slide.

Apparatus:

Spherometer, plane surface, spherical surfaces, microscopic slide, ruler.

Theory:

The spherometer is an instrument used for measuring the radius of curvature of a spherical surface. In many cases as, for example, when dealing with a lens, the surface is only a small portion of a sphere. In such cases the radius of curvature is the radius of the imaginary sphere of which the surface forms a part.

The spherometer, as shown in figure 1, has three arms radiating from the center. The legs are mounted on these anus; the legs and micrometer screw at the center have hardened and polished points. The micrometer screw is accurately cut and the large graduated head is used to determine fractions of a turn. The vertical scale on the left is used to determine the number of complete turns. It is obvious that the reading of the spherometer, which indicates the vertical position of the point on the micrometer screw, is obtained by combining the readings of the vertical and circular scales.

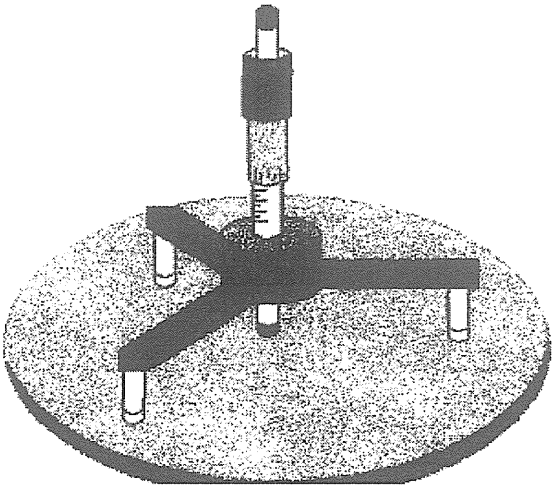


Figure I: The spherometer.

Since the points of the spaced at a distance S from each other, and an equilateral triangle (d e f) may be constructed with these points as shown in figure 2, these three points determine a circle of radius r, and when the point of the micrometer screw is in the plane of this figure it is at the center of the circle and at a distance r from each leg. It can be shown that

$$r = \frac{S}{\sqrt{3}} \quad \text{.....} \quad (1)$$

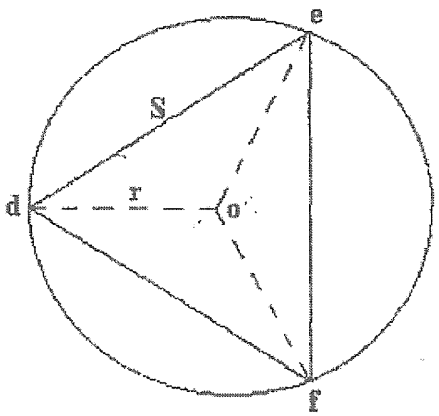


Figure 2: The equilateral triangle formed by the points of the spherometer's legs.

Figure 3 is a vertical cross-section spherometer's legs are equally showing the spherometer resting on a spherical surface. The leg L and the micrometer screw M are in the plane of the paper. The other two legs, one behind and one in front of the

plane of the paper, are indicated by L . From this diagram, it should be evident that the distance a is given by the difference in reading of the spherometer when all four points touch the plane surface and when these points touch the spherical surface. From the geometry of the figure it may be shown that the radius of curvature R of the spherical surface is given by the equation:

$$R = \frac{S^2}{6a} + \frac{a}{2} \quad \text{.....} \quad (2)$$

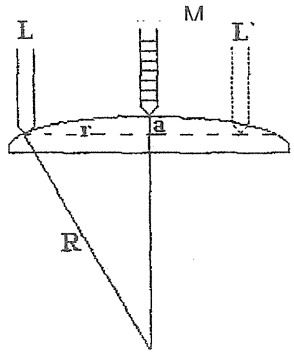


Figure 3: Cross -section showing the spherometer on a spherical surface.

In using a spherometer the first thing to be done is to determine the value of the divisions of the two scales, since all instruments are not graduated in the same way. Find out how far the screw advances when the head is turned through one complete revolution. The way of taking the spherometer reading is the same as that described in the micrometer caliper (Lab. 2; section B).

Procedure:

Before proceeding to take observations, it is necessary to become familiar with the spherometer. Study the spherometer and make sure that you understand the method of combining the vertical and circular readings.

1. Place the spherometer on the plane surface, using the knurled knob. Adjust the instrument so that all four legs rest equally on the plane surface. Various methods may be used to indicate when tins adjustment has been made properly. The

following one is suggested. Hold one of the arms lightly between thumb and finger, and push the arm gently back and forth in a direction perpendicular to its length. It is evident from the feel of the instrument when it is resting on all four legs. If the fourth leg is too low, the instrument rotates freely around it. Make three observations of the reading on a plane surface. To reduce the chance of error it may be advisable to record the readings of the vertical and circular scales separately, as well as the combined reading as shown in data table I in the laboratory report.

2. Take the first spherical surface (the large one) and make a set of three readings with the fourth leg of the micrometer touching the top of the surface (the convex surface). In a similar manner take a set of readings with the fourth leg of the spherometer touching the bottom of the surface (the concave surface). Care must be taken that the fourth leg is in the middle of the surface. Record all the results in data table 2.

3. Place a piece of smooth paper on a flat plate and press the points of the spherometer legs against this paper so that these legs leave fine punctures in the paper. Use a ruler to measure the distance S between each pair of legs. Record the results in data table 2.

4. In a manner similar to the one outlined above, take sets of spherometer readings for the other two spherical surfaces. Be sure to replace the legs of the spherometer to fit with each surface.

5. Place the microscopic slide on the plane surface and take a set of three readings with the fourth leg of the spherometer touching the top o fthe slide. Record the results in data table 3.

6. Compute the radius of curvature of each of the spherical surfaces and the thickness of the microscopic slide.

Experiment no.4 Static Equilibrium

Composition of Concurrent Forces

Objectives:

1.Demonstration of the process of the addition of several vectors to form a resultant vector.

2. Demonstration of the relationship between the resultant of several vectors and the equilibrant of these vectors.

3. Illustration and practice of graphical solutions for the addition of vectors.

4. Illustration and practice of analytical solutions for the addition of vectors.

Apparatus:

I. Force table with pulleys, ring, and string.
2. Mass holders and slotted masses.
3. Protractor, ruler.

Theory:

Physical quantities that can be completely specified by magnitude only are called scalars. Examples of scalars include temperature, volume, mass and time. Some physical quantities have both magnitude and direction, and these are called vectors. Examples of vector quantities include displacement, velocity and force. In this laboratory a force table will be used to determine the magnitude and direction of several simultaneously applied forces to accomplish the objectives of the experiment.

As an example of the process of vector addition, consider the case of several forces with different magnitudes and directions which act at the same point. It is desired to find the net effect produced by several forces by finding a single force which is equivalent in its effect to the effects produced by the several applied forces. That single force is called the resultant force.

This resultant force can be found theoretically by a special addition process known as vector addition.

First consider the process of force addition by geometrical teclmiques. Fig.1a shows the case of two vectors A and B which are assumed to represent two forces. The forces are assumed to act at the same point (concurrent forces) with an angle θ between the forces A and B.

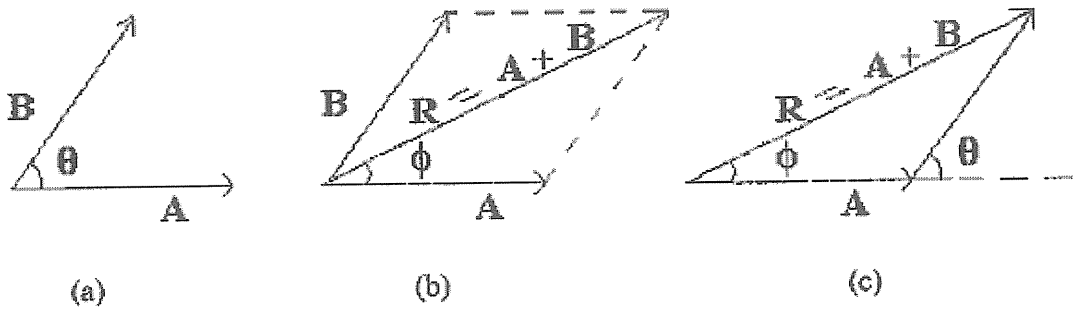


Figure 1:1llustration of the parallelogram and triangle addition of vectors.

The parallelogram rule of addition is shown in fig. 1 .b. In this method, the resultant vector R is the diagonal of the parallelogram formed with A and B as its sides. The resultant vector R acts in a direction <I> with respect to the direction of A.

In the geometrical method known as the polygon method, one of the vectors to be added is drawn with its tail starting at the head of the preceding vector. The resultant vector is then the vector drawn from the tail of the first vector to the head of the last one. Fig.1c. shows this process for the case of only two vectors. Note that the second vector B, must be drawn at the proper angle relative to A by extending a dotted line in the direction of A and constructing B relative to that dotted line.

The polygon method is illustrated for the case of three vectors in fig2.
Note carefully that each successive vector must be drawn in the proper relationship to the previous vector. Thus vector A is first drawn, B is then drawn at the proper angle *a* relative to A and C is drawn at the proper angle I) relative to B. Finally the resultant vector R is the vector connecting the tail of A and the head of C.

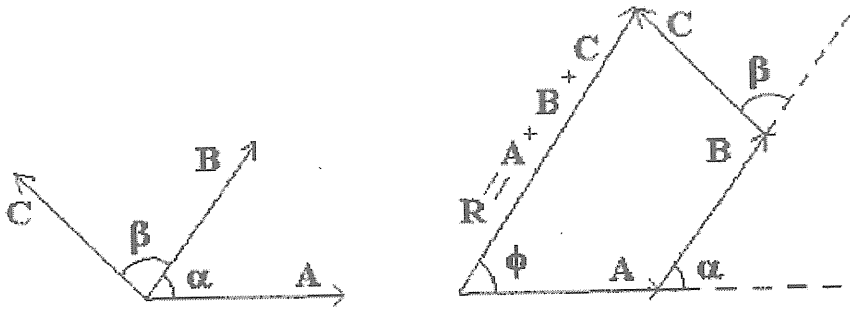


Figure 2: Illustration of the geometrical method for vector addition

The analytical process uses trigonometry to express each vector in terms of its components projected on the axes of a rectangular coordinate system. The process of determining the components of a vector is illustrated in figure 3.

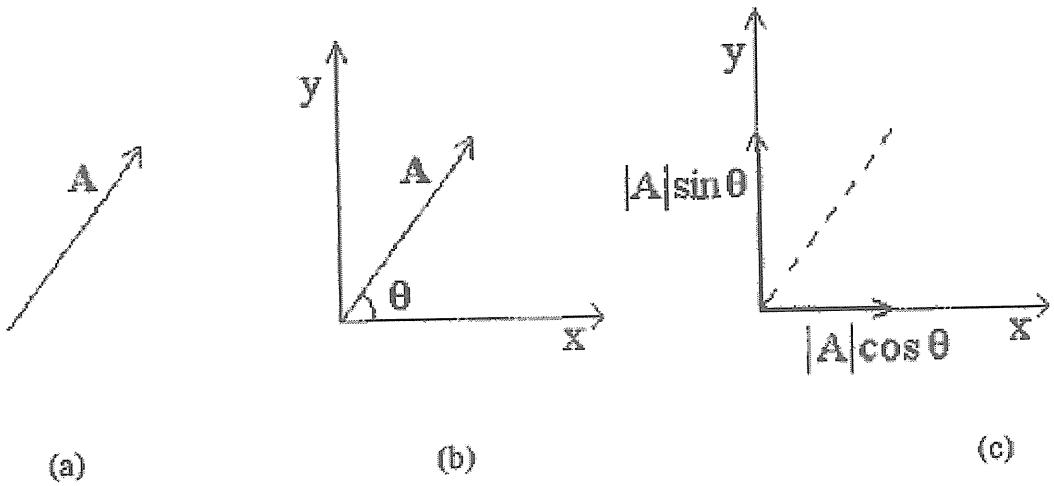


Figure 3: Illustration of analytical resolution of a vector.

In figure 3.a a vector A is shown. In figure 3.b the vector A is shown with a rectangular coordinate system, and in figure 3.c the components of the vector along the axes are shown to be |A| cos θ along the x-axis and |A| sin θ along the y-axis,

In the process of vector addition each vector to be added is first resolved into components as shown in figure 3.c. The components along each axis are then added algebraically to produce the net component of the resultant vector along this axis. Those components are at right angles, and thus the magnitude of the resultant vector can be found from the Pythagorean theorem.

Consider the case of three vectors A, B and C shown in figure 4. Assume that their magnitudes are 10, 15 and 20 and their directions relative to the x-axis are as shown in that figure. Taking the algebraic sum of each of the components of the three vectors leads to the following :

$$R_x = A_x + B_x + C_x = 10\cos 0^0 + 15\cos 30^0 - 20\cos 45^0$$
$$R_y = A_y + B_y + C_y = 10\sin 0^0 + 15\sin 30^0 + 20\sin 45^0$$

Note carefully that the x-component of the C vector is negative because it points to the left which is the negative x-direction. The magnitude of the resultant vector, **R,** is found to be the following:

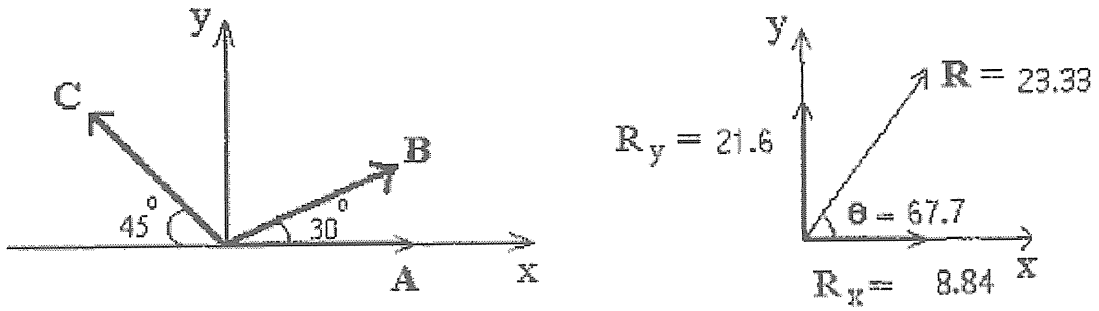


Figure 4: Illustration of the analytical addition vectors.

$$\lfloor R \rfloor = \sqrt{R_x^2 + R_y^2} = \sqrt{(8.84)^2 + (21.6)^2} = 23.3$$

The angle θ that the resultant vector makes with the positive x-axis is given by the following equation:

$$\theta = \tan^{-1}\left(\frac{R_y}{R_x}\right) = \tan^{-1}\left(\frac{21.6}{8.84}\right) = 67.7^0$$

The process of experimentally determining the value of the resultant of several forces is complicated by the fact that when a non zero-resultant force acts on an object it tends to be accelerated. Thus, another force must be applied to produce an equilibrium. For example, if two known forces F_1 and F_2, are applied to some object, they will have some resultant R. In order to keep the object in equilibrium, a force equal in magnitude and opposite in direction of R must be applied. The force applied in order to produce equilibrium is called the equilibrant force E.

For any numbers of applied forces ($F_1, F_2, F_3, \ldots$)The equilibrant force E is the force that must be applied in order to keep an object in equilibrium. The magnitude and direction of this equilibrant force E can be found from the knowledge that Rand E have the same magnitude but opposite directions.

The force table used in the experiment is designed to allow the application of forces of any chosen magnitude at any chosen angle. The force is provided by the gravitational attraction on masses that are attached to a ring by a string passing over a pulley, and the pulley's position can be adjusted to any desired position around a circular plate. It is important to note that the force applied when a mass is hung on the string is equal to the weight of the mass. The weight (in Newton) is equal to the product of mass (in kilograms) multiplied by the acceleration due to gravity (9.8 m/s').

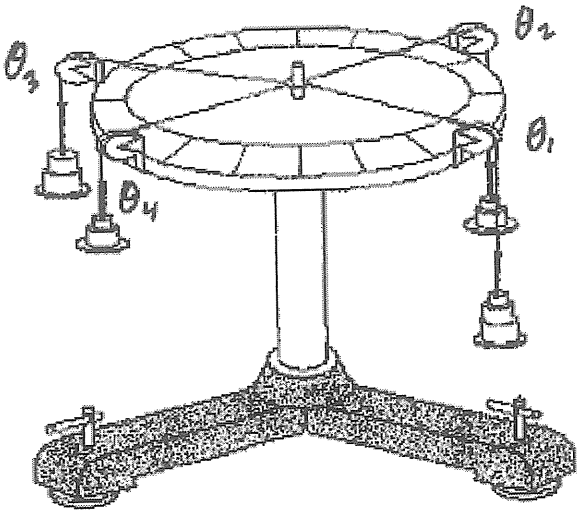


Figure 5: The force table apparatus.

Procedure:

Part 1. Two applied forces

1. Place a pulley at the mark θ_j on the force table and place a mass A kg on the end of the string, (θ, and the mass A will be defined by the instructor). Be sure to include the mass of the holder in the total mass hanged. Calculate the magnitude of the force (in Newton) produced by the mass. Record the value of θ_1) and the value of the force F_1 in data table 1 in the laboratory report.

2. Place a second pulley at the mark θ_2 on the force table and place a mass of B kg on the end of the string. Calculate the force produced as F_2. Record θ_2 and F_2 in data table 1.

3. Experimentally determine the magnitude of mass needed and the angle at which it must be placed in order to place the ring in equilibrium. The ring is in equilibrium when it is centered on the force table. Be sure that all the strings are in such a position that they are directed along a line that passes through the center of the table.

4. For the experimentally determined mass calculate the force produced as E and record the magnitude of the equilibrant force E and its direction Φ in data table 1.

5. Using trigonometry, calculate the components of F, and F_2 . Add the components algebraically and determine the magnitude of the resultant R by using the Pythagorean theorem. Determine the angle of the resultant from the arctan of the components. Record the results in data table 1.

6. Repeat the above steps for many different values of A and Band their locations. Record the results for each case in data table 1.

Part 2. Three applied forces.

1 Place a pulley at θ 1 with A kg on it, and place another one at θ_2 with B kg on it and one at $\theta_3$with C kg on it (θ_1, θ_2, θ_3, A, B and C will be defined by the instructor).
2 Calculate the force produced by those masses and record the results as F_1, F_2, and F_3 in data table 2 in the laboratory report.
3 Follow the procedure in part 1 from step 3 to step 6, and record the result in data table 2.

Experiment no. 5 Newton's Second Law
Acceleration Due to Gravity (g)

Objectives:

To determine acceleration by analysis of displacement versus time, and to determine the acceleration due to gravity.

Apparatus:

Air Track, photo gates and stands, photoelectric timer, trolley, air pump.

Theory:

When a net force F acts on a mass M, an acceleration a is produced. The relationship between these quantities is given by Newton's second law as F=Ma.

Consider a trolley mass m_2 placed on a horizontal air track and connected to a second mass m, by a string running over a pulley, as shown in Fig.1. Then the trolley system mass M ($M = m_1 + m_2$) is subject to a net force m.g, and undergoes one dimension motion with a uniform acceleration a. That is

$$F = m_1 g = Ma = (m_1 + m_2)\, a \quad \ldots\ldots\ldots\ldots\ldots (1)$$

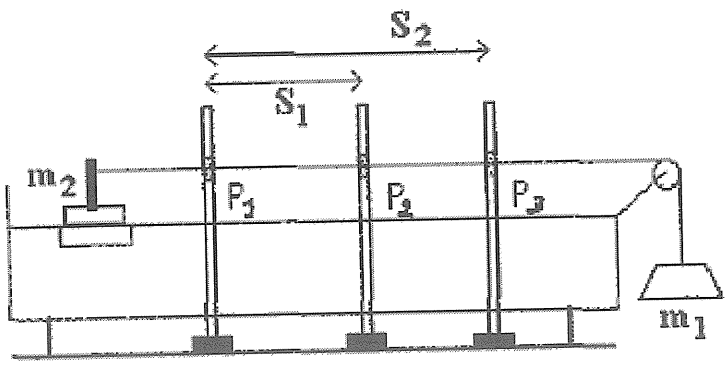


Figure 1: Force applied to mass m_2 by the weight of mass m_1

In this experiment offer three (or four) photo gates and stands on the air track, as shown in Fig.1. When the trolley passes any position where a photo gate has been mounted, then the photoelectric timer automatically record the time.

As shown in Fig.1, we can determinate the acceleration as follows; the trolley passes the position P_1 of the first photo gate at time $t = 0$ with velocity V_1 and it passes the second photo gate P_2 at time $t = t_1$, and passes the third photo gate P_3 at time $t = t_2$. Then we have the relations:

$$S_1 = P_2 - P_1 = V_1 t_1 + a t_1^2 /2 \quad \text{.....} \quad (2)$$

and

$$S_2 = P_3 - P_1 = V_1 t_2 + a t_2^2 /2 \quad \text{.....} \quad (3)$$

therefore due to equations (2) and (3), one obtains

$$a = 2(S_2 t_1 - S_1 t_2) / t_1 t_2 (t_2 - t_1) \quad \text{.....} \quad (4)$$

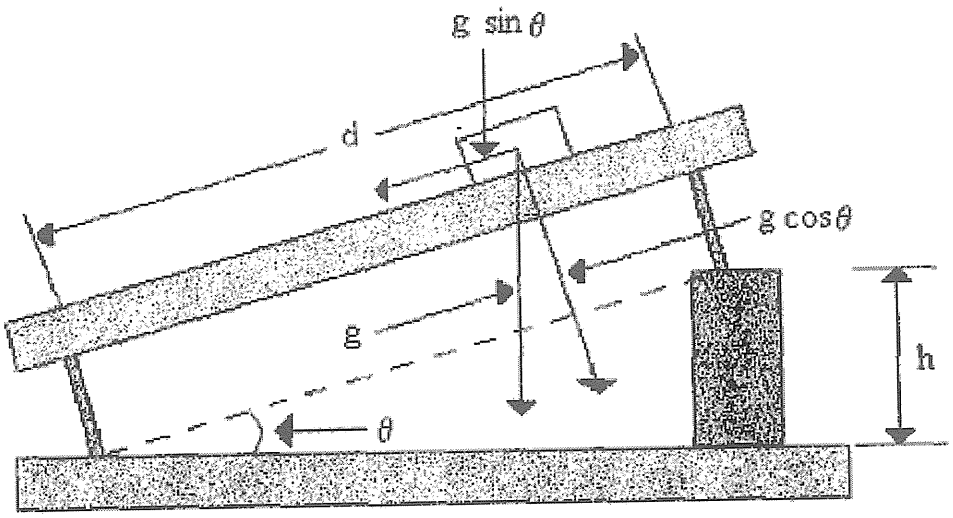


Figure 2: Components of g (the acceleration due to gravity) on an air track. If an object goes down an inclined plane, then its acceleration is the component of the acceleration due to gravity g, as shown in Fig.2, i.e.

$$a = g \sin(\theta) \quad \text{.....} \quad (5)$$

If θ is given (or $\theta = \pi/2$, free fall body) and a is determined experimentally, equation (5) can yield the value of g.

Procedure:

1. Set up the apparatus as shown in Figure 1, and insert a block under one end of the air track as shown in Figure 2.

2. Start the air pump, and put the rubber band on the air track to avoid the trolley colliding the air track.

3. Connect the photo gates to the photoelectric timer and adjust their heights to fit the trolley.

4. Let the trolley slide down the air track. Record the data P_1, P_2, P_3, t_1, t_2, h, and d in the data table in the laboratory report.

5. Employ the formulae mentioned in the theoretical part of the experiment to calculate the other quantities as listed in the data table.

Experiment no.6 The Simple Harmonic Motion
Single Spring

Objectives:

1. Direct determination of the spring constant k of a spring by measuring the elongation of the spring for specific forces.

2. Indirect determination of the spring constant k of a spring from measurements of the variation of the period T of oscillation for different values of mass.

3. Comparison of the two values of the spring constant k.

4. Demonstration that the period T of oscillation of a mass on a spring is independent on the amplitude of the motion.

Apparatus:

Simple harmonic apparatus, spring, weights, scale pan, electric balance, stop timer.

Theory:

Simple harmonic motion is an oscillatory motion that can be described by a single sine or cosine function. An object undergoes simple harmonic motion when it is subject to a force that is proportional to its displacement from an equilibrium position. In equation form
$F = -kx$ describes such a force where k is a constant whose dimensions are N/m. The minus sign indicates that the force is in the opposite direction of the displacement. If the spring is the object exerting such a force, the constant k is called the spring constant. An object that experiences a restoring force proportional to its displacement from an equilibrium position is said to obey Hooke's law.

An object subject to a restoring force will undergo a type of oscillatory motion that is called simple harmonic motion. If the object is displaced from its equilibrium position by some value A and then released, the object will oscillate back and forth about the equilibrium position. The values of its displacement x from the equilibrium position will range between $x = A$ and $x = -A$. The quantity A is called the amplitude of the

motion. For the initial condition described above, the displacement x as a function of time t is given by:

$$x = A\cos\left(\frac{2\pi}{T}t\right) \quad \text{.....} \quad (1)$$

Where T is the period of the motion. The period T is equal to the time for one completed oscillation from the maximum displacement on one side of equilibrium (+A), to the maximum displacement on the other side of equilibrium (-A), and back to the original position (+A)

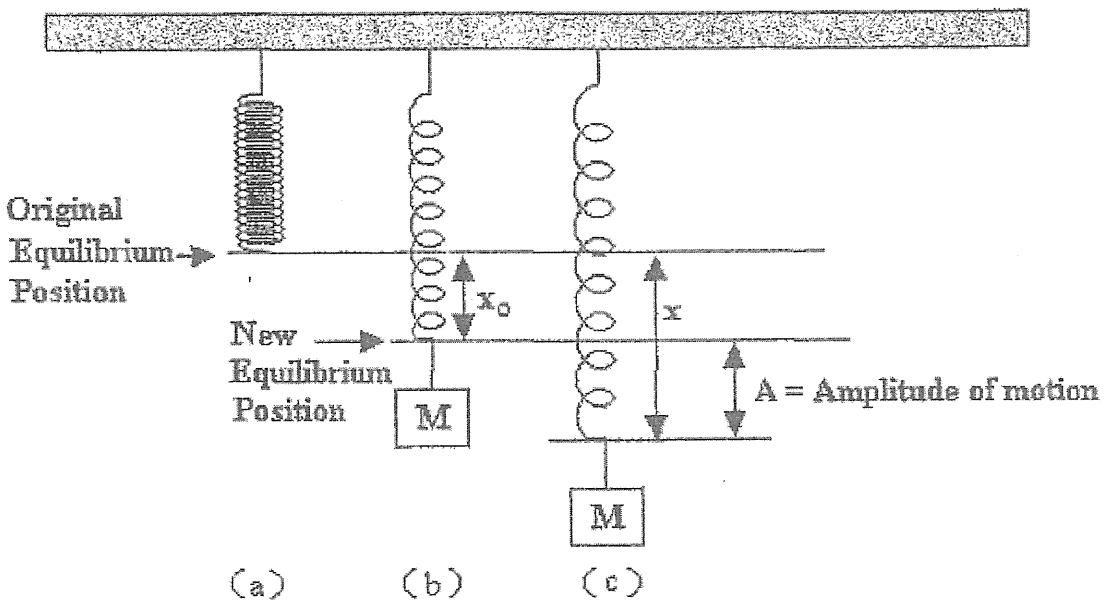


Figure 1: New equilibrium position with mass M placed on a spring.

Consider a mass M placed on the end of a spring which is hanging vertically as shown in figure 1. The original equilibrium position of the lower end of the spring is shown in figure I-a, and the position of the lower end of the spring when the mass is applied is shown in figure I-b. For purpose of determining the oscillatory motion, the position shown in figure I-b can be considered as the new equilibrium position, and displacement can be measured from that point. In figure I-c the mass is shown pulled down to displacement A from the equilibrium position. When released, the mass will oscillate with amplitude A.

The period of oscillation of the spring is independent of the amplitude A. It depends only upon the spring constant k and the mass M. The period T is given by

$$T = 2\pi\sqrt{\frac{M}{k}} \quad \text{.....} (2)$$

Equation (2) is strictly true only if the spring is mass less.

Procedure:

Determination of the spring constant *k*.

1. Suspend the spring so that it hangs vertically from a rigid support, and attach the scale pan to the lower end. Clamp a small pointer to the scale pan so that it moves lightly against the scale as shown in figure 2.

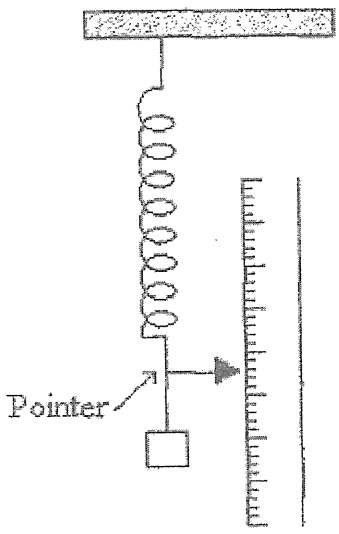


Figure 2: Spring and attachments.

2. Place a slotted weight of mass 100 gm on the scale pan. Wait until it hangs at rest in equilibrium when released. Carefully read the position of the pointer on the meter stick scale. Record the value of the mass M (including the mass of the scale pan) and the pointer reading x in data table 1 in the laboratory report.

3. Increase the load by successive increment of 100 gm, and record the pointer readings each time.

4. When about ten readings have been taken, start unloading the weights and again record the pointer readings. Record all values in data table 1.

5. Draw a graph with the values of the mass M as ordinates against the corresponding values of the mean pointer readings x.

The graph will probably of the shape shown in figure 3.

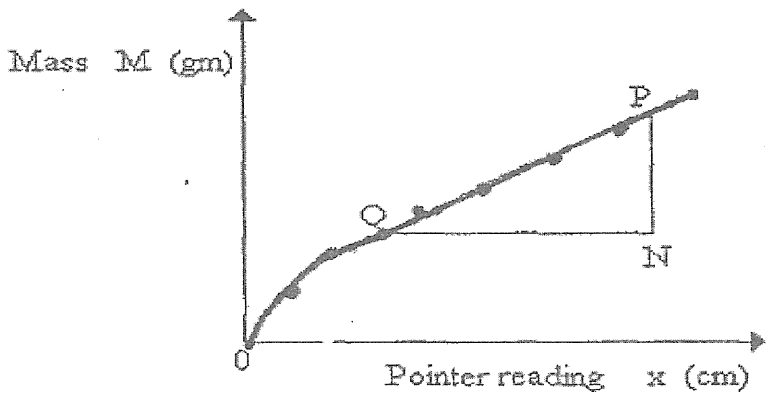


Figure 3: A plot of mass against the pointer reading for a spring.

For the straight line portion of the graph QP it is seen that any increase in the mass is proportional to the extension PN it produces, which is Hooke's law.

Note that the initial curved portion of the graph AB is probably due to the fact that in the early stages of the experiment some turns of the spring are pressing against each other.

From the slope of the straight line, the value of the spring constant k is obtained.

Experiment no.7 Simple Harmonic Motion

Combination of two springs

Objectives:

To find the equivalent force constant of two springs connected first in parallel and second in series connection.

Apparatus:

Simple harmonic motion apparatus, two identical springs, set of weights.

Theory:

A. Compound Springs

The physical concepts of motion, force, energy, and momentum, are often confused. The distinctions are particularly clear in the spring–model of matter.

Combining two or more identical springs, yields a new object with the properties of a spring, but with a combined spring constant that can be larger than, equal to, or smaller than the original. The combined spring changes the amount of distortion that results from a given set of applied forces or, equivalently, increases (or decreases) the reaction forces generated by a given length change.

Examples given in the previous chapters showed springs placed in a side-by-side orientation called a *parallel* combination. Springs can also be attached end-to-end in a *series* combination. The parallel combination will be treated first, followed by the series combination, with its surprisingly different behavior, that will illustrate the difference between the concepts of force and energy.

B. Springs in parallel

Springs placed side by side and joined at the ends by a strong coupling will act in parallel. Springs with the same natural length and spring constant k are considered first.

It makes sense that the parallel connection of springs each with a spring constant k, shown in Figure1, is stronger than any one of the springs. The parallel combination, therefore, exhibits a spring constant that is larger than k. Consider stretching the parallel combination so that each spring provides an inward force, F. To create that stretch, an outward force, $3F$, is required on each side. The force required to change the length of the parallel combination by an amount, x, is three times as large as is needed to make the same change to only one of the springs. This means that the spring constant of the parallel combination is $3k$, or three times the spring constant of a single spring.

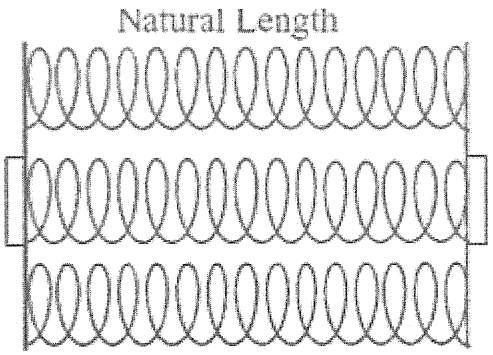


Figure .1 Three identical springs, spring constant, k, connected in parallel

The reasoning above can be translated into a derivation using one step of algebra. That derivation, though simple, is an example of what can be done with physics: take a simple law ($F = kx$ for an ideal spring, in this case), apply it to new conditions (springs grouped in parallel and series), and predict the resulting behavior (the combined spring constant).

To illustrate, we start with a natural length ideal spring with spring constant, k, which is then stretched a distance, x, by a force, F (one on each side), as shown in Figure2a. The force and resulting stretch are related through Hooke's Law, $F = kx$. At each end, the tension force generated by the stretched spring has the same magnitude as the applied force, $T = F = kx$, as demanded by Newton's 3rd law.

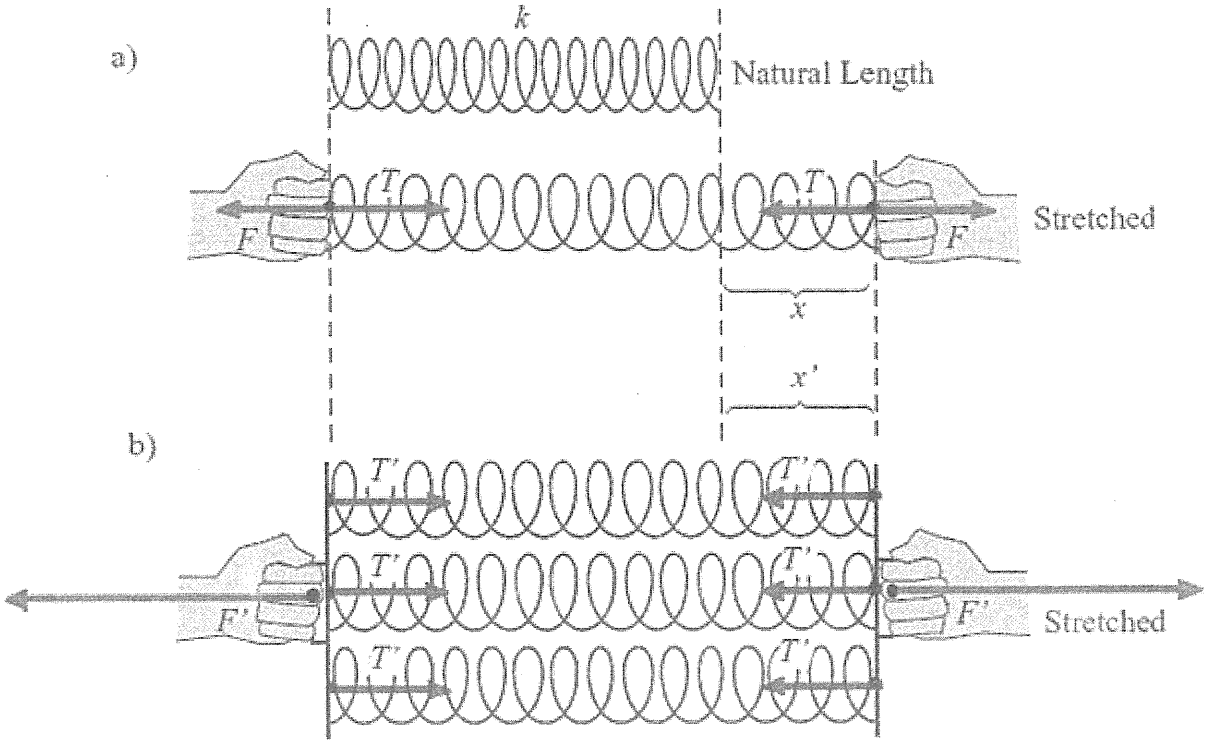


Figure 2 a) A spring with spring constant k, being stretched a distance, x, and b) three of these springs connected in parallel and stretched by the amount, $x' = x$.

Three of these springs are placed side by side, as shown in Figure 2b, with their ends connected to form a parallel combination, and stretched by a different force, F', stretched by a distance, x', generating a tension force, T', in each spring. The stretch is adjusted to be equal to the previous stretch

of the single spring, $x' = x$. For the three springs in parallel, how does the combined spring constant, k_{eq}, compare to k of a single spring
(a prime, ', is attached to a variable if its value may have changed).

The parallel combination of three springs should behave like a new spring, spring constant, k'. The relationship between the applied force, F', and the length change, x', should be, $F' = k_{eq}x'$, and therefore,

$$k_{eq} = \frac{F'}{x'} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad 1$$

The connected springs, and the single spring, are stretched the same distance $x' = x$, and therefore the response of *each* spring to this stretch is to generate the same tension, $T' = T = kx$. The net effect of the three tension forces acting inward on the connection bracket, must be *balanced* by the applied force, F', acting outward on the handle. These words translate into the algebraic equivalent, $F' = 3T' = 3kx$.

Replacing F' and x' in Equation 1 with their equivalents completes the proof,

$$k_{eq} = \frac{F'}{x'} = \frac{3kx}{x} = 3\,k \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 2$$

A parallel combination of n identical springs is n times as strong as one spring: $k_{eq} = 3k$.

C. Springs in series

A series connection of three ideal springs, as shown in Figure 3, is actually *weaker* than any one of the individual springs. The reasoning here is as follows: a single spring stretched a distance x, by a force F, creates a tension $T = F$.

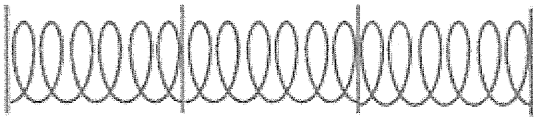


Figure 3 Three identical springs, spring constant, k, connected in series

Applying the same force, $F' = F$, to three such springs attached in series, as shown in Figure 4, yields a stretch three times as great. This implies a *weaker* spring. There is an action – reaction pair of tension forces at each contact point. The tension in the two outer springs stretches the central spring, and the tension in the central spring provides one of the applied forces on the outer springs.

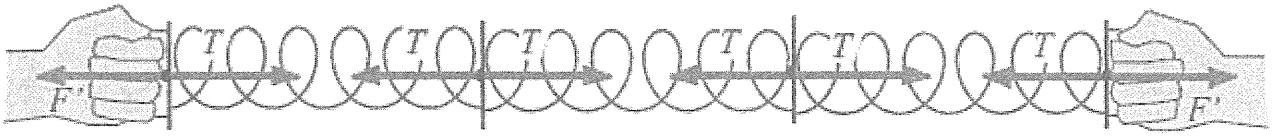


Figure 4 The tension T in each spring in response to the stretching forces F'.

The spring constant, k_{eq}, of the series combination is determined by relating the force on the end springs, F', to the full stretch of the combination, x', by Hooke's law, repeated below in Equation 3,

$$k_{eq} = \frac{F'}{x'} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; 3$$

The formal solution for the new spring constant, k_{eq}, starts with three identical stationary springs, spring constant, k, each stretched a distance, x, by a force, F, of a pair of hands, as shown below in Figure 5.

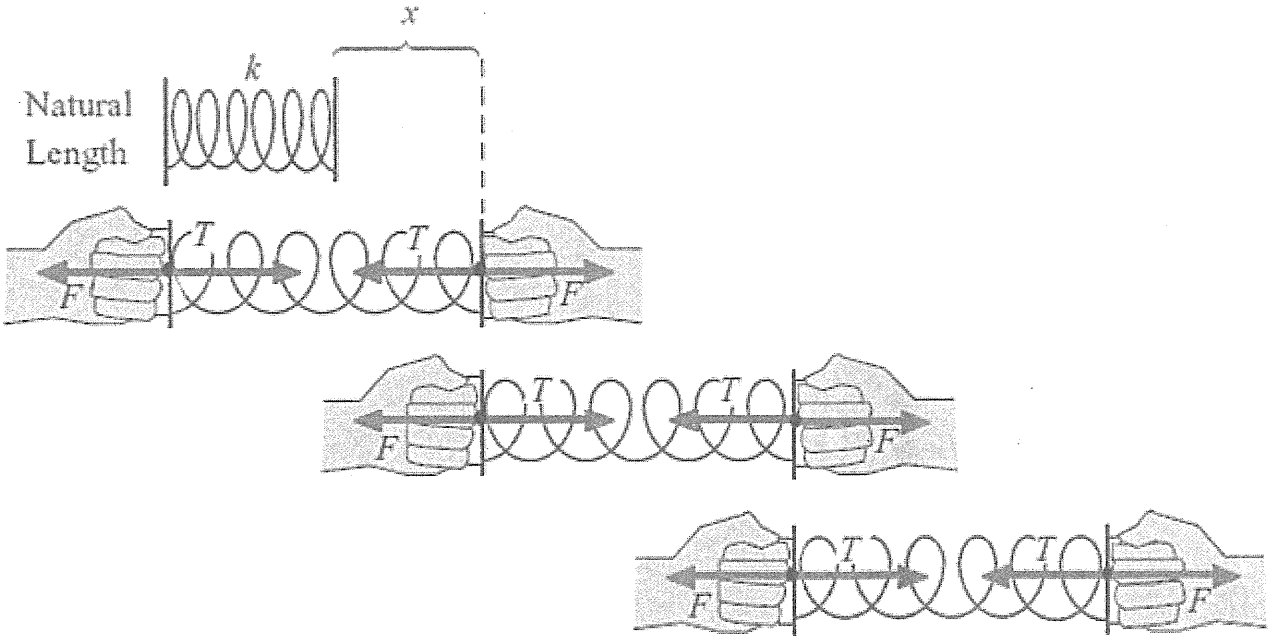


Figure 5 Three identical springs each stretched a distance, x, by a force, F.

By attaching the two outer springs to the central spring, the springs at each joint pull on each other with an action - reaction pair of tension forces, magnitude T. The inner hand scan removes their forces without affecting the tension forces of the springs, as shown below in Figure 6.

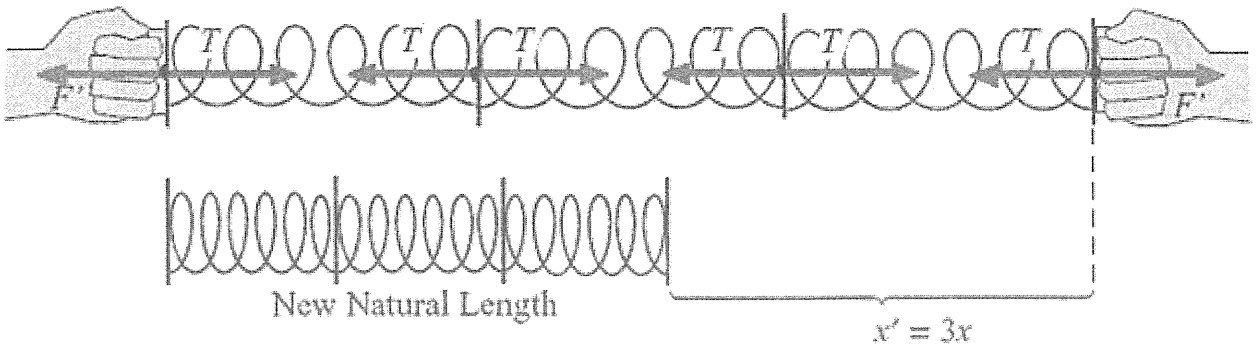


Figure 6 A series combination of three identical springs, spring constant, k, each stretched a distance, x.

The total stretch must be the sum of the stretches of the individual springs $x' = 3x$. The tension T

$=kx$ at each end of the springs has not changed, nor has the applied force, $F' = F = kx$. Substituting for both x' and F' in Equation 3 yields:

$$k_{eq} = \frac{F'}{x'} = \frac{kx}{3x} = \frac{k}{3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

This means that the series combination of three springs is only 1/3 as strong as one of the springs. A series is longer and weaker than one spring.

This picture of an ideal spring with pairs of tension forces acting at each interior point has important implications for all internal forces. Newton's third law of motion is not only a statement regarding the interface between two objects but also refers to any point within a single object where a separation into two pieces could occur. Internal forces are drawn as "back to back" tension vectors (or "head to head" compression vectors) at each joint in a series connection of springs, as shown in Figures 6. In the action - reaction pairs, the two forces of each pair *act on a different object*, the objects on each side of the boundary.

Also, the phrase, "a stationary object has a tension, T..." though stated in a singular fashion, implies that two tension forces (an action reaction pair) act with an equal magnitude and opposite direction at each point within the object. At each end of the spring, the tension forces pull inward on the objects providing the stretching forces.

> In general, a number, n, of identical springs, spring constant, k, *connected in parallel* make a stronger spring with spring constant, $k_{eq} = nk$. A number, n, of identical springs, spring constant, k, connected *in series* makes a weaker spring with spring constant, $k_{eq} = k/n$.

These results can be reversed to show that when a long spring with spring constant, k, is cut into a number, n, of equal length pieces, each small piece will be a stronger spring with a larger spring constant,
$k_{eq} = nk$. For example, a spring cut into three pieces, as shown in Figure 7, yields three springs each three times as strong as the original.

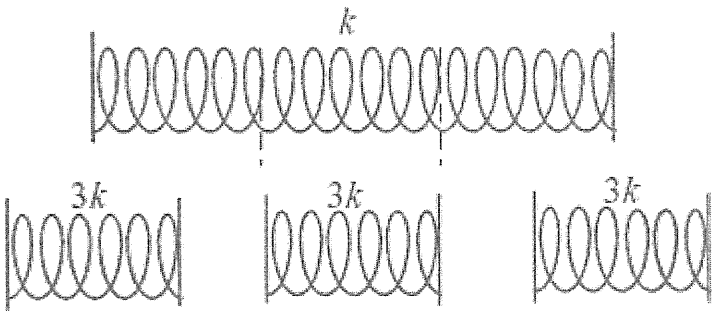


Figure 7 A long spring cut into three equal length pieces.

When a wide elastic bar with spring constant, k, is cut (lengthwise) into a number, n, of equal width pieces, each piece will be a weaker spring with a new spring constant, $k_{eq} = k/n$. For example, when a bar is cut into three equal width strips, as shown in Figure 8, each strip is 1/3 as strong as the original bar.

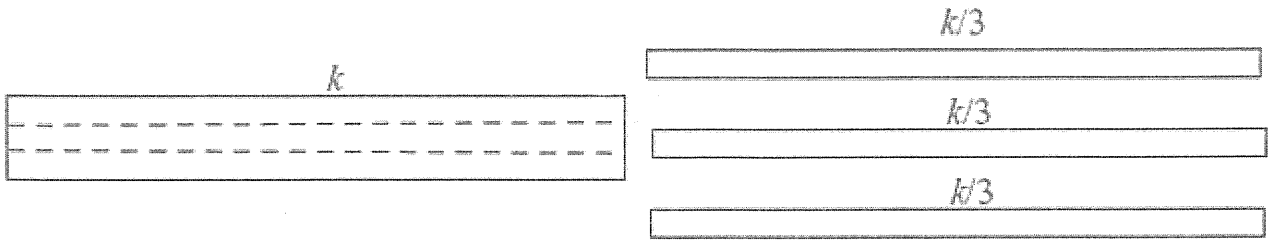


Figure 8 A wide bar cut into three equal width pieces.

A parallel combination of three springs, with a different spring constant for the middle spring, can be shown to have an effective spring constant that is the sum of the individual spring constants. It can also be shown (although, with a little more algebra) that the spring constant of a series combination of springs, each with a different spring constant, is smaller than the spring constant of the weakest of the individual springs.

Procedure:

2. Place a slotted weight of mass 100 gm on the scale pan. Wait until it hangs at rest in

Determination of the spring constant k_1.

1. Suspend the spring so that it hangs vertically from a rigid support, and attach the scale pan to the lower end. Clamp a small pointer to the scale pan so that it moves lightly against the scale as shown in figure 9.

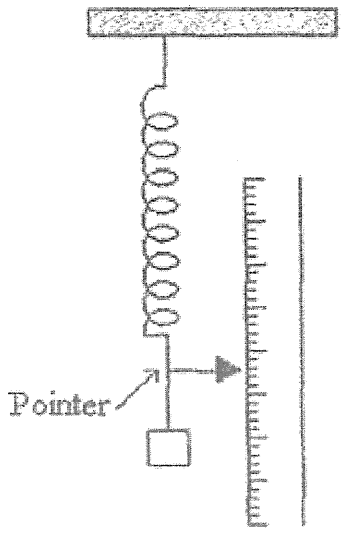


Figure 9 Spring and attachments.

equilibrium when released. Carefully read the position of the pointer on the meter stick scale. Record the value of the mass M (including the mass of the scale pan) and the pointer reading x in data table 1 in the laboratory report.

3. Increase the load by successive increment of 100 gm, and record the pointer readings each

4. When about ten readings have been taken, start unloading the weights and again record the pointer readings. Record all values in data table 1.

5. Draw a graph with the values of the mass M as ordinates against the corresponding values of the mean pointer readings x.

The graph will probably of the shape shown in figure 3.

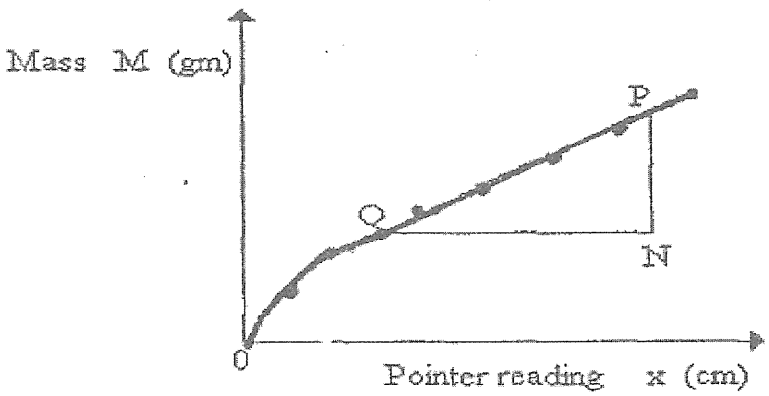


Figure 10 A plot of mass against the pointer reading for a spring.

For the straight line portion of the graph QP it is seen that any increase in the mass is proportional to the extension PN it produces, which is Hooke's law.

Note that the initial curved portion of the graph AB is probably due to the fact that in the early stages of the experiment some turns of the spring are pressing against each other.

From the slope of the straight line, the value of the spring constant k_1 is obtained.

Determination of force constant k_2

Replace now the first spring by the second one, repeat the steps from 1 to 5 to determine the force constant k_2.

Determination of the equivalent k_{eq} in case of parallel combination

1. Connect the two springs in parallel vertically as shown in fig. 11.

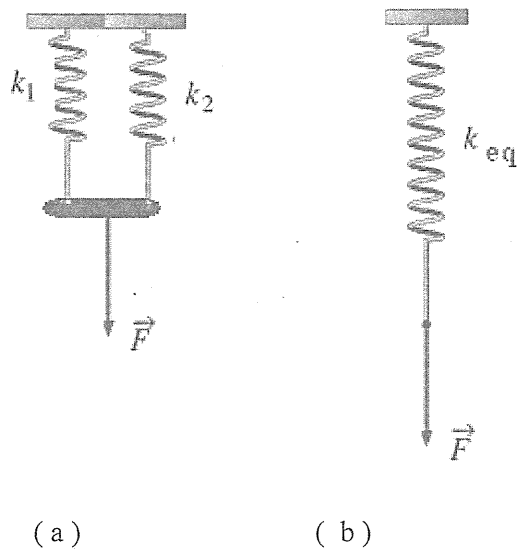


Fig. 11 (a) Two springs connected in parallel . (b) The equivalent form of parallel connection.

2. Repeat the above steps from 1 to 5 in this case, from the graph, determine the equivalent force constant k_{eq} for the two springs in parallel connection.

Determination of the equivalent k_{eq} in case of series combination

1. Connect the two springs in series vertically as shown in fig. 12.

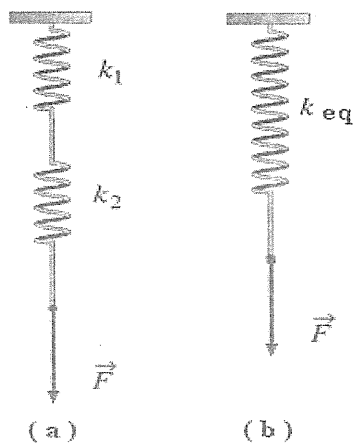


Fig 12 (a) Two springs in series connection. (b) The equivalent form of series connection.

2. Repeat the above steps from 1 to 5 to determine the equivalent force constant k_{eq} for the two springs connected in series.
3. Complete all the steps required in your report.

Experiment no.8 Moment of Inertia

Objectives:

To determine experimentally the moment of inertia of a body about an axis, and to compare this with the theoretical value computed from the mass and the dimensions of the body.

Apparatus:

Moment of inertia apparatus, Vernier caliper, weight set, a large caliper, a stop watch, electric balance, four test bodies,

Theory:

For linear motion Newton's second law F = Ma describes the relationship between the applied force F, the mass M of an object, and its acceleration a. The force is the cause of the acceleration, and the mass is a measure of the tendency of the object to resist a change in its linear translational motion.

For rotational motion of some object about a fixed axis, an equivalent description for the relationship between the applied torque τ, the moment of inertia I, and the angular acceleration α of the object is given by

$$\tau = I\,\alpha$$

Thus the torque τ is the cause of the angular acceleration α, and the moment of inertia I is a measure of the tendency of the body to resist a change in its rotational motion.

The moment of inertia I of a rigid body depends upon the mass of the body and the way in which the mass is distributed relative to the axis of rotation.

Consider the system schematically illustrated in Fig. 1. The body A, free to rotate about the vertical. axis 00', is set in rotation as the result of the mass m, falling through the height h. The cord which constrains the motion of the mass m, is wound around the drum of the body A, the

radius of the drum being equal to r In the experiment the axis 00' passes through the center of mass of the body A, the moment of inertia of which is 1_1. When the mass m., starting from rest, is displaced a distance h under the action of the force of gravity, the body A is set in rotation. When in the displaced position, the mass m, has a velocity v_1 and the body A an angular velocity ω_1; the two quantities are simply related by

$$v_1 = r\,\omega \quad \text{.....} \quad (1)$$

On the assumption that energy is conserved,

$$m_1 gh = \frac{1}{2} m_1 v_1^2 + \frac{1}{2} I_1 \omega_1^2 \quad \text{.....} \quad (2)$$

Since the driving force is constant, the mass mi will be uniformly accelerated; consequently its displacement h, time of fall t_1 and velocity vi are related by

$$v_1 = \frac{2h}{t_1} \quad \text{.....} \quad (3)$$

Substituting Eqs. (1) and (3) in to Eq. (2)

$$m_1 g = \frac{2m_1 h}{t_1^2} + \frac{2I_1 h}{t_1^2 r^2} \quad \text{.....} \quad (4)$$

and

$$I_1 = m_1 r^2 \left(\frac{g t_1^2}{2h} - 1 \right) \quad \text{.....} \quad (5)$$

from which the moment of inertia may be determined in terms of measurable quantities and the acceleration g due to the gravity.

As illustrated in Fig. 1, the body A may have such shape that it should be either difficult or impossible to compute its moment of inertia about the axis 00' from its mass and dimensions. In general, therefore, the moment of inertia of a body A could be determined only experimentally by this method using Eq. (5) or by similar experimental procedure. It is desirable, however, to determine experimentally the moments of inertia of certain regularly shaped objects and to calculate their theoretical values as a check.

Suppose the system to be altered to include a regular geometrical mass B (Fig. 1) having a moment of inertia of I, about its center of mass located on the axis 00'. The total moment of inertia of the system about the axis 00' is $I_1 + I_2$ and a large mass 1112 is required to produce the displacement h in a conveniently measurable time t2. As before, however, Eq. (5) applies and

$$I_1 + I_2 = m_2 r^2 \left(\frac{g t_2^2}{2h} - 1 \right) \quad \text{.....} (6)$$

From observed values of m., T_1, h and r, I_1 may be computed for the body A. Similarly from observed values m_2, t_2, h and r, $1_1 + I_2$ may be experimentally determined, and hence the moment of inertia 1_2 of the body B

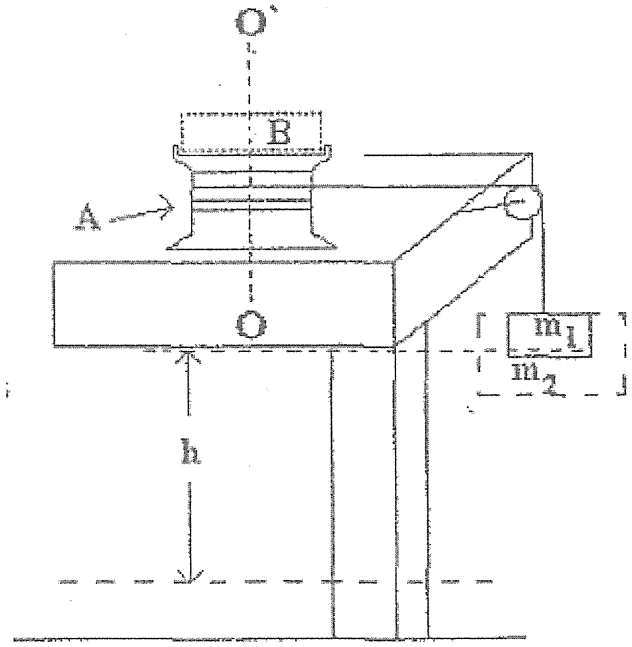


Figure 1: Schematic diagram of a body set in rotation by a falling mass.

Procedure:

1. With the Vernier caliper measure the diameter 2r of the drum. Determine the linear dimensions and the masses of the regularly shaped objects whose moments of inertia are to be determined.

2. Take a cord about 2 meters long and, after passing it over the pulley, wind a little more than a meter of it on the drum. Adjust until tile possible distance of fall is at least one meter. Make a loop in the free end of the cord.

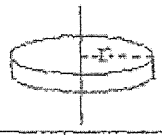
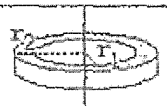
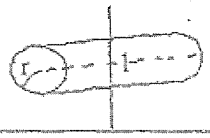
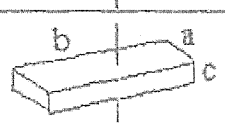
3. Now attach an additional mass m, (20 to 50 gm) to the cord. This mass is the body whose weight furnishes the driving force. Select and accurately measure the distance of fall h and make three or four determinations of the time of fall t_1 through this distance. Record the results in data table B in the laboratory report. Use Eq. (5) to calculate the moment of inertia I_1 of the rotating carrier.

4. Place one of the regularly shaped objects on the metal cross so that its center of mass is on the axis of rotation. Now add a mass m_2 and observe the time of fall t_2 over the distance h. The mass m2 should be much larger (100 to 200 gm), since the moment of inertia of the cross, c1n1l11 and object is much larger than the moment of inertia of the cross and drum alone.

5. Repeat the measurements as in step 4, placing other regularly shaped objects on the cross as directed by the instructor. Record the results in the appropriate data tables C and F in the laboratory report.

6. In table I the theoretical value for the moment of inertia of regularity shaped bodies about various axes is indicated. Compute the theoretical values of the moments of inertia of the regularly shaped objects used. Record the results in data table A in the laboratory report and compare these with the experimental values obtained.

Table I

Body	Axis	Moment of Inertia	
Solid cylinder or disk	Longitudinal through center	$\frac{Mr^2}{2}$	
Cylindrical ring of rectangular cross section	Perpendicular to plane of ring, through center	$M\left(\frac{r_1^2}{2}+\frac{r_2^2}{2}\right)$	
Solid cylinder	Transverse through center	$M\left(\frac{r^2}{4}+\frac{l^2}{12}\right)$	
Rectangular bar having edges a, b and c	Perpendicular to face ab at center	$M\left(\frac{a^2}{12}+\frac{b^2}{12}\right)$