IZMIR INSTITUTE OF TECHNOLOGY
Department of Physics

GENERAL PHYSICS I LABORATORY MANUAL

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Contents

LABORATORY RULES

1 . Students may enter a laboratory only when a lecturer or demonstrator is present unless special permission has been granted.

2. Eating and drinking in any laboratory is prohibited.

3. Before starting an experiment;

- Check that all apparatus is present and has no obvious defect.

- Report to the person in charge any damaged or missing equipment.

4. During an experiment the student should report to the person in charge;

- any equipment that does not seem to be functioning properly.

- any accidents and breakages that occur.

- NEVER borrow equipment from another bench without permission.

5. Before leaving the laboratory,

- Switch off all power supplies and remove all AC/DC power plugs.

- Disconnect electrical circuits and collect the leads in a neat bundle.

- Ensure that the apparatus has been left tidily.

ANALYSIS OF MEASUREMENTS AND EXPERIMENTAL UNCERTAINTIES

1. RANDOM UNCERTAINTIES

The arithmetic mean $\bar{x}$ of a quantity obtained from a number (N) of readings x_i is the most probable value of that quantity. If the uncertainties are entirely random and is large, then $\bar{x}$ is close to the true value.

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$$

If the uncertainties of measurement are entirely random an estimate of the precision is given by the standard deviation

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

where $(x_i - \bar{x})$ is the deviation of a reading x_i from the mean $\bar{x}$.

The standard error (SE) of the mean $SE = (S/N)^{1/2}$ and the error at a 95% confidence level is $2SE$.

The significance of S can be seen by consideration of the distribution of a large collection of measurements, known as the normal or Gaussian distribution. It can be shown that for large N the probability of an individual reading differing from the mean by more than S is about 32%. $2S$ is about 5% and $3S$ is less than 1%.

In practice, when N **is less than 6 the statistical analysis is not appropriate** and an estimate of the uncertainty may be obtained from the range of values obtained.

2. PROPAGATION OF UNCERTAINTIES

Almost all experiments require calculations to be performed which involve manipulation of the measured uncertainties. In order to calculate the uncertainty in the final result it is necessary to know how the computed or estimated uncertainties in each quantity combine or propagate.

2.1 A General Approach

The easiest method of estimating the uncertainty is to substitute the extreme values of the quantities into the expression and calculate the result. The uncertainty is the difference between this value and the preferred value. e.g.

$\lambda = \dfrac{d \sin\theta}{n}$

Preferred value
$d = (1.00x10^{-6} \pm 0.05x10^{-6})m$
$\theta = 30.0^o \pm 0.5^o$, and $n = 1$
$\lambda = 10^{-6}xsin\ 30.0^o = 0.50\mu m$

Maximum value of λ is obtained with maximum value of d and maximum value of θ.

$\lambda_{max} = (1 + 0.05)x10^{-6}xsin(30 + 0.5) = 0.53\mu m$

$\lambda_{min} = (1 - 0.05)x10^{-6}xsin(30 - 0.5) = 0.47\mu m$

$\lambda = 0.50 \pm 0.03\mu m$

Note: The same method may be used for any uncertainty calculation e.g.

Density = mass/volume.

$Mass\ \ of\ \ object = (2.00 \pm 0.01)kg$
$Volume\ \ of\ \ object = (2.50 \pm 0.05)x10^{-3}m^3$
$Density(\rho) = 800kgm^{-3}$

Maximum value of ρ obtained using maximum mass and minimum volume

$\rho_{max} = \dfrac{2.01kg}{2.45x10^{-3}m^3} = 820kgm^{-3}$

Minimum value of ρ is obtained using minimum mass and maximum volume

$\rho_{min} = \dfrac{1.99kg}{2.55x10^{-3}m^3} = 780kgm^{-3}$

$\rho = 800 \pm 20kgm^{-3}$

2.2 Additions and Subtractions

It is usually fairly easy to write down the possible uncertainty in any single measurement. Thus suppose that in an experiment with a spring the length of the spring is measured with a metre scale. With care such a scale allows you to measure to about 1 mm. If you take a number of careful readings with the scale you should find that they do not differ among themselves by more than this. Thus for one particular reading you may be able to say:

$Length\ of\ spring = 302 \pm 1mm$

If additional masses are added and the spring is re-measured, you may find

$$New\ length\ of\ spring = 488 \pm 1mm$$

Now consider what you know about the change in length. According to our figures the change is equal to 186 mm. But each of the figures may have been wrong by 1 mm. If one of them happened to be too high by this amount while the other was too low, then the uncertainty in the difference would be 2 mm. **To be on the safe side we must assume that the worst has happened.** So we say

$$Change\ in\ length = 186 \pm 2mm$$

The same thing applies if we are concerned with adding the two lengths. The worst possible case will be when both figures were too high or both figures were too low. We assume the worst possiblee case and say

$$Sums\ of\ lengths = 790 \pm 2mm.$$

Thus if you are adding or subtracting two figures the actual uncertainty is the sum of the separate uncertainties.

2.3 Multiplications and Divisions

Now suppose that you are measuring the volume of a cylinder. You measure the diameter d and the length l and then calculate the volume from the equation

$$Volume = \frac{\pi d^2 l}{4}$$

In a case such as this the fractional uncertainty in the volume is the sum of the fractional uncertainty in the length plus twice the fractional uncertainty in the diameter. The fractional uncertainty in the diameter is doubled as a consequence of the fact that it is the square of the diameter that comes into the formula. If the formula had involved d^3, three times the fractional uncertainty would have been added and so on.

To take a very general case, suppose we are concerned with a formula of the type

$$x = \frac{k^a t^b}{m^c n^d}$$

In this case:

$$\frac{\triangle x}{x} = \frac{a \triangle k}{k} + \frac{b \triangle t}{t} + \frac{c \triangle m}{m} + \frac{d \triangle n}{n}$$

Fractional uncertainty in x=a(fractional uncertainty in k)+ b(fractional uncertainty in t) +c(fractional uncertainty in m) + d(fractional uncertainty in n)

This general rule can be proved, but the student is advised to accept the rule and leave the proof until later.

The rule is simple: if you are multiplying together or dividing a number of figures, the possible fractional uncertainty in the result is the sum of the separate fractional uncertainties

3.SIGNIFICANT FIGURES

In quoting a result only one uncertain figure should be retained; then the number of figures indicates the order of accuracy. For example, suppose the speed of light was calculated as $2.988x10^8ms^{-1}$ and is known to 1%. The possible uncertainty is then $0.03x10^8ms^{-1}$

This shows that the third and subsequent significant figures are unreliable, hence we retain only three figures and express the result in its neatest form as
$(2.99 \pm 0.03)x10^8ms^{-1}$

4. GRAPHICAL UNCERTAINTIES

In laboratory work a graph is often used to illustrate the behaviou of system; to assist in the calculation of a quantity or to determine the relationship between variables. It is essential that the graph displays the characteristics of the results and their uncertainties as clearly as possible. This involves the **proper selection of scale and the physical arrangement of the axis.**

The best way to indicate the uncertainties of the variables is to locate the point of the graph by a dot at the centre of bars indicating the range of uncertainty. A method of estimating the uncertainty in the gradient of a straight line is to draw lines of maximum and minimum gradient which are possible fits to the experimental points.The uncertainty in the gradient of the line of best fit is then one half the difference between the maximum and minimum gradients. A similar method can be used to estimate the uncertainty in an intercept. These techniques are illustrated on the graph in Figure 1.

5. THE SI SYSTEM OF UNITS

5.1 Classes of SI Units

There are three classes of SI units. These are:
Base units
Derived units
Supplementary units.

The base units are seven well-defined units: metre, kilogram, second, ampere, kelvin, candela and mole.

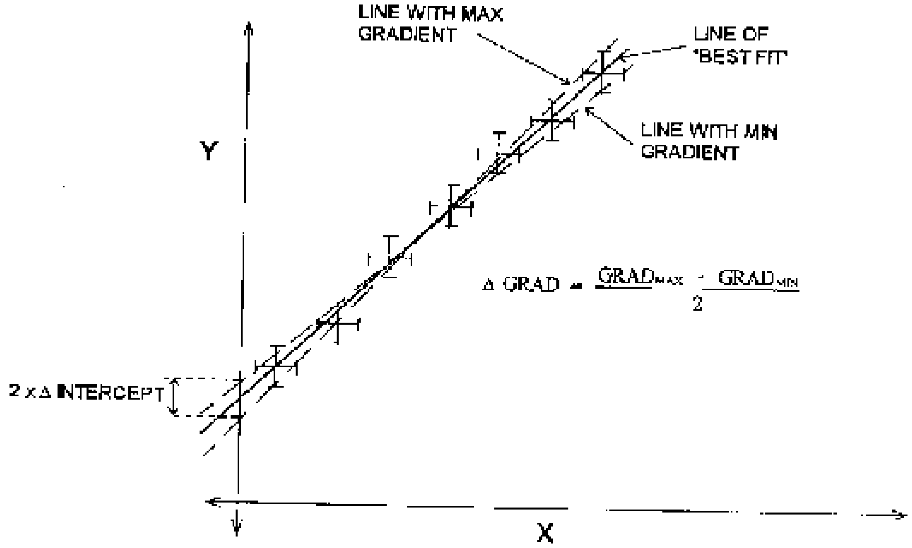

Figure 1:

The derived units are units which can be obtained by combining base units according to the algebraic relations linking the corresponding quantities.

The supplementary units, the **radian** and **steradian** (symbol, rad and sr respectively) are dimensionless quantities used when defining derived units for quantities such as angular frequency.

5.2 Definition of Base Units

metre (unit of length, symbol m)

The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second. Note that the metre is defined in terms of the speed of light.

kilogram (unit of mass, symbol kg)

The kilogram is equal to the mass of the international prototype of the kilogram. Once the mass of a litre of water, it may soon be redefined as the mass of a number of carbon-12 atoms.

second (unit of time, symbol s)

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom. This is a highly monochromatic **microwave** emission.

ampere (unit of electric current symbol A)

The ampere is that **constant current** which, if maintained in two straight parallel conductors of **negligible circular cross-section**, placed one metre apart **in vacuum**, would produce beetwen these conductors a force equal to $2x10^{-7}$ Newton per metre of length.

Earlier metric systems used the coulomb as the base unit, but it was too hard to measure with sufficient precision.

Kelvin (unit of thermodynamic temperature, symbol K)

The Kelvin is the fraction 1/273.15 of the thermodynamic temperature of the triple point of water. The Kelvin is used to express an interval or a difference in temperature, so it tends to appear in the denominator of derived units.

(Celsius temperature, symbol T, is defined by the expression $T = K - 273.15$)

candela (unit of luminous intensity, symbol cd)

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540x10^{12}$ Hertz and that has a radiant intensity in that direction of 1/683 watt per steradian. This unit is used when the instrument of comparison is the human eye. Its use is in decline.

mole (unit of amount of substance, symbol mol)

The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 12 g of carbon-12. When the mole is used, the elementary entities must be specified. It is properly used as a number, but is often used as a mass.

5.3 Writing of Symbols

Roman lower case is used for symbols of units unless the symbols are derived from proper names, when capital roman type is used for the first letter. These symbols are not followed by a stop.

Unit names and symbols do not change in the plural, even though we often add an ”s” in common speech. ($2K$ reads as two degree Kelvins.)

5.4 Derived Units, Special Names

Several derived units have been given special names and may be used to obtain further derived units. This is much simpler than expressing all units in terms of base units. e.g. $1Pa = 1Nm^{-2}$

Table 1 Derived units which have been given special names

PHYSICAL QUANTITY	UNIT	SYMBOL	IN TERMS OF BASE UNITS
activity	becquerel	Bq	s^{-1}
capacitance	farad	F	$m^{-2}kg^{-1}s^{4}A^{2}$
conductance	siemens	S	$m^{-2}kg^{-1}s^{3}A^{2}$
dose absorbed	gray	Gy	$m^{2}s^{-2}$
dose equivalent	sievert	Sv	$m^{2}s^{-2}$
electric charge	coulomb	C	s A
electric potential	volt	V	$m^{2}kgs^{-3}A^{-1}$
electric resistance	ohm	Ω	$m^{2}kgs^{-3}A^{-2}$
energy, work, heat	joule	J	$m^{2}kgs^{-2}$
force	newton	N	$mkgs^{-2}$
frequency	hertz	Hz	s^{-1}
illuminance	lux	lx	$m^{-2}cdsr$
inductance	henry	H	$m^{-2}kgs^{-2}A^{-2}$
luminous flux	lumen	lm	$cdsr$
magnetic flux	weber	Wb	$m^{2}kgs^{-2}A^{-1}$
magnetic induction	tesla	T	$kgs^{-2}A^{-1}$
power, radiant flux	watt	W	$m^{2}kgs^{-3}$
pressure	pascal	Pa	$m^{-1}kgs^{-2}$

5.5 Recommendations for Use of Units

(i) It is **preferable** to indicate the product of **two units with a dot** when there is a risk of confusion with another symbol. When **no dot is used a space should be left between the symbols** for the two units.

(ii) A negative power, horizontal line, or a solidus (/), may be used to express a derived unit obtained from two other units by division.

(iii) The solidus must not be repeated unless parentheses are used to avoid ambiguity.

5.6 Number Notation

The decimal point should be expressed by a dot placed on the line. Then multiplication should be indicated by an "x". If a dot half-high is used for this purpose, the decimal point must be a comma. **A number should never commence with a decimal point.**

Long numbers should be arranged in groups of three with a space, not a comma, separating them. The grouping should start at the decimal point.

A space should be left between the number and the unit.

5.7 Multiples and Sub-multiples

Table 2

FACTOR	PREFIX	SYMBOL	FACTOR	PREFIX	SYMBOL
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a

The prefixes hecto, deca, deci and centi are still legal but should be avoided in technical work. An exponent attached to a symbol containing a prefix indicates that the multiple, or submultiple, of the unit is raised to the power of the exponent: e.g. a sand grain of 2 mg has a volume of about $1mm^3$. (The metre is cubed and so is the milli). A **prefix should not appear in the denominator of a derived unit**: e.g. thus the sand grain has a density of about $2Mgm^{-3}$

NOTE: The kilogram is the only base unit containing a prefix, retained for historical reasons. It may appear in the denominator: e.g. a specific activity of $1.5kBqkg^{-1}$, not $1.5Bqg^{-1}$.

5.8 Units which are not within the SI

Some units, not within the SI are in widespread use. They should be converted to SI units before calculations. These are:

minute (min) tonne (t) (1 Mg)
hour (h) degree (o)
day (d) minute (')
year (a) second (")
litre (l,L)

Jargon survives in all disciplines despite a general willingness to conform (to SI) for the general good. In physics, the following non-SI units have survived:

electronvolt (eV)
The energy acquired by an electron when moved through a potential difference of one volt. (6 eV = 1 aJ approx; 6 MeV = 1 pJ approx)

atomic mass unit (u)
1/12 of the mass of one ^{12}C atom. An energy of 149 pJ or 931 MeV has approximately 1 u of mass. Atomic masses are expressed in u.

light year (ly)

The distance light travels in a year. (1 ly = 10 Pm, approx).

curie (Ci)

An activity of 37 GBq. This number is similar to the number of events per second in a gram of radium.

Other jargon units will be encountered in specialist areas; their conversion factors will be found in the references below.

Other disciplines have their jargon units, too. For instance - engineering has rpm (1 Hz = 60 rpm), geophysics has milligals ($1mgal = 10\mu ms^{-2}$) and surveying has hectares ($1ha = 10^4m^2$, $1km^2 = 100ha$).

6. UNITS, ERRORS AND DIGITS

When an experimental value is to be reported, it must be put into the standard form. Here is how to do it:

Take a fresh page. Lay out the value to be processed. Rewrite it as you make each of the following corrections:

1. Reduce the units' denominator to base units: (DENOM)
2. Reduce the units' numerator to an appropriate unit: (NUM)
3 . Choose a 10^{3N} prefix which brings the main value to between 1 and 999 (PREFIX)
4. Express the error in the same units as the value: (SAME UNITS)
5. Round the error to one or two significant figures: (SIG. FIG.)
6. Round the main value and error to the same decimal place: (D.P.)
7. Check the spaces and cases: (FORMAT)

A difficult example: $605.643calories/gK \pm 1.567\%$

=$605643calorieskg^{-1}K^{-1} \pm 1.567\%$	DENOM
=$2537648.Jkg^{-1}K^{-1} \pm 1.567\%$	NUM
=$2.537648MJkg^{-l}K^{-1} \pm 1.567\%$	PREFIX
=$2.537648 \pm 0.039765MJkg^{-1}K^{-1}$	SAME UNIT
=$2.537648 \pm 0.04MJkg^{-1}K^{-1}$	SIG. FIGS.
=$2.54 \pm 0.04MJkg^{-1}K^{-1}$	D.P.
=$2.54 \pm 0.04MJkg^{-1}K^{-1}$	FORMAT

Practice the following, using pencil, eraser and scratch paper

$2.3 \pm 0.37Jg^{-1}$

$6.71 \pm 0.022Bqcm^{-2}$

$1191300GJ \pm 15TJ$

$171 \pm 9.666666 N/mm^2$
$1050.3 \pm 18.33 hectopascals$
$55 tonnes\ km^{-3} \pm 2\%$
$1.2345x10^{-7}g \pm 75875fg$
$\sim 6miles, \sim 6ft, \sim 17min., \sim 3kWh, \sim 100light\ years$
$\sim 60MeV, \sim 10^{-5}kgs^{-2}A^{-2}$ (magnetic unit)

7. USE OF GRAPHS

This session is designed to give an understanding of the use of graphs. For those who are good at mathematics it will serve as revision, for the rest of you please use the time to master the following:

- Knowledge and understanding of the equation of a straight line.
- Ability to write an equation for a straight line given the graph.
- Ability to draw the graph given the equation without plotting out all the points.
- Understanding of "directly proportional".
- Ability to use a graphical method to show direct proportion in a variety of situations.
- Understanding of the term "inversely proportional".
- Ability to use a graphical method to show inverse proportionality.
- Ability to check equations using log graphs.

7.1 Gradient of a Stright Line

The straight line shown in Figure 2 has a constant gradient. In other words, as point P moves along the line in the direction of x increasing (i.e. from A to B) y changes at a constant rate, and in this case it is a simple matter to find the gradient.

7.1.1 Calculation of Gradient

In moving from A to B the x-coordinate has increased by 10 (from 0 to 10) while the y-coordinate has increased by 5 (from 2 to 7).

$$Gradient = \frac{increase\ in\ y}{increase\ in\ x} = \frac{5}{10} = \frac{1}{2}$$

The gradient is positive as y is increasing as x increases. So we say that the gradient of the line in Figure 2 is 1/2 or 0.5. In fact to find the gradient of the line we can take any two points on the line; e.g. we could have considered the points C add D with co-ordinates (4,4) and (8,6) respectively. To obtain the most accurate answer choose points which are as far apart as is convenient.

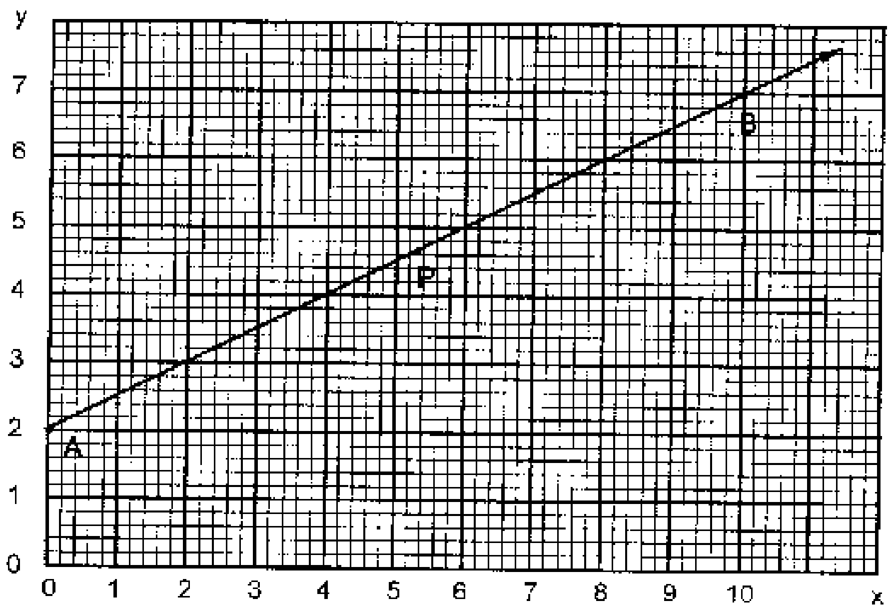

Figure 2:

7.1.2 Equation of a Straight Line

Consider the line shown in Figure 3. What is its gradient? Answer is 2. Now look at the points marked and write down their coordinates. Answer:
A : (0,1)
B : (1,3)
C : (2,5)
D : (3,7)
E : (4,9)

You might like to add a few more points of your own. Can you now find a connection between the y and x coordinates?

The first thing to notice is that the x-coordinate increases by 1 at each step as you go from A to E, and as we would expect the y-coordinate increases by 2 each time, since 2 is the gradient of the line (remember gradient is the change in y for an increase of 1 in x). Can you find the rule which connects y with x? The answer is that to get the y-coordinate you double the x-coordinate and add 1. Since the y-coordinate is referred to simply as 'y' and the x-coordinate as 'x':

$y = 2x + 1$, (gradient)x + (intercept on y axis)

or in general terms $y = mx + c$

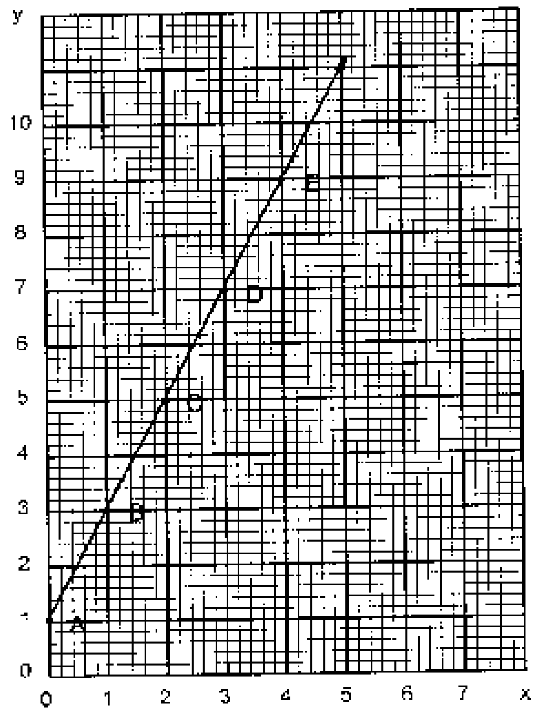

Figure 3:

7.2 Direct Proportion

Imagine you go shopping and buy items at \$3 each. If you tabulated the cost then you would get:

Number of items	cost
1	\$3
2	\$6
3	\$9
.	.
.	.
.	.
10	\$30

Draw a graph of cost on y-axis against number of items on the x-axis. The graph represents a graph of two quantities which are proportional.

$y \propto x \quad \text{or} \quad y = kx$

The two main features of a graph showing that two quantities are directly proportional are:
1. the graph is a straight line

2. the graph passes through the point (0,0).

If you added the cost of the journey to the shop then the cost would no longer be directly proportional to the number of items. (If you bought twice the number of items it would cost less than twice as much). The graph would still be a straight line but it would not pass through (0,0), i.e. a **straight line alone is not sufficient proof of direct proportionality**.

Choose a value for the cost of the journey and plot the graph.

Write down the equation of the line. It should be
Cost = \$3 x number of items + cost of journey

Another shopping example, this time the cost of tiling a square room at \$10 a square metre.

side of room	area of room	cost
lm	$1m^2$	\$10
2m	$4m^2$	\$40
3m	$9m^2$	\$90
4m	$16m^2$	\$160

Question

Draw a graph of cost against side of room and of cost against $(side\ of\ room)^2$. What do you find?

Which graph enables you to deduce the relationship between cost and the length of the side of the room?

7.3 Inverse Proportion

The term inverse proportion is often wrongly used. It has a very precise meaning and refers to the situation where doubling one quantity halves the other, trebling one causes the other to be a third etc.

$y \propto \frac{1}{x}$ or $xy = constant$

Question

Which of the following sets of pairs of numbers are inversely proportional?

a	b		c	d		e	f
1	24		1	20		1	144
2	12		2	16		2	48
3	8		3	12		3	32
4	6		4	8		4	16
5	4.8		5	4		5	8
6	4		6	0		6	6

Draw a graph of each. What do you notice?

What graph can you draw to establish without doubt that the two quantities are inversely proportional?

Note: You need a straight line graph before you can be sure about the relationship between two variables.

7.4 Linear Graph from Non-linear Equations

The aim of many experiments is to find an equation relating two variables. If the graph obtained by plotting these two variables is a straight line, it is an easy matter to measure the slope and intercept and write out an equation in the form $y = mx + c$. If the graph is a curve, the solution is not so simple but it is often possible to choose the variables so that a straight line is obtained. Here are distances moved by a trolley from rest after various times.

Time, t	Distance, s
0.7	0.141
1.3	0.372
1.9	0.794
2.3	1.113
2.9	1.850

If s is plotted against t the graph will not be a straight line since s increases much more rapidly than t because the trolley is accelerating.

For an object travelling with constant acceleration from rest, the equation relating acceleration (a), distance (s) and time (t) is

$$s = (1/2)at^2$$

comparing this with $y = mx + c$ shows that a graph of s against t^2 should be a straight line passing through (0,0) and having a gradient of $(1/2)a$.

Question

How would you check graphically whether experimental results fit the following equations?

1. $F = k/r^2$, where k is constant.
2. $E = (1/2)mv^2$, where m is constant,
3. $V = RE/(R + r)$, when E and r are constant.

7.5 Log Graphs

Sometimes, two variables are related by an equation of the form

$y = Ax^n$

where A and n are unknown constants.
You can use trial and error to try to find n but this would involve graphing;

y against x
y against x^2
y against $1/x$

etc. until you obtained a straight line and, in the end, you might give up without getting a solution. However, if

$y = Ax^n$ then
$log\ y = log(Ax^n)$
$log\ y = logA + log\ x^n$
$log\ y = logA + nlog\ x$

(compare this with) $y = mx + c$.

The graph of $logy$ against $logx$ would be a straight line. The constant n is the gradient and the intercept is $logA$. From this graph we would be able to find both A and n.

Question

Under certain conditions (when heat cannot flow into or out of the gas) the pressure p and volume V are related by the equation

$pV^\gamma = k$

where γ and k are constants.

If you obtained experimental data under these conditions, what graph would you plot to find the values of γ and k and how would you find the values of γ and k?

Question

Theory suggests that the power P dissipated in a heated filament of resistance R is given by an equation of the form

$$P = kR^n$$

where k and n are constants.
Plot a suitable graph of the following data so that the values of n and k can be found.

P(W)	R(Ω)
4.41	0.91
8.11	1.11
12.59	1.27
17.70	1.41
23.88	1.51

7.6 Use of Graphs-Assignment

1. A 100 watt heater and a thermometer were immersed in a copper calorimeter containing water. The following readings were obtained:

temperature (^oC)	22	36	40	45	49	54	58
time (minutes)	3	4	5	6	7	8	9

Plot a graph of temperature against time (reminder: this means that time should be on the x axis).

The relevant equation is: *power x time = heat capacity x temperature rise*
Compare this equation with the equation of a straight line: $y = mx + c$

From your graph determine the initial temperature of the water and the heat capacity of the calorimeter + water.

2. The tension of a vibrating string is kept constant and its length varied to tune it to a series of tuning forks. The necessary lengths are given below:

Tuning Fork	C	D	E	F	G
frequency of tuning fork (Hz)	256	288	320	384	512

length of string (cm)	117	104	94	78	59

Plot a graph of length against frequency. What possible relationship is there between the frequency of vibration and the length of the string? Draw a suitable graph to confirm this.

Chapter 1

MEASUREMENT

Purpose

To give you some feeling for the magnitude of measurement uncertainties when using a metre ruler, a vernier callipers, a micrometer and a balance,

To use the measurements obtained to calculate the density of the samples,

To see how measurement uncertainties affect the final results.

Introduction

In physics it is always important to be aware of the limitations of any equipment used and to be able to estimate the uncertainty inherent in any measurement taken. This is often called *the error of the reading*, a term which is itself misleading as it suggests that the experimenter has made a mistake when taking the reading. An uncertainty is present on every reading regardless of the care and skill of the experimenter or of the accuracy of the instrument.

Formulae Required:

$$density = \frac{mass}{volume}$$

Volume of a cylinder $= \pi r^2 h$

(r is the radius of one of the bases and h is the length of cylinder)

Volume of a sphere $= \frac{4}{3}\pi r^3$

(r is the radius of sphere)

Volume of a hexagonal based object $= \frac{\sqrt{3}}{2} h d^2$

(h is the length of object and d is the distance from one edge to the other of the base)

Densities of Materials

$d_{aluminum} = 2.70\ g/cm^3$

$d_{brass} = 8.75\ g/cm^3$

$d_{copper} = 8.96\ g/cm^3$

$d_{steel} = 7.85\ g/cm^3$

Equipments

A ruler
A vernier callipers
A micrometer
A balance
Brass, copper, aluminum and steel objects

Procedure

1. Record the smallest scale division for each measuring instrument in Table 1.1.

2. Then record your reasonable estimate of a "reading uncertainty" for each instrument, record in Table 1.1.

3. Measure each dimension three times at different places around the object in order to obtain a reasonable average over the whole object. Do this with each measuring instrument and record your data in Table 1.2 .

4. Calculate the densities of the objects and record in Table 1.3.

REPORT SHEET

EXPERIMENT 1: MEASUREMENT

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 1.1

Instrument	Size of smallest division on scale	Reasonable estimate of reading uncertainty

Table 1.2

Object	Instrument	Quantity measured	Readings	Mean	Best estimate of uncertainty

Table 1.3

Object	Mass (g)	Volume (cm^3)	Density (g/cm^3)

Questions

Is there a "zero error" in your measuring instruments? If so, how do you make a correction for this?

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How do the results of using different measuring instruments compare? Are they within your combined uncertainty estimates? If not, then what does this signify?

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What is the most accurate instrument?

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What, as a result of all your measurements would you give as the 'best' values of mass, length and diameter of the objects?

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Would you consider the uncertainties you have found to be random (i.e. the probability that the reading is too high is the same as the probability that it is too low) or systematic' (the error is usually of the same sign, such errors may be produced by an incorrectly calibrated measuring instrument or by a zero error)?

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How may random uncertainties be reduced?

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How may systematic errors be detected and then eliminated or reduced?

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What are the volumes of the objects? How accurate are your answers?

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What are the densities of the specimens? How accurate are your answers? What units have you used g/cm^3 or kg/m^3?

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In the measurement of density of each object, is there a measuring instrument that has contributed significantly more to the uncertainty in the density?

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If you needed to improve the precision of your density measurements, for each object, what would be your first step?

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Chapter 2

INSTANTANEOUS VERSUS AVERAGE VELOCITY

Purpose

To grasp the difference between the average and the instantaneous velocities and their most proper places of applications.

Introduction

Average velocity of a motion is the total displacement achieved within the total time elapsed from the start of the motion. Then the *instantaneous velocity* is the displacement for so small a time interval that we cannot say when the motion started and ended, as if everything occurred in one instant of time. However we can express it mathematically as in dx/dt, where dx and dt are the infinitesimal displacement and the infinitesimal time.

Both average and the instantaneous velocities have their proper places of applications. For example in the famous parable of a race between a hare and a turtle, it is the average velocity that helps the slow turtle to win it. The hare, resting for the most part of the race (having a zero instantaneous velocity) and dashing at the end (producing a very high instantaneous velocity) looses it, simply because his average velocity does not add up to that of the turtle.

On the other hand, a karate master can break a wooden block, because he is well trained and so able to produce an immensely high instantaneous velocity (and momentum) with his hand at the moment of the blow.

In this experiment you'll investigate the relationship between instantaneous and average velocities, and see how a series of average velocities can be used to deduce an instantaneous velocity.

Equipments

Photogate Timer
Accessory Photogate
Air Track System with one glider
Air Supply

Procedure

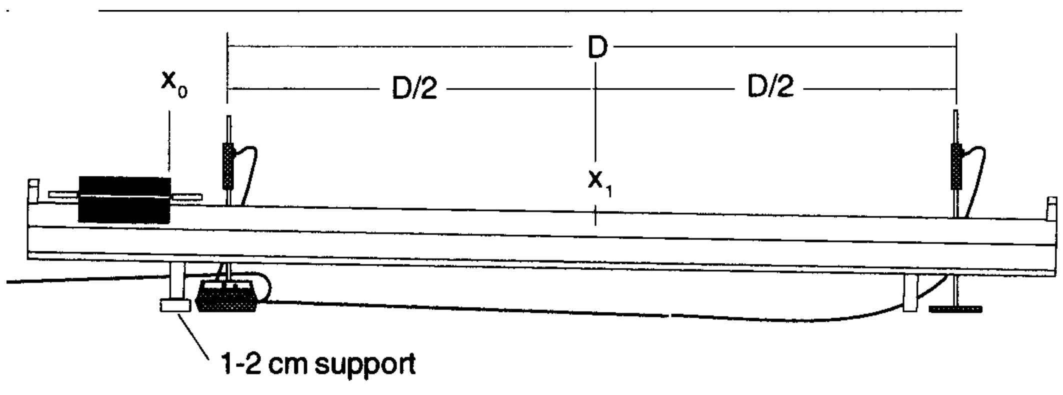

Figure 2.1:

1. Set up the air track as shown in Figure 2.1, elevating one end of the track with a 1-2 cm support.

2. Choose a point x_1 near the center of the track. Measure the position of x_1 on the air track metric scale, and record this value in Table 2.1.

3. Choose a starting point x_o for the glider, near the upper end of the track. With a pencil, carefully mark this spot on the air track so you can always start the glider from the same point.

4. Place the Photogate Timer and Accessory Photogate at points equidistant from x_1, as shown in the figure. Record the distance between the photogates as D in Table 2.1.

5. Set the slide switch on the Photogate Timer to PULSE.

6. Press the RESET button.

7. Hold the glider steady at x_o, then release it. Record time t_1, the time displayed after the glider has passed through both photogates.

8. Repeat steps 6 and 7 at least two more times, recording the times as t_2 through t_3.

9. Now repeat steps 4 through 9, decreasing D by approximately $10cm$.

10. Continue decreasing D in $10cm$ increments. At each value of D, repeat steps 4-8.

You can continue using smaller and smaller distances for D by changing your timing technique. Tape a piece of cardboard on top of the glider. Use just one photogate and place it at x_1. Set the timer to GATE. Now D is the length of the cardboard. Then start the glider from x_o as before, and make several measurements of the time it takes for the glider to pass through the photogate. As before, record your times as t_1 through t_3. Continue decreasing the value of D, by using successively smaller pieces of cardboard.

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REPORT SHEET

EXPERIMENT 2: INSTANTANEOUS VERSUS AVERAGE VELOCITY

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 2.1

x_1=....................

$D(cm)$	$t_1(s)$	$t_2(s)$	$t_3(s)$	$t_{avg}(s)$	$v_{avg}(cm/s)$

1. For each value of D, calculate the average of t_1 through t_3. Record this value as t_{avg}.

2. Calculate $v_{avg} = D/t_{avg}$. This is the average velocity of the glider in going between the two photogates.

3. Plot a graph of v_{avg} versus D with D on the x-axis.

Questions

1. Which of the average velocities that you measured do you think gives the closest approximation to the instantaneous velocity of the glider as it passed through point x_1?

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2. Can you extrapolate your collected data to determine an even closer approximation to the instantaneous velocity of the glider through point x_1? From your collected data, estimate the maximum error you expect in your estimated value.

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3. In trying to determine an instantaneous velocity, what factors (timer accuracy, object being timed, type of motion) influence the accuracy of the measurement? Discuss how each factor influences the result.

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4. Can you think of one or more ways to measure instantaneous velocity directly, or is an instantaneous velocity always a value that must be inferred from average velocity measurements?

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Chapter 3

PROJECTILE MOTION

Purpose

To find how the range of the ball depends on the angle at which it is launched and the angle that gives the greatest range.

Introduction

Let us consider a special case of two-dimensional motion: A particle moves in a vertical plane with some initial velocity $\vec{v_o}$ but its acceleration is always the free-fall acceleration $\vec{g}$, which is downward. Such a particle is called a *projectile* (meaning that it is projected or launched) and its motion is called *projectile motion.* During its two-dimensional motion, the projectile's position vector and velocity vector change continuously, but its acceleration vector is constant and always directed vertically downward. The projectile has *no* horizontal acceleration.

In projectile motion, the horizontal motion and the vertical motion are independent of each other; that is, neither motion affects the other.

The Vertical Motion

The vertical motion is the motion for a particle in free fall. Most important is that the acceleration is constant. Thus, the equations for motion with constant acceleration apply, provided we substitute $-g$ for a and switch to y notation.Then, for example, the equation becomes

$$y - y_o = v_{oy}t - \frac{1}{2}gt^2$$

$$y - y_o = (v_o \sin\theta)t - \frac{1}{2}gt^2$$

where the initial vertical velocity component v_{oy} is replaced with the equivalent $v_o \sin\theta$.

The vertical velocity component behaves just as for a ball thrown vertically upward. It is directed upward initially and its magnitude steadily decreases to zero, *which marks the maximum height of the path.* The vertical velocity component then reverses direction, and its magnitude becomes larger with time.

The Horizontal Motion

Because there is *no acceleration* in the horizontal direction, the horizontal component v_x of the projectile's velocity remains unchanged from its initial value v_{ox} throughout the motion. At any time t, the projectile's horizontal displacement $x - x_o$ from an initial position x_o is given by

$$x - x_o = v_{ox} t$$

Because $v_{ox} = v_o \cos\theta$, this becomes

$$x - x_o = (v_o \cos\theta)t.$$

The *range* is the horizontal distance, x, between the muzzle of the Launcher and the place where the ball hits (Figure 3.1), given by $x = (v_o \cos\theta)t$, where v_o is the initial speed of the ball as it leaves the muzzle, θ is the angle of inclination above horizontal, and t is the time of flight. Of course in this type of experiment the air resistance is totally ignored.

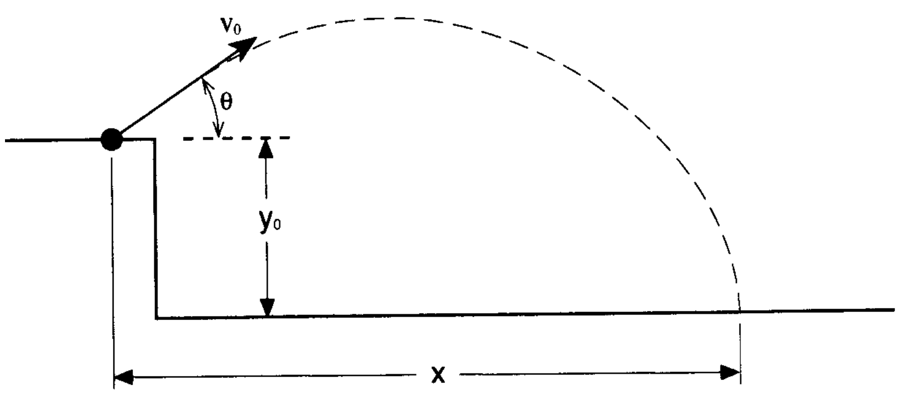

Figure 3.1:

Equipments

Mini Launcher and steel ball
Photogate Mounting Bracket
Photogate Timer
Time of Flight Accessory

Procedure

Determining the Initial Velocity of the Projectile

The vertical distance the ball drops in time t is given by $y = \frac{1}{2}gt^2$.
The initial velocity of the ball can be determined by measuring x and y. The time of flight of the ball can be found using : $t = \sqrt{\frac{2y}{g}}$
and then the initial velocity can be found using $v_o = \frac{x}{t}$.

1. Put the steel ball into the Mini Launcher and cock it to short range position. Fire one shot to locate where the ball hits the floor. At this position, tape a piece of white paper to the floor. Place a piece of carbon paper (carbon-side down) on top of this paper and tape it down. When the ball hits the floor, it will leave a mark on the white paper.

2. Fire about three shots.

3. Measure the vertical distance from the bottom of the ball as it leaves the barrel (this position is marked on the side of the barrel) to the floor. Record this distance.

4. Use a plumb bob to find the point on the floor that is directly beneath the release point on the barrel. Measure the horizantal distance along the floor from the release point to the points where the ball hits the floor. Record these values in Table 3.1.

5. Find the average of the three distances and record the value in the table.

6. Using the vertical distance and the average horizontal distance, calculate the time of flight and the initial velocity of the ball.

Determining the Time of Flight

Put the Photogate Mounting Bracket onto the Mini Launcher and mount the Photogate Timer's Photogate Head at the front of the launcher. Connect the Time-of-Flight Accessory stereo phone plug into the side of the Photogate Timer as in Figure 3.2.

1. Adjust the angle of the Mini Launcher.

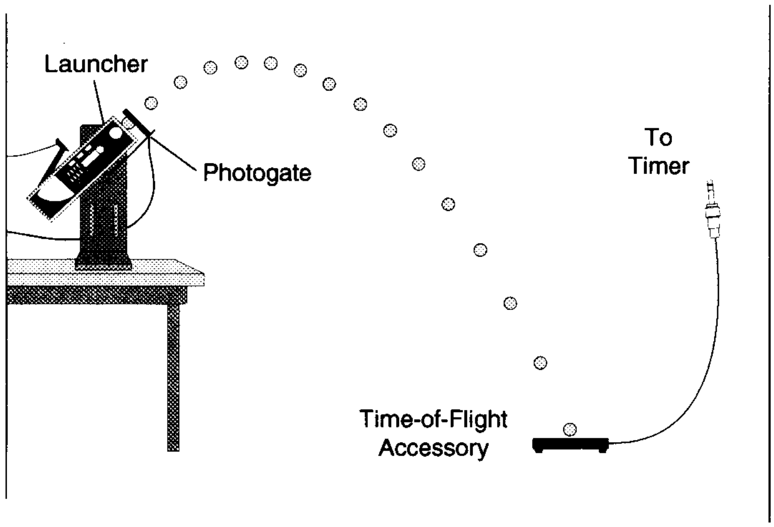

Figure 3.2:

2. Put the steel ball into the Mini Launcher and cock it to the short range position.

3. Test fire the ball to determine where to place the timer plate on the floor. Put the timer plate where the ball hits.

4. Set the Photogate Timer to PULSE mode to measure the time of flight of the projectile from the launcher to the pad.

5. Shoot the ball and record the time of flight.

Part I: Projectile Range Versus Angle (Shooting on a Level Surface)

1. Adjust the angle of the Mini Launcher to ten degrees.

2. Put steel ball into the Mini Launcher and cock it short range position.

3. Fire one shot to locate where the ball hits the table. At this position, tape a piece of white paper to the table. Place a piece of carbon paper (carbon-side down) on top of this paper and tape it down. When the ball hits the table, it will leave a mark on the white paper.

4. Fire about three shots.

5. Measure the horizontal distance from the launch position of the ball to the leading edge of the paper ($x\prime$). Record in Table 3.2.

6. Measure from the leading edge of the paper to each of the three dots and record these distances (x_1, x_2, x_3) in Table 3.2.

7. Find the average of the three distances and record it.

8. Add the average distance to the distance to the leading edge of the paper to find the total measured range ($x_{measured} = x\prime + x_{avg}$) in each case. Record it in Table 3.2.

9. Using the values of initial velocity of the projectile and the time of flight, find the calculated range, $x_{calculated} = (v_o \cos\theta)t$. Compare with the measured value.

10. Increase the angle by 10 degrees and repeat all the steps for angles up to and including 80 degrees.

Part II: Projectile Range Versus Angle (Shooting from an Initial Height)

Set the Mini Launcher to a initial height and aim it so that the ball will hit the table. Repeat steps 1 through 10 in Part I and record the data in Table 3.3.

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REPORT SHEET

EXPERIMENT 3: PROJECTILE MOTION

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 3.1

Vertical distance, y=...............
Calculated time of flight, t=...............
Initial velocity, v_o=...............

Trial Number	Distance
1	
2	
3	
Average Distance	

Table 3.2 Shooting on a Level Surface

θ	$t(s)$	$x\prime(cm)$	$x_1(cm)$	$x_2(cm)$	$x_3(cm)$	$x_{avg}(cm)$	$x_{measured}$	$x_{calculated}$
10^o								
20^o								
30^o								
40^o								
50^o								
60^o								
70^o								
80^o								

Table 3.3 Shooting from an Initial Height

y_o=...............

θ	$t(s)$	$x\prime(cm)$	$x_1(cm)$	$x_2(cm)$	$x_3(cm)$	$x_{avg}(cm)$	$x_{measured}$	$x_{calculated}$
10^o								
20^o								
30^o								
40^o								
50^o								
60^o								
70^o								
80^o								

For data in Table 3.2 and Table 3.3, plot the measured range versus angle and draw a smooth curve through the points.

Questions

1. From the graph, what angle gives the maximum range for each case?

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2. Is the angle for the maximum range greater or less for shooting from an initial height?

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3. Is the maximum range further when the ball is shot from an initial height or on the level surface?

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Chapter 4

NEWTON'S SECOND LAW

Purpose

To demonstrate that the force to acceleration ratio is a constant dependent on the amount of the matter that is subjected to the various forces, gravitational or not.

Introduction

There's nothing obvious about the relationships governing the motions of objects. In fact, it took around 4000 years of civilization and the genius of Isaac Newton to figure out the basic laws. Fortunately for the rest of us, hindsight is a powerful research tool. In this experiment you will experimentally determine Newton's second law by examining the motion of an air track glider under the influence of a constant force. The constant force will be supplied by the weight of a hanging mass that will be used to pull the glider. By varying the mass of the hanging weight and of the glider, and measuring the acceleration of the glider, you'll be able to determine Newton's second law.

Equipments

Photogate Timer

Accessory Photogate

Air Track System with one glider

Pulley, Mass hanger and Masses (1x5g, 2x10g, 2x20g)

Procedure

1. Set up the air track as shown in Figure 4.1. Level the air track very carefully by adjusting the air track leveling feet. A glider should sit on the track without accelerating in either direction. There may be some small movement of the glider due to unequal airflow beneath the glider, but it should not accelerate steadily in either direction.

2. Measure the effective length of the glider and record your value as L in Table 4.1.

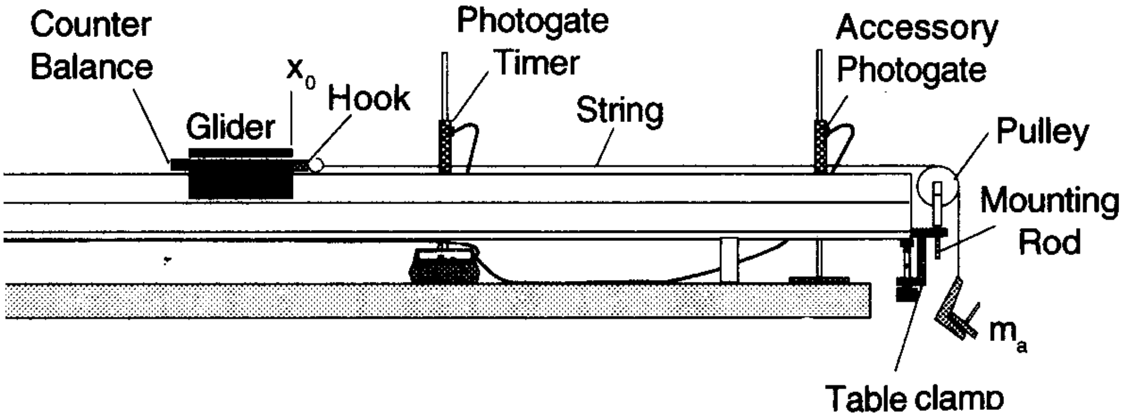

Figure 4.1:

3. Mount the hook into the bottom hole of the glider. To counterbalance its weight, add a piece of similar weight on the opposite end as shown on Figure 4.1.

4. Add 60 grams of mass to the glider using 10 or 20gram masses. Be sure the masses are distributed symmetrically so the glider is balanced. Determine the total mass of your glider with the added masses and record the total as m in Table 4.1.

5. Place a mass of 5 grams on the mass hanger. Record the total mass (hanger plus added mass) as m_a.

6. Set your Photogate Timer to GATE mode.

7. Choose a starting point x_o for the glider, near the end of the track. Mark this point with a pencil so that you can always start the glider from this same point.

8. Press the RESET button.

9. Hold the glider steady at x_o, then release it. Note t_1, the time it took for the glider to pass through the first photogate, and t_2, the time it took for the glider to pass through the second photogate. Repeat this measurement two times. Take the average of your measured t_1's and t_2's and record these averages as t_1 and t_2 in Table 4.1.

Note: Use the memory function of the timer to measure the two times. Turn the MEMORY switch to ON. Press RESET. Run the experiment. When the first time t_1 is measured, it will be immediately displayed. The second time t_2 will be automatically measured by the timer, but it will not be shown on the display. Record t_1, then push the MEMORY switch to READ. The display will now show the TOTAL time, $t_1 + t_2$. Subtract t_1 from the displayed time to determine t_2.

10. Set the Photogate Timer to PULSE mode.

11. Press the RESET button.

12. Again, start the glider from x_o. This time measure and record t_3, the time it takes the glider to pass between the photogates. Repeat this measurement two more times and record the average of these measurements as t_3 in Table 4.1.

13. Vary m_a, by moving masses from the glider to the hanger (thus keeping the total mass, $m + m_a$, constant). Record m and m_a and repeat steps 5 through 11. Try at least four different values for m_a.

14. Now leave m_a, constant at a previously used value. Vary m by adding or removing mass from the glider. Repeat steps 5-11. Try at least four different values for m.

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REPORT SHEET

EXPERIMENT 4: NEWTON'S SECOND LAW

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 4.1

Glider Length, L=....................

$m(g)$	$m_a(g)$	$t_1(s)$	$t_2(s)$	$t_3(s)$	$v_1(m/s)$	$v_2(m/s)$	$a(m/s^2)$	$F_a(N)$

For each set of experimental conditions:

1. Use the length of the glider and your average times to determine v_1 (L/t_1) and v_2 (L/t_2), the average glider velocity as it passed through each photogate.

2. Use the equation $a = (v_2 - v_1)/t_3$ to determine the average acceleration of the glider as it passed between the two photogates.

3. Determine F_a the force applied to the glider by the hanging mass. ($F_a = m_a g$, $g = 9.8 m/s^2$)

4. Draw a graph showing average acceleration as a function of applied force, F_a.

5. Draw a second graph showing average acceleration as a function of the glider mass with m_a being held constant.

6. Examine your graphs carefully. Are they straight lines? Use your graphs to determine the relationship between applied force, mass, and average acceleration for the air track glider.

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7. Discuss your results. In this experiment, you measured only the average acceleration of the glider between the two photogates. Do you have reason to believe that your results also hold true for the instantaneous acceleration? Explain. What further experiments might help extend your results to include instantaneous acceleration?

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Chapter 5

THE FORCE OF GRAVITY

Purpose

Using *Newton's Second Law* to measure the force exerted on an object by the Earth's gravitational field.

Introduction

In this experiment, we will use Newton's Second Law ($F = ma$) to measure the force exerted on an object by the Earth's gravitational field. Ideally, you would simply measure the acceleration of a freely falling object, measure its mass, and compute the force. However, the acceleration of a freely falling object is difficult to measure accurately. Accuracy can be greatly increased by measuring the much smaller acceleration of an object as it slides down an inclined plane. Figure 5.1 shows a diagram of the experiment. The gravitational force F_g can be resolved into two components; one acting perpendicular and one acting parallel to the motion of the glider. Only the component acting along the direction of motion can accelerate the glider. The other component is balanced by the force from the air cushion of the track acting in the opposite direction. From the diagram, $F = F_g \sin\theta$, where F_g is the total gravitational force and F is the component that accelerates the glider. By measuring the acceleration of the glider, F can be determined and F_g can be calculated.

Equipments

Photogate Timer

Accessory Photogate

Air Track System with one glider

A block of known thickness

Masses

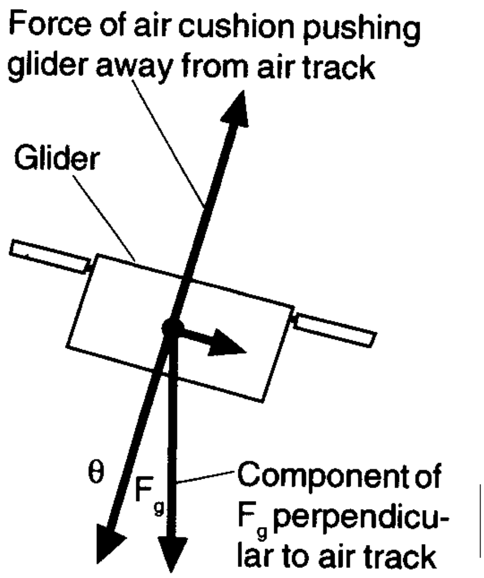

Figure 5.1:

Procedure

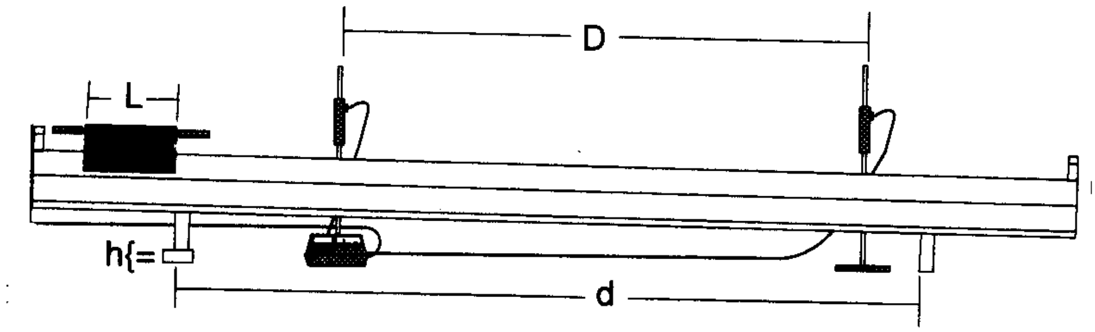

Figure 5.2:

1. Set up the air track as shown in Figure 5.2. Level the air track very carefully.

2. Measure d, the distance between the air track support legs. Record this distance.

3. Place a block of thickness h under the support leg of the track. Measure h with calipers and record it.

4. Measure and record D, the distance the glider moves on the air track from where it triggers the first photogate to where it triggers the second photogate.

5. Measure and record L, the effective length of the glider.

6. Measure and record m, the mass of the glider.

7. Set the Photogate Timer to GATE mode and press the RESET button.

8. Hold the glider steady near the top of the air track, then release it so it glides freely through the photogates. Record t_1, the time during which the glider blocks the first photogate, and t_2, the time during which it blocks the second photogate.

Use the memory function of the timer to measure the two times. Turn the MEMORY switch to ON. Press RESET. Run the experiment. When the first time t_1 is measured, it will be immediately displayed. The second time t_2 will be automatically measured by the timer, but it will not be shown on the display. Record t_1, then push the MEMORY switch to READ. The display will now show the TOTAL time, $t_1 + t_2$. Subtract t_1 from the displayed time to determine t_2.

9. Repeat the measurement several times and record your data in Table 5.1. You needn't release the glider from the same point on the air track for each trial, but it must be gliding freely and smoothly (minimum wobble) as it passes through the photogates.

10. Change the mass of the glider by adding weights and repeat steps 6 through 8. Do this for at least five different masses, recording the mass m for each set of measurements.

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REPORT SHEET

EXPERIMENT 5: THE FORCE OF GRAVITY

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

d =......................
h =......................
D =......................
L = ...
θ =......................
m (mass of the glider with the flag) = ...

Table 5.1

$m(g)$	$t_1(s)$	$t_2(s)$	$v_1(m/s)$	$v_2(m/s)$	$a(m/s^2)$	$F(N)$	$F_g(N)$

a_{avg}=.....................

1. Calculate θ, the angle of incline for the air track, using the equation $\theta = \arctan(h/d)$.

2. For each set of time measurements, divide L by t_1 and t_2 to determine v_1 and v_2, the velocities of the glider as it passed through the two photogates.

3. For each set of time measurements, calculate a, the acceleration of the glider, using the equation $v_2^2 - v_1^2 = 2a(x_2 - x_1) = 2aD$.

4. For each value of mass that you used, take the average of your calculated accelerations to determine a_{avg}.

5. For each of your average accelerations, calculate the force acting on the glider along its line of motion ($F = ma_{avg}$).

6. For each measured value of F, use the equation $F = F_g \sin\theta$ to determine F_g.

7. Construct a graph of F_g versus m, with m as the independent variable (x-axis).

Does your graph show a linear relationship between F_g and m? Does the graph go through the origin? Is the gravitational force acting on the mass proportional to the mass? If so, the gravitational force can be expressed by the equation $F_g = mg$, where g is a constant. If this is the case, measure the slope of your graph to determine the value of g.

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Questions

1. In this experiment, it was assumed that the acceleration of the glider was constant. Was this a reasonable assumption to make? How would you test this?

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2. The equation $v_2^2 - v_1^2 = 2a(x_2 - x_1)$ was used to calculate the acceleration. Under what conditions is this equation valid? Are those conditions met in this experiment? (You should be able to find a derivation for this equation in your textbook.)

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3. Could you use the relationship $F_g = mg$ to determine the force acting between the Earth and the Moon? Explain.

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Chapter 6

MEASURING g, THE ACCELERATION CAUSED BY GRAVITY

Purpose

To familiarize the students with a practical measurement technique of the important mechanical constant g.

Introduction

The equation of motion for a body starting from rest and undergoing constant acceleration can be expressed as: $x = (1/2)at^2$ where x is the distance the object has traveled from its starting point, a is the acceleration, and t is the time elapsed since the motion began. In order to measure the acceleration caused by gravity, several questions must be answered:

Is the acceleration constant? If it is, then the distance an object falls will be proportional to the square of the elapsed time, as in the above equation.

If the acceleration is constant, what is the value of the acceleration? Is it the same for all objects or does it vary with mass or size of the object, or with some other quality of the object? If it is not constant, how does it vary with time?

In this experiment you will answer these questions by carefully timing the fall of a steel ball from various heights.

Thanks to our electronics age, we are much luckier than our good old Galilee Galileo when he had to drop objects off the top of the leaning tower of Pizza and time them with his pulse.

Equipments

Free-Fall Timer with two steel balls
Rod stand
Multi clamp

Procedure

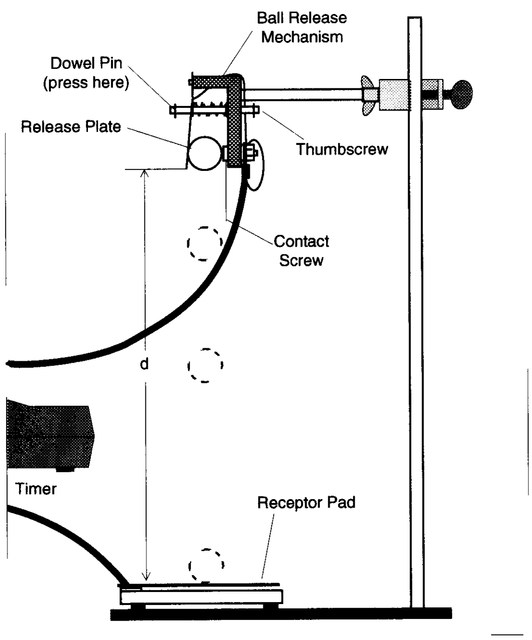

Figure 6.1:

1. First use the steel ball 13mm in diameter.

2. Set d, the height from which the ball drops. Measure the distance as accurately as possible and record the distance in Table 6.1. Press the RESET button on the timer, then loosen the thumbscrew so the ball drops. Record the measured time as t_1 in Table 6.1. Repeat the measurement at least two more times and record these values as $t_2 - t_3$. Calculate the average of your three measured times and record this value as t_{avg}.

3. Set d to different values and repeat step 2 for each value of d. Be sure you measure it carefully.

4. Repeat steps 2 and 3 using the steel ball 16mm in diameter and record your data in Table 6.2.

REPORT SHEET

EXPERIMENT 6: MEASURING g, THE ACCELERATION CAUSED BY GRAVITY

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 6.1

$d(cm)$	$t_1(s)$	$t_2(s)$	$t_3(s)$	$t_{avg}(s)$	$t_{avg}^2(s^2)$

Table 6.2

$d(cm)$	$t_1(s)$	$t_2(s)$	$t_3(s)$	$t_{avg}(s)$	$t_{avg}^2(s^2)$

For each ball, plot a graph of d versus t_{avg}^2 with d as the dependent value (y-axis). Within the limits of your experimental accuracy, do your data points define a straight line for each ball? Was the acceleration constant for each ball?

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If your graphs were linear, measure the slope of each graph. Using your measured slopes and the equation shown in the introduction to this experiment, determine the acceleration caused by gravity. Be sure to include the units. Was the acceleration the same for each ball?

Questions

Describe your laboratory experiment and discuss your results. Consider the following questions:

1. Is the acceleration caused by gravity constant?

2. Is the acceleration caused by gravity the same for all objects?

Discuss the conditions under which you believe your results to be true. Include a discussion of the errors in your measurements and how they affect your conclusions. How linear was your graph? How might you alter your technique, or the experiment, in order to reduce experimental errors?

Chapter 7

ELASTIC-KINETIC ENERGY

Purpose

To familiarize oneself with the idea that the kinetic energy can be stored and imparted at a later time. Spring provides an ingenious mechanism to this effect.

Introduction

It takes work to stretch or compress a spring. Suppose a spring has a natural (unstretched) length L_o and a spring constant k. If that spring is stretched or compressed to a new length, $L = L_o \pm\ x$, the work required is given by the expression $(1/2)kx^2$. If the energy stored in the spring is then used to accelerate an object, the kinetic energy of the object, $(1/2)mv^2$, will be equivalent to the work that was originally stored in the spring. In this lab you will investigate this equivalency between the work stored in a stretched spring and the kinetic energy it can impart to an object.

Equipments

Photogate Timer
Air Track with one glider
Mass hanger with masses
Spring (with a low spring constant)

Procedure

1. Set up the equipment as shown in Figure 7.1 and level the track. As shown, attach a cardboard flag to your glider with masking tape. The flag can be from 1 to 5cm wide. Make a platform for your spring, so it will be supported horizontally and will not sag. Attach the platform securely to the end of the air track. Connect the spring to the glider with a piece of thread so that the glider is about in the middle of the air track with the spring unstretched. Run another piece of thread from the glider over a pulley at the end of the track and attach it to a hanger.

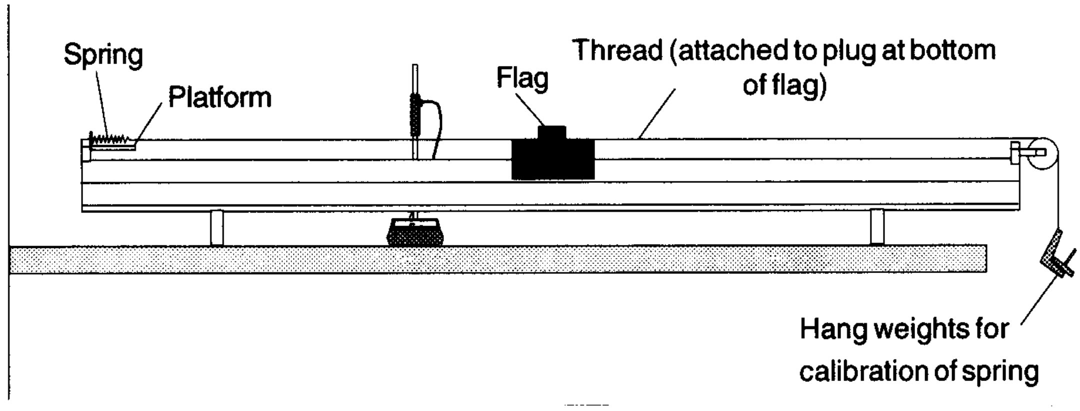

Figure 7.1:

2. Hang masses on the hanger and determine how far the spring stretches. This is easily done using the metric scale on the side of the air track and using the glider to monitor the distance the spring has extended. Record the masses added and the position of the glider in Table 7.1. (The air flow should be on while gathering this data.) Then remove the hanger and thread.

3. Measure and record m, the mass of your glider and flag, in Table 7.2. Then pass the glider slowly through the photogate and note the position of the glider when the LED on the photogate first goes on and again when the LED goes off. The difference between these positions is Δd. Record it.

4. Position the glider so the spring exerts no force on the glider, but the thread does not sag. Record this glider position as x_l. Position the photogate between the glider and the spring.

5. Pull the glider approximately 5cm farther away from the spring. Measure the distance between this glider position and x_1 and record this distance as the spring stretch in Table 7.2.

6. Set the Photogate Timer to GATE mode and press the RESET button.

7. Hold the glider steady as you turn the air flow on. Release the glider, but catch it before it crashes into the spring platform. Record the measured time as t_1 in Table 7.2.

8. Repeat steps 5-8 two more times. Record your times as t_2 through t_3 in Table 7.2. Determine the average of these three times and record this value as t_{avg}.

9. Repeat steps 5-9 for different distances of stretch of the spring up to $20cm$. Also try varying the mass of the glider by adding masses to it. Note the new masses in Table 7.2.

REPORT SHEET

EXPERIMENT 7: ELASTIC-KINETIC ENERGY

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 7.1 Determining the spring constant

Hanging Mass,(g)	Applied Force, $mg(N)$	Spring Stretch, $x(m)$

Determine k, the spring constant of your spring by constructing a graph of the stretch of the spring versus the amount of force applied to it by the hanging weights with the spring stretch values on the x-axis. The slope of this graph in, newtons/meter, is equal to k.

k=......................

Table 7.2

x_1=..................

Flag width, Δd=................

$m(g)$	stretch,$x(m)$	$t_1(s)$	$t_2(s)$	$t_3(s)$	$t_{avg}(s)$

$v_{avg}(m/s)$	$(1/2)mv_{avg}^2(J)$	$(1/2)kx^2(J)$	%Error

1. For each set of trials you performed for a given spring stretch and glider mass, divide Δd by your average time to determine the average velocity of the glider as it passed through the photogate. Calculate the final kinetic energy of the glider, $(1/2)mv_{avg}^2$.

2. Calculate the energy stored in the spring in each case, $(1/2)kx^2$ where k is the spring constant and x is the spring stretch.

3. For each trial, determine the percentage difference between the elastic potential energy stored in the spring and the final translational kinetic energy of the glider.

Chapter 8

CONSERVATION OF MECHANICAL ENERGY

Purpose

To demonstrate that the sum total of potential and kinetic energies is another conserved quantity in elastic collisions and mechanically isolated objects that are subjected to gravity only.

Introduction

Though conservation of energy is one of the most powerful laws of physics, it is not an easy principle to verify. If a boulder is rolling down a hill, for example, it is constantly converting gravitational potential energy into kinetic energy (linear and rotational), and into heat energy due to the friction between it and the hillside. It also loses energy as it strikes other objects along the way, imparting to them a certain portion of its kinetic energy. Measuring all these energy changes is no simple task.

This kind of difficulty exists throughout physics, and physicists meet this problem by creating simplified situations in which they can focus on a particular aspect of the problem. In this experiment you will examine the transformation of energy that occurs as an air track glider slides down an inclined track. Since there are no objects to interfere with the motion and there is minimal friction between the track and glider, the loss in gravitational potential energy as the glider slides down the track should be very nearly equal to the gain in kinetic energy. Stated mathematically:

$\Delta E_k = \Delta(mgh) = mg\Delta h$

where ΔE_k is the change in kinetic energy of the glider ($\Delta E_k = (1/2)mv_2^2 - (1/2)mv_1^2$) and $\Delta(mgh)$ is the change in its gravitational potential energy (m is the mass of the glider, g is the acceleration of gravity and Δh is the change in the vertical position of the glider).

Equipments

Photogate Timer
Accessory Photogate
Air track system with one glider
A block of known thickness

Procedure

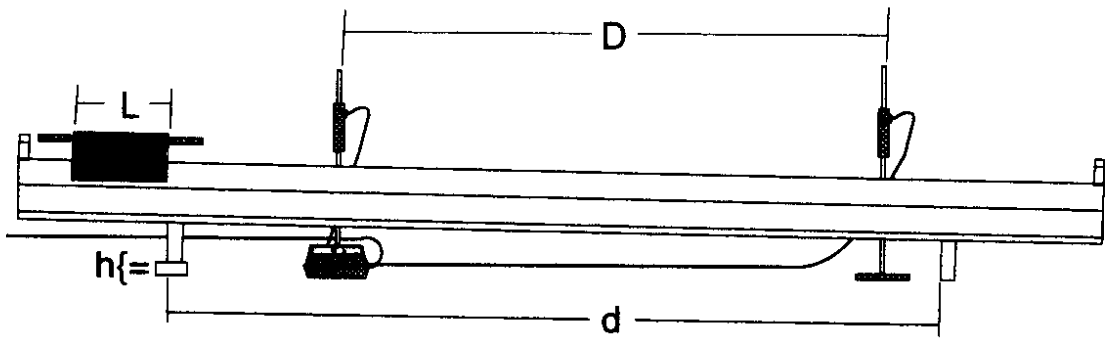

Figure 8.1:

1. Level the air track as accurately as possible.

2. Measure d, the distance between the air track support legs. Record this distance in Table 8.1

3. Place a block of known thickness under the support leg of the track. For best accuracy, the thickness of the block should be measured with calipers. Record the thickness of the block as h in Table 8.1.

4. Setup the Photogate Timer and Accessory Photogate as shown in Figure 8.1.

5. Measure and record D, the distance the glider moves on the air track from where it first triggers the first photogate to where it first triggers the second photogate. (You can tell when the photogates are triggered by watching the LED on top of each photogate. When the LED lights up, the photogate has been triggered.)

6. Measure and record L, the effective length of the glider. (The best technique is to move the glider slowly through one of the photogates and measure the distance it travels from where the LED first lights up to where it just goes off.)

7. Measure and record m, the mass of the glider.

8. Set the Photogate Timer to GATE mode and press the RESET button.

9. Hold the glider steady near the top of the air track, then release it so it glides freely through the photogates. Record t_1, the time during which the glider blocks the first photogate, and t_2, the time during which it blocks the second photogate. (The memory function of the Photogate Timer will make it easier to measure the two times.)

10. Repeat the measurement several times and record your data in Table 8.1. You needn't release the glider from the same point on the air track for each trial, but it must be gliding freely and smoothly (minimum wobble) as it passes through the photogates.

11. Change the mass of the glider by adding weights and repeat steps 7 through 10. Do this for at least five different masses, recording the mass m for each set of measurements.

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REPORT SHEET

EXPERIMENT 8: CONSERVATION OF MECHANICAL ENERGY

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

d=...........
D=..........
h=...........
L=...........
m=..........

Table 8.1

m	θ	t_1	t_2	v_1	v_2	E_{k1}	E_{k2}	ΔE_k	$\Delta(mgh)$

1. Calculate θ, the angle of incline for the air track, using the equation $\theta = \arctan(h/d)$.

For each set of time measurements:

2. Divide L by t_1 and t_2 to determine v_1 and v_2, the velocity of the glider as it passed through each photogate.

3. Use the equation $E_k = (1/2)mv^2$ to calculate the kinetic energy of the glider as it passed through each photogate.

4. Calculate the change in kinetic energy, $\Delta E_k = E_{k2} - E_{k1}$.

5. Calculate Δh, the distance through which the glider dropped in passing between the two photogates ($\Delta h = D \sin \theta$).

6. Compare the kinetic energy gained with the loss in gravitational potential energy. Was mechanical energy conserved in the motion of the glider?

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Chapter 9

CONSERVATION OF MOMENTUM

Purpose

To demonstrate that linear momentum is conserved in every collision that is free from any other force except that is due to the collision itself and to demonstrate that if collision is elastic and horizontal, the total kinetic energy of the system is a conserved quantity, ie, a constant throughout the act.

Introduction

When objects collide, whether locomotives, shopping carts or your foot and the sidewalk, the results can be complicated. Yet even in the most chaotic of collisions, as long as there are no external forces acting on the colliding objects, one principle always holds and provides an excellent tool for understanding the dynamics of the collision. That principle is called *the conservation of momentum.* For a two-object collision, momentum conservation is easily stated mathematically by the equation:

$$p_i = m_1 v_{1i} + m_2 v_{2i} = m_1 v_{1f} + m_2 v_{2f} = p_f$$

where m_1 and m_2 are the masses of the two objects, v_{1i} and v_{2i} are the initial velocities of the objects (before the collision), v_{1f} and v_{2f} are the final velocities of the objects (after the collision), and p_i and p_f are the combined momentums of the objects, before and after the collision. In this experiment, you will verify the conservation of momentum in a collision of two air track gliders.

Momentum is always conserved in collisions that are isolated from external forces. Energy is also always conserved, but energy conservation is much harder to demonstrate since the energy can change forms: energy of motion (kinetic energy) may be changed into heat energy, gravitational potential energy, or even chemical potential energy. In the air track glider collisions you'll be investigating, the total energy before the collision is simply the kinetic energy of the gliders:

$$E_{ki} = (1/2)m_1 v_{1i}^2 + (1/2)m_2 v_{2i}^2$$

After the collision, the total kinetic energy of the system is:

$E_{kf} = (1/2)m_1v_{1f}^2 + (1/2)m_2v_{2f}^2$

In this experiment you'll examine the kinetic energy before and after a collision to determine if kinetic energy is conserved in air track collisions.

Equipments

Two Photogate Timers
Air Track System with two gliders

Procedure

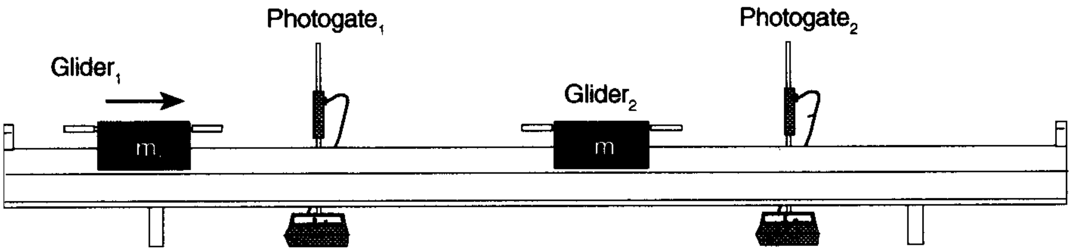

Figure 9.1:

1. Set up the air track and photogates as shown in Figure 9.1, using bumpers on the gliders to provide an elastic collision. Carefully level the track.

2. Measure m_1 and m_2, the masses of the two gliders to be used in the collision. Record your results in Table 9.1.

3. Measure and record L_1 and L_2 the length of the gliders. (e.g., push glider through photogate and measure the distance it travels from where the LED comes on to where it goes off again.)

4. Set both Photogate Timers to GATE mode, and press the RESET buttons.

5. Place *glider*$_2$ at rest between the photogates. Give *glider*$_1$ a push toward it. Record four time measurements in Table 9.1 as follows:

t_{1i} = the time that *glider*$_1$ blocks *photogate*$_1$ before the collision.

t_{2i}= the time that *glider*$_2$ blocks *photogate*$_2$ before the collision. (In this case, there is no t_{2i} since *glider*$_2$ begins at rest.)

t_{1f}= the time that $glider_1$ blocks $photogate_1$ after the collision.

t_{2f}= the time that $glider_2$ blocks $photogate_2$ after the collision.

6. Repeat the experiment several times, varying the mass of one or both gliders and varying the initial velocity of $glider_1$.

7. Try collisions in which the initial velocity of $glider_2$ is not zero. You may need to practice a bit to coordinate the gliders so the collision takes place completely between the photogates.

Optional Equipment

Design and conduct an experiment to investigate conservation of kinetic energy in an inelastic collision in which the two gliders, instead of bounching off each other, stick together so that they move off with identical final velocities. Replace the bumpers with the wax and needle.

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REPORT SHEET

EXPERIMENT 9: CONSERVATION OF MOMENTUM

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Table 9.1

L_1=................ L_2=................

$m_1(g)$	$m_2(g)$	$t_{1i}(s)$	$t_{2i}(s)$	$t_{1f}(s)$	$t_{2f}(s)$

$v_{1i}(m/s)$	$v_{2i}(m/s)$	$v_{1f}(m/s)$	$v_{2f}(m/s)$	$p_i(kg*m/s)$	$p_f(kg*m/s)$	$E_{ki}(J)$	$E_{kf}(J)$

1. For each time that you measured, calculate the corresponding glider velocity (e.g., $v_{1i} = \pm L_1/t_{1i}$ where the velocity is positive when the glider moves to the right and negative when it moves to the left).

2. Use your measured values to calculate p_i and p_f, the combined momentum of the gliders before and after the collision. Record your results in the table.

3. Use your measured values to calculate E_{ki} and E_{kf} the combined kinetic energy of the gliders before and after the collision. Record your results in the table.

Questions

1. Was momentum conserved in each of your collisions? If not, try to explain any discrepancies.

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2. If a glider collides with the end of the air track and rebounds, it will have nearly the same momentum it had before it collided, but in the opposite direction. Is momentum conserved in such a collision? Explain.

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3. Suppose the air track was tilted during the experiment. Would momentum be conserved in the collision? Why or why not?

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4. Was kinetic energy conserved in each of your collisions?

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5. If there were one or more collisions in which kinetic energy was not conserved, where did it go?

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Chapter 10

ROTATIONAL MOTION

Purpose

To see how the reading on the Rotational Dynamics Apparatus display relates to the angular velocity of the rotating disk.

Applying a constant force to the rotating disk under a variety of circumstances, in an attempt to determine how the force on the disk relates to its angular acceleration.

Finally, to determine that if the angular momentum of rotating objects is conserved in a collision as like their linear momentum.

Introduction

Suppose that our rotating body is at angular position θ_1 at time t_1 and at angular position θ_2 at time t_2. We define the *average angular velocity* of the body in the time interval Δt from t_1 to t_2 to be

$$\omega_{avg} = \frac{\theta_2 - \theta_1}{t_2 - t_1} = \frac{\Delta\theta}{\Delta t}$$

in which $\Delta\theta$ is the angular displacement that occurs during Δt.

The *(instantaneous) angular velocity* ω is the limit of the ratio in equation above as Δt approaches zero. Thus,

$$\omega\ (lim\ \Delta t \rightarrow 0) = \frac{\Delta\theta}{\Delta t} = \frac{d\theta}{dt}$$

If we know $\theta(t)$, we can find the angular velocity ω by differentiation.

The angular velocity ω of a rotating rigid body is either positive or negative, depending on whether the body is rotating counterclockwise (positive) or clockwise (negative).

If the angular velocity of a rotating body is not constant then the body has an angular acceleration. Let ω_2 and ω_1 be its angular velocities at times t_2 and t_1, respectively. The *average angular acceleration* of the rotating body in the interval from t_1 to t_2 is defined as:

$$\alpha_{avg} = \frac{\omega_2 - \omega_1}{t_2 - t_1} = \frac{\Delta\omega}{\Delta t}$$

in which $\Delta\omega$ is the change in the angular velocity that occurs during the time interval Δt.

The *(intantaneous) angular acceleration* α is the limit of this quantity as Δt approaches zero. Thus,

$$\alpha\ (lim\ \Delta t \to 0) = \frac{\Delta\omega}{\Delta t} = \frac{d\omega}{dt}$$

If the motion of an object undergoing constant acceleration, then the average acceleration is equal to the instantaneous acceleration.

Angular momentum of a system of particles that form a rigid body that rotates about a fixed axis with constant angular speed ω, can be written as; $L = I\omega$. I, in that equation is the rotational inertia about that same axis. The law of conservation of angular momentum can be written as;

$$L_i = L_f \qquad \text{(isolated system)}$$

We can apply this law to a isolated body which rotates around a fixed axis. Suppose that the initially rigid body somehow redistributes its mass relative to that rotation axis, changing its rotational inertia about that axis. The law of conservation states that the angular momentum of the body cannot change. So we write this conservation law as;

$$I_i\omega_i = I_f\omega_f$$

Here the subscripts refer to the values of the rotational inertia I and angular speed ω before and after the redistribution of mass.

In this experiment you will use the Rotational Dynamics Apparatus. The optical readers of the apparatus count the number of black bars that pass by them in one second. This is the number that is displayed. R is the reading in *bars/second.* So you can use this information to convert the measurement to *radians/second.*

$$\omega = \kappa R$$

where κ, is the rotation of the disk in radians for each bar detected by the optical reader.

Equipments

Rotational Dynamics Apparatus
Air Pump

Part I: Angular Velocity

Procedure

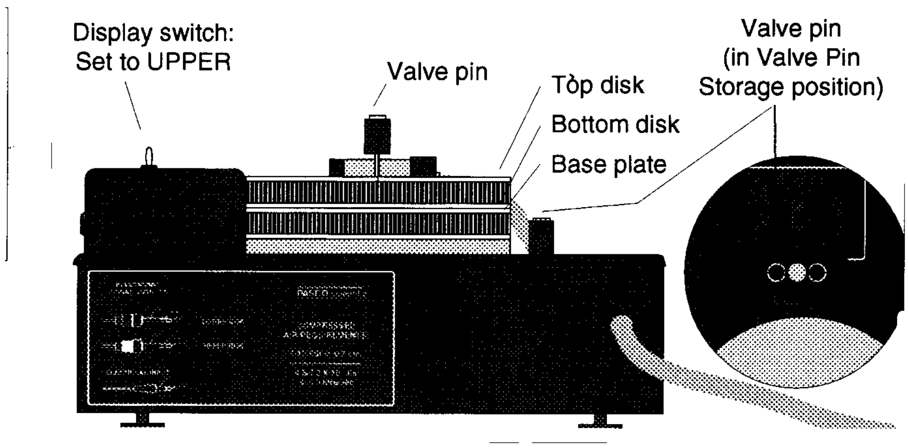

Figure 10.1:

1. Set up the equipment as shown in Figure 10.1. Use either the steel or aluminum disk as the top disk.

2. Use the bubble level to check that the base of the apparatus is level. If not, adjust the leveling feet.

3. Flip the switch on the display to UPPER, so the top disk is monitored by the optical readers.

4. Check that the valve pin for the lower disk is in the storage position, so that the lower disk rests firmly on the base plate.

5. Give the top disk a gentle spin, so that the digital display reads somewhere 100 and 200 counts/sec. Watch the reading on the digital display for several minutes. Is it constant or does the reading increase or decrease?

6. Place a narrow piece of tape on the top of the top disk, at some point near the rim.

7. Give the disk a gentle spin (again to about 100-200 counts/sec) and record the initial reading on the digital display (R_i) in Table 10.1.

8. By watching the tape, count the number of revolutions of the disk in some specified time interval, about one minute. Record the number of revolutions as N and the time interval as t. At the end of the time interval, record the final reading on the digital display (R_f).

9. From your data, calculate the total angle θ, in radians, through which the disk rotated during the time t ($\theta = 2\pi N$). From this, determine the average angular velocity (ω_{avg}) of the disk during the time t ($\omega_{avg} = \theta/t$).

10. Calculate the average display reading during the time t, $R_{avg} = (R_i + R_f)/2$.

11. Repeat the experiment a few more times.

Part II: Angular Acceleration

Procedure

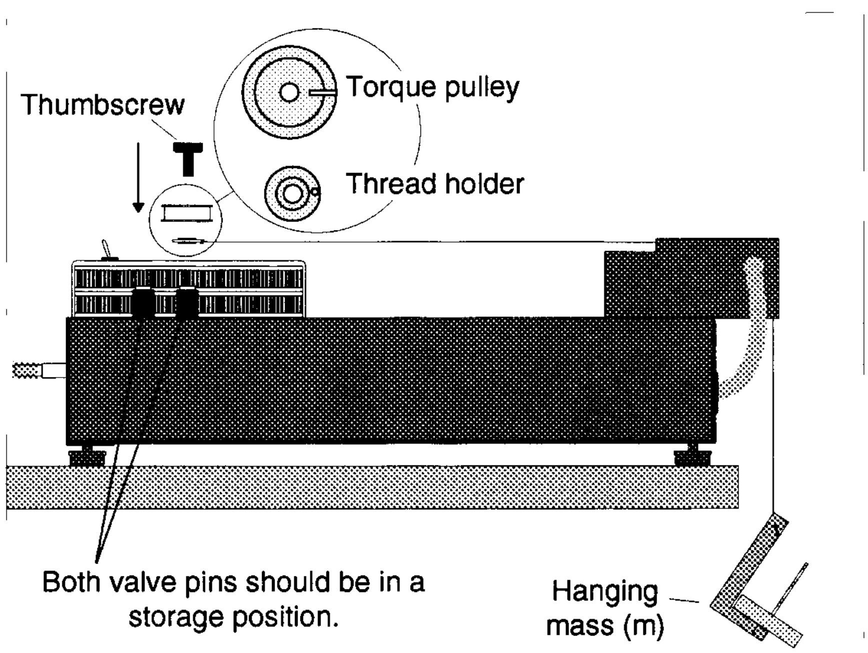

Figure 10.2:

1. Set up the equipment as shown in Figure 10.2. Use the steel disk as the top disk, and use the small torque pulley.

2. Attach the mass hanger to the end of the thread. When the thread is extended, the mass should almost reach the floor.

3. Check that the bottom disk sits firmly on the base plate. Only the top disk should spin.

4. Record the hanging mass (m), the radius of the torque pulley (r), and the mass of the rotating disk (M) in Table 10.2. Be sure to include the mass of the hanger, $5g$, in your value for m.

To measure the acceleration of the disk under the force applied by the hanging mass:

5. Wind the thread onto the torque pulley, until the hanging mass is almost against the air pulley.

6. Hold the disk still until the display reads zero.

7. Release the disk. As the disk rotates, record each successive, non-zero reading of the display (R_1-R_8) in Table 10.2. Record these values as the hanging mass falls, and again as it rises back up. Do not record any values that appear after the mass has reached its highest point and started back down. You should get at least six different values. If you don't get that many, raise the apparatus and use a longer piece of thread.

Two of your recorded values will not be useable data. The first is R_1. The second is the value that was counted as the hanging mass reached its lowest point and then started back up. Leave these values in your data table, but mark them clearly so you do not use them in your later calculations.

8. Repeat steps 5-7 at least three times (the more the better).

9. Leaving all other experimental conditions the same, change the value of m, and repeat steps 5-8.

10. Leaving all other experimental conditions the same, change the value of r (use the large torque pulley), and repeat steps 5-8.

11. Leaving all other experimental conditions the same, change the value of M. Replace the steel top disk with the aluminum top disk, and repeat steps 5-8.

Part III: Conservation of Angular Momentum

Procedure

1. Record the mass of all rotating disks (the top and bottom steel disks and the top aluminum disk) and measure the inner and outer radii of the disks. Record your measurements in Table 10.4.

2. Set up the equipment as in Figure 10.3. Use the steel disk as the top disk.

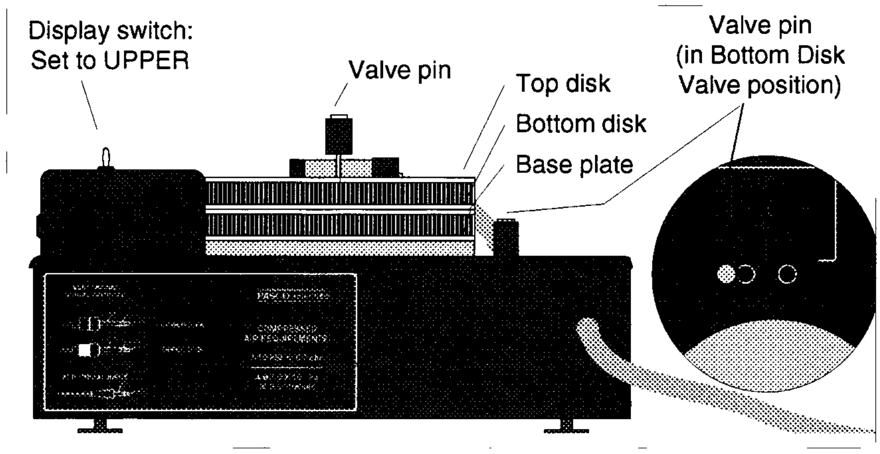

Figure 10.3:

3. Insert one valve pin in the bottom disk valve and the other in the hole in the center of the top disk. Spin the disks. They should rotate smoothly and independently.

4. Set the display switch so that the display monitors the motion of the upper disk.

5. Hold the bottom disk stationary and give the top disk a spin, so that the display reads approximately 300-400 counts/s. Wait several seconds, then record the display reading for the top disk as R_{top} in Table 10.5. Immediately after recording the reading, pull the valve pin from the top disk so that the top disk falls onto the bottom disk. Wait a full two seconds, then record the reading, on the display as R_{final} in the data table. (The initial reading for the bottom disk, R_{bot}, is zero, since it was held stationary.)

6. Repeat the experiment several times. Try different initial angular velocities for the top disk. Also try some runs in which R_{bot} is not zero. Experiment with both disks spinning initially in the same direction, and also with both disks spinning initially in opposite directions. (When both disks are spinning initially, you will need to flip the display switch to measure both R_{top} and R_{bot}, before removing the drop pin. Each time you flip the switch or pull the pin, be sure to wait a full two seconds before recording the new display reading. Also be sure to record the direction in which each disk spins, cw or ccw.)

7. Exchange the top steel disk for the aluminum disk, and repeat the experiment. Try a variety of initial angular velocities.

REPORT SHEET

EXPERIMENT 10: ROTATIONAL MOTION

Student's Name:
Experiment Date:
Group Member Name(s):
Laboratory Bench Number:
Assistant's Name and Signature:

Data and Calculations

Part I: Angular Velocity

Table 10.1

R_i	R_f	N	t	θ	ω_{avg}	R_{avg}	κ

1. Using your calculated values, determine a constant κ, that relates the average display reading to the average angular velocity ($\kappa R_{avg} = \omega_{avg}$).

2. How accurate does your measured value of κ seem to be?

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3. Determine the number N of black bars on the circumference of the disk (count them or determine the number per centimeter and multiply by the circumference of the disk or use some other method).

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4. Divide 2π by N to determine κ. Convince yourself of this by comparing the units of the relevant variables: R (bars/second), ω (radians/second), N (bars), 2π (radians). Notice that $(2\pi/N)R = \omega$ gives the proper units.

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5. Compare your value of κ from step 2 with that from step 4. Are they the same? If not, which value do you have more confidence in? If necessary, experiment some more to determine a value of κ that you trust.

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Part II: Angular Acceleration

The display shows you the number of bars that pass by every second. However, there is a dead time of one second between each counting interval, so the time between successive displayed values is 2.00 seconds. Therefore, if you convert all your display readings into angular velocities, you can easily calculate the average angular acceleration within each time interval. For example; $\alpha_3 = (\omega_3 - \omega_2)/(t_3 - t_2)$ where $t_3 - t_2 = 2.00$ *seconds*, and ω is determined using the conversion factor that you measured before (e.g., $\omega_3 = \kappa R_3$).

Table 10.2

$m = 10$g, $r = 1.27$cm, $M = 1600$g

R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
ω_1	ω_2	ω_3	ω_4	ω_5	ω_6	ω_7	ω_8
α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_{avg}

$m = 20$g, $r = 1.27$cm, $M = 1600$g

R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
ω_1	ω_2	ω_3	ω_4	ω_5	ω_6	ω_7	ω_8
α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_{avg}

$m = 10$g, $r = 2.54$cm, $M = 1600$g

R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
ω_1	ω_2	ω_3	ω_4	ω_5	ω_6	ω_7	ω_8
α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_{avg}

$m = 10$g, $r = 1.27$cm, $M = 600$g

R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
ω_1	ω_2	ω_3	ω_4	ω_5	ω_6	ω_7	ω_8
α_1	α_2	α_3	α_4	α_5	α_6	α_7	α_{avg}

For each trial of the experiment that you performed:

1. Calculate the angular velocity within each counting interval.

2. Calculate the average angular acceleration within each valid timing interval.

For each set of trials in which the experimental conditions were the same:

3. Determine the average of your measured values of α. Record this value as α in Table 10.3.

For each value of α that you determine:

4. Calculate and record the total moment of inertia (I) of the accelerated disk(s).

5. Calculate and record $I\alpha$.

6. Calculate the applied torque (τ) and record this value in Table 10.3.

7. Calculate the percentage difference between τ and $I\alpha$.

Table 10.3

α	I	$I\alpha$	τ	%diff

Questions

1. Is it reasonable to assume that your measured values of α are the same as the instantaneous angular acceleration within each counting interval? Explain your answer. (Hint: Is the angular acceleration constant?)

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2. Within the limits of accuracy of your measurements, did $\tau = I\alpha$ for all your experimental run? Discuss any discrepancies.

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Part III: Conservation of Angular Momentum

Table 10.4

	Mass, M	Inner Radius	Outer Radius	Moment of Inertia
Bottom steel disk	1600g			
Top steel disk	1600g			
Top aluminum disk	600g			

1. Using the data you collected in Table 10.4, calculate I, the moment of inertia of each rotating disk, $I = \frac{1}{2}M(r_{inner}^2 + r_{outer}^2)$. Record your results in the table.

Table 10.5

I_{top}	I_{bot}	R_{top}	R_{bot}	R_{final}	ω_{top}	ω_{bot}	ω_{final}	L_{top}	L_{bot}	L_{final}

For each run of the experiment that you performed:

2. Calculate the initial angular velocity of each disk (w_{top} and w_{bot}).

3. Multiply the calculated angular velocity of each disk by its moment of inertia to determine the initial angular momentum of each disk, $L_{top} = I_{top}\omega_{top}$, etc.

4. Calculate the total final angular momentum of the disks, $L_{final} = (I_{top} + I_{bot})\omega_{final}$.

5. Calculate the percent difference between the combined initial angular momentums and the combined final angular momentums.

Questions

1. Within the limits of your experimental error, was angular momentum conserved in your collisions. Discuss any discrepancies.

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2. Discuss the role of friction in the experiment. How might you change the apparatus, and/or the design of the experiment, to compensate for frictional effects?

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3. Suppose you performed the experiment without the valve pin in the bottom disk valve, so that the bottom disk was sitting firmly on the base plate. The initial angular momentum would be that of the top disk. The final angular momentum would be zero. Would momentum be conserved? Explain your answer.

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