1st Science
Physics Laboratory Manual

PHYC 10120
Physics in Medicine
2018-2019

Name..

Partner's Name ....

Demonstrator ....

Group ....

Laboratory Time ....

Contents

Introduction

Physics is an experimental science. The theory that is presented in lectures has its origins in, and is validated by, experiment.

Laboratories are staged through the semester in parallel to the lectures. They serve a number of purposes:

- ***an opportunity, as a scientist, to test theories by conducting meaningful scientific experiments;***
- ***a means to enrich and deepen understanding of physical concepts presented in lectures;***
- ***an opportunity to develop experimental techniques, in particular skills of data analysis, the understanding of experimental uncertainty, and the development of graphical visualisation of data.***

Based on these skills, you are expected to present experimental results in a logical fashion (graphically and in calculations), to use units correctly and consistently, and to plot graphs with appropriate axis labels and scales. You will have to draw clear conclusions (as briefly as possible) from the experimental investigations, on what are the major findings of each experiment and whetever or not they are consistent with your predictions. You should also demonstrate an appreciation of the concept of experimental uncertainty and estimate its impact on the final result.

Some of the experiments in the manual may appear similar to those at school, but the emphasis and expectations are likely to be different. Do not treat this manual as a 'cooking recipe' where you follow a prescription. Instead, understand what it is you are doing, why you are asked to plot certain quantities, and how experimental uncertainties affect your results. It is more important ***to understand and show your understanding*** in the write-ups than it is to rush through each experiment ticking the boxes.

This manual includes blanks for entering most of your observations. Additional space is included at the end of each experiment for other relevant information. All data, observations and conclusions should be entered in this manual. Graphs may be produced by hand or electronically (details of a simple computer package are provided) and should be secured to this manual.

There will be six 2-hour practical laboratories in this module evaluated by continual assessment. Note that each laboratory is worth 5% so each laboratory session makes a significant contribution to your final mark for the module. Consequently, attendance and application during the laboratories are of the utmost importance. At the end of each laboratory session, your demonstrator will collect your work and mark it.

Laboratory Schedule

Your physics laboratories will be on Tuesday 11-13, the weeks depending on your timetable.

Please consult the lab notice board or contact the lab manager, Thomas O'Reilly (Room Science East 1.41) to see which of the experiments you will be performing each week. This information is also summarized below.

Semester Week	Week Start Date 2018	Room		
		Science East 143	Science East 144	Science East 145
2	17th Sep	Springs: 1	Springs: 2	Springs: 5
3	24th Sep	Springs: 3	Springs: 4	Springs: 6
4	1st Oct	Gas: 2	Momentum: 1	
5	8th Oct	Gas: 4	Momentum: 3	
6	15th Oct	Gas: 1	Momentum: 2	
7	22nd Oct	Gas: 3	Momentum: 4	
8	29th Oct	Gas: 5	Momentum: 6	
9	5th Nov	Gas: 6	Momentum: 5	
10	12th Nov	Rotation: 1	Acceleration: 2	
11	19th Nov	Rotation: 3	Acceleration: 4	
12	26th Nov	Rotation: 5	Acceleration: 6	

Grading Process

Grading is an important form of feedback for students, who benefit from this feedback for continuous improvement. Grading is staged through the semester in synchronisation with the labs. This is the grading process:

1. See appendix 2 for the labs grading scheme.

2. A lab script is graded by the lab demonstrator and returned to the student in the subsequent scheduled lab slot. Students resolve concerns regarding their grade with this demonstrator either during or immediately after this lab slot.

3. The grade is visible online within a week of the script being returned. Grades are preliminary but can be expected to count towards a module grade once visible online.

   If the above doesn't happen, it is the student responsibility to resolve this with the demonstrator as early as possible.

Lab Rules

1. No eating or drinking.

2. Bags and belongings are placed on the shelves provided in the labs.

3. Students are only permitted to start a lab where they have this school of physics manual in print. The school of physics lab manual for your module is available in print from the school of physics admin office and is also available online from the school of physics pages.

4. It is the student's responsibility to attend an originally assigned lab slot. Zero grade is assigned by default for no attendance at this lab.

   In the case of unavoidable absence, it is the student's responsibility to complete the lab in an alternative slot as soon as possible. If this is done, the default student grade of zero is updated online with the awarded grade after an additional two weeks. However, such an alternative lab slot can't be guaranteed as lab numbers are strictly limited. The lab manager, Thomas O'Reilly (Room Science East 1.41), may be of help in discussing potential alternative lab times. Where best efforts have been made to attend an alternative lab slot but this hasn't been possible, students should then discuss with their module coordinator.

5. Students work in pairs in the lab, however reports are prepared individually and must comply with UCD plagiarism policy (see next page).

UCD Plagiarism Statement

(taken from http://www.ucd.ie/registry/academicsecretariat/docs/plagiarism_po.pdf)

The creation of knowledge and wider understanding in all academic disciplines depends on building from existing sources of knowledge. The University upholds the principle of academic integrity, whereby appropriate acknowledgement is given to the contributions of others in any work, through appropriate internal citations and references. Students should be aware that good referencing is integral to the study of any subject and part of good academic practice.

The University understands plagiarism to be the inclusion of another person's writings or ideas or works, in any formally presented work (including essays, theses, projects, laboratory reports, examinations, oral, poster or slide presentations) which form part of the assessment requirements for a module or programme of study, without due acknowledgement either wholly or in part of the original source of the material through appropriate citation. Plagiarism is a form of academic dishonesty, where ideas are presented falsely, either implicitly or explicitly, as being the original thought of the author's. The presentation of work, which contains the ideas, or work of others without appropriate attribution and citation, (other than information that can be generally accepted to be common knowledge which is generally known and does not require to be formally cited in a written piece of work) is an act of plagiarism. It can include the following:

1. Presenting work authored by a third party, including other students, friends, family, or work purchased through internet services;
2. Presenting work copied extensively with only minor textual changes from the internet, books, journals or any other source;
3. Improper paraphrasing, where a passage or idea is summarised without due acknowledgement of the original source;
4. Failing to include citation of all original sources;
5. Representing collaborative work as one's own;

Plagiarism is a serious academic offence. While plagiarism may be easy to commit unintentionally, it is defined by the act not the intention. All students are responsible for being familiar with the University's policy statement on plagiarism and are encouraged, if in doubt, to seek guidance from an academic member of staff. The University advocates a developmental approach to plagiarism and encourages students to adopt good academic practice by maintaining academic integrity in the presentation of all academic work.

UCD Physics Laboratory: Investigation of Springs

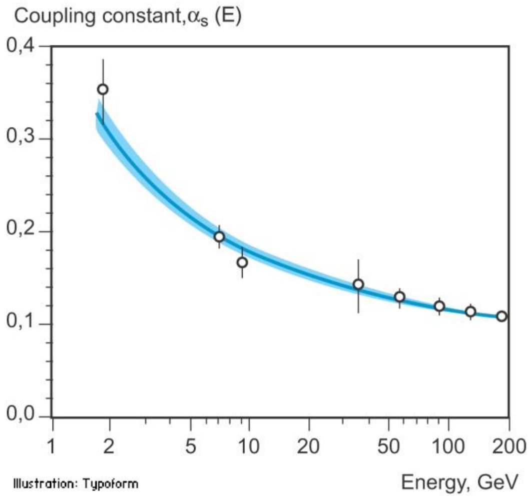
Student Name: ______________ **Student Number:** ___________
Lab Partner Name: ______________ **Demonstrator Name** ___________
Lab Date/Time: ______________

Goal

You will physically interpret experimental measurements with a straight line fit to data that you measure. Specifically, you will investigate how springs stretch when different objects are attached to them and you will learn about the graphing of scientific data. You will compare the stiffness of two springs. You do not need prior knowledge of this topic to participate in this laboratory session.

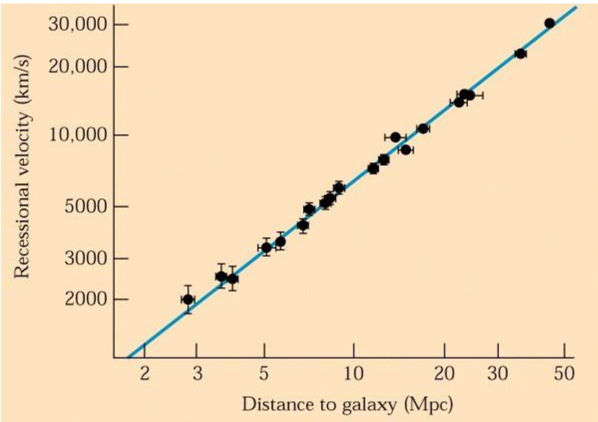
Warm-up exercises: Plotting scientific data

In many scientific disciplines and particularly in physics, you will come across plots similar to those shown here.



Note some common features:

- horizontal and vertical axes;
- axes have labels and units;
- axes have a scale;
- points with vertical and/or horizontal lines through them;
- a curve or line superimposed.



Why do we make such plots?

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What features of the graphs do you think are important and why?

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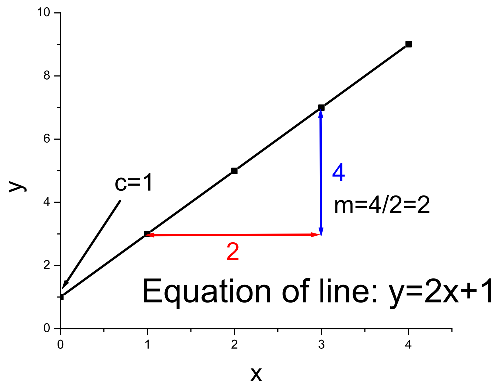
The equation of a straight line can be written as:

$$y = m\,x + c$$

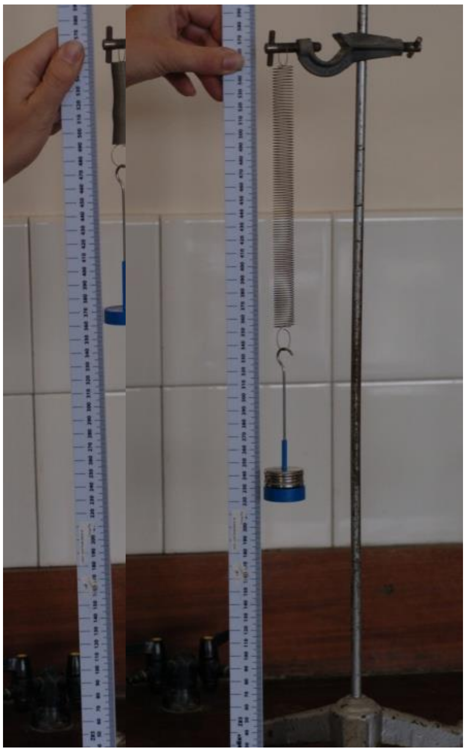
The variable '*y*' is how far up the point is, whilst the variable '*x*' is how far along the x-axis the point is.

The variable *m* is the slope or gradient of the line. It tells you how steep a line is and is calculated by dividing the change in *y* by the change is *x* for the same part of the line.

c is the intercept of the line and is the point where the line crosses the *y*-axis, at *x* = 0.



In this experiment, you will demonstrate the way a spring extends. The more a spring is pulled, the more it extends. For reference, the relationship between a pulling force and the extension of a spring is given by 'Hooke's Law', however you don't need knowledge of this law to do this experiment. Instead, you will discover the behaviour of a spring through your own measurements.



Experimental set-up

In this experiment, we apply a controlled force to a spring by means of hanging weights from it. You will use 2 different springs, a retort stand, a ruler, a mass hanger and a number of 10-g masses.

Set up the experiment to be used as shown in the photographs. Let's call one of your two springs 'spring 1' and the other 'spring 2'.

Calculate the initial (unstretched) length of spring 1: ________________

Calculate the initial (unstretched) length of spring 2: ________________

Think about how you can most easily determine the length of each spring as you add weights and it extends. You might want to keep the top of the spring at a fixed position and just determine the revised position of the bottom of the spring to more quickly work out the length of the spring each time.

Add the mass hanger to each of the springs in turn. We know that springs should extend when pulled, but do the lengths of the springs change on adding this hanger? Explain.

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Add masses to the hanger one at a time, for each of spring 1 and spring 2. What are the minimum number of masses required for each spring to begin to extend?

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Now you will collect all your data. Then you will interpret the data graphically.

Procedure and Data

It is a typical scientific process to take data whilst increasing a (controlled) parameter and then also while decreasing it. This is what you are asked to do here, where the controlled parameter is the mass on the spring.

Add the 10-g disks to the mass hanger one at a time whilst measuring the revised length of the spring. Once all your masses have been added, continue taking measurements by taking measurements where taking one mass off at a time. Fill in the following tables.

Measurements for spring 1:

Object Added	Total mass added to the spring hanger (g)	Spring length whilst adding masses, in cm *(plot as crosses)*	Spring length for taking away masses, in cm *(plot as dots)*
Disk 1	10		
Disk 2	20		

Measurements for spring 2:

Object Added	Total mass added to the spring hanger (g)	Spring length whilst adding masses in cm *(plot as crosses)*	Spring length whilst taking away masses, in cm *(plot as dots)*
Disk 1	10		
Disk 2	20		

<u>Results</u>

Add the data you have gathered for both springs to your graph on the following page. You should plot the length of the spring in centimetres on the vertical *y*-axis and the total mass added to the hanger in grams on the horizontal axis. Plot your first column points as *crosses* and your second column of points as *dots (small solid circles)*. You might also differentiate these with different colour pens if you are able.

Suggested is for you to start the *y*-axis at -10 cm and have the *x*-axis run from -40 g to 100 g. Choose a scale that is simple to read and that spreads the data across the page. Label your axes and give them units, something you should always do even if not asked. Include other features of the graph that you consider important.

Plot your graph by hand on this page and make your best estimate for a straight line fit to your data. *Note, your tutor will account for fitting done by hand.*

Note: we want to examine how a spring extends as a function of the mass hanging from it. For this, it's only useful to fit a line to data from where the spring starts to extend. Let's assume that your data follows a straight line for each spring, once it starts to extend.

Taking note of the above, fit a straight line as best as you can to your data for each of the two springs (2 lines in total). *Do this by eye. Your tutor will account for your fitting by hand.*

At what mass-value does your straight fitted lines intercept (cross) the x-axis:

Intercept with *x*-axis for the spring 1 fitted line: _______________ g

Intercept with *x*-axis for the spring 2 fitted line: _______________ g

Considering measurement errors, how well do these values compare to the previous measurement that you made at the end of the 'Experimental set-up' section for the mass required to begin to stretch each of the springs?

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Is it possible that these intercept values measured from your graphs are more accurately determined than those in the 'Experimental set-up' section? If so, explain why and state any assumptions necessary for this.

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In everyday language we may use the word 'slope' to describe a property of a hill. For example, we may say that a hill has a steep or gentle slope. Generally, the slope tells you how much a value on the *y*-axis changes for a change on the *x*-axis.

As discussed in the 'warm-up', a straight line can be described by $\boldsymbol{y = mx + c}$, where $\boldsymbol{m}$ is the steepness (slope) of the line i.e., the change in y divided by the change in x for the line, and $\boldsymbol{c}$ is the y-value where the line intercepts (crosses) the *y*-axis i.e., where $x = 0$. Note that $\boldsymbol{c}$ is not the same intercept that we calculated above, which was for where the line crosses the *x*-axis.

Calculate the slopes of the two lines that you have drawn (fitted by eye) for each of springs 1 and 2. Also provide correct units for your slopes in terms of grams and centimetres.

Use the slopes of these two lines to compare the stiffness of the springs and explain.

Physically interpret the meaning of your *c*-values i.e., the values of *y* where your fitted lines intercept the *y*-axis.

Look at the example graphs given in the earlier ‘warm-up exercises’ section. Horizontal and vertical lines through the data points represent experimental uncertainty derived either from taking measurements many times (say 10 times or more) and seeing a variation in values, or from determining a precision from known accuracies of instruments. In this experiment, uncertainty in the masses is insignificant, but there may be uncertainty in the length measurements.

Compare your data taken where adding weights (first column of your data tables) to that taken where taking away weights (second column of your data tables). Estimate (don't calculate) to what accuracy these two columns of data agree for spring 1, and likewise for spring 2. Do this by inspecting your tables and/or your graphs.

Is this observed uncertainty in length larger or smaller than that determined from the accuracy of your ruler? Discuss.

Conclusion

The behaviour of springs is said to be 'linear'. Explain this more clearly with reference to your responses and graphs in this lab.

Implications

An ear receives small forces from sound waves that result in small mechanical deviations of the eardrum and ossicles. How do these deviations approximate to being 'linear' with the applied force even though the coupling mechanisms are so complex?

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The mechanics of the ear stiffens in aging and hearing declines as a result. If the eardrum and ossicles stiffen by a factor of three, by how much would the maximum deviation of the ossicles change as a result? Explain your reasoning referring to what you have learned in this laboratory.

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The deviation of a car suspension can be considered 'linear' with an applied force. Assume this for comparing the suspensions of the following two cars. Car 1 is twice as heavy as car 2 and it compresses its suspension by one third as much as Car 2. Comment on the relative stiffness of the suspensions referring to what you have learned in this laboratory.

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UCD Physics Laboratory: Investigating the Behaviour of Gases

Student Name: ________________ **Student Number:** ____________
Lab Partner Name: ______________ **Demonstrator Name** ____________
Lab Date/Time: ______________

Goal

You will experimentally investigate the validity of a physical law. After this session, you will have more understanding of the process of experimental verification, and how the law you are testing is relevant to everyday experiences.

Specifically, you will test the Ideal Gas Law relating three variables of Volume, Pressure and Temperature using containers of air. To do this, you will keep one quantity fixed so that you can investigate how two other variables are related. In the first part you will keep the temperature constant and vary the volume to see how the pressure changes. In the second part you will keep the volume constant and vary the temperature to see how the pressure changes.

Warmup exercises

In this laboratory session, we investigate the relationship between the three properties of gases that we can most readily sense: volume, temperature and pressure. We call these macroscopic properties. But we understand that these properties derive from the movement of individual atoms/molecules (microscopic behaviour) that make up a gas, which move randomly, colliding with each other and the sides of the container.

- Pressure, *P*. The motion of billions of billions of gas particles in a container, causes them to collide with each other and with the sides of their container. In doing so they push on the sides of the container and we measure this as a pressure. For pressure, we use the S.I., unit of a force divided by an area, N/m^2 which is also called the Pascal, Pa.

- Volume, *V*. A gas is a collection of atoms and/or molecules that expands to fill any container of any shape. For volume, we use the S.I., unit of m^3.

- Temperature, *T*. When a container of gas is heated, energy is transferred to the gas from a source of heat. Both the temperature and the internal energy (*U*) of the gas increase, and we find that $T \propto U$. This internal energy is in the form of a kinetic (motion) energy for the molecules. The molecules move faster as the temperature of a gas increases. Likewise, when a gas is cooled, the molecules slow down.

Using the above information, circle the correct answers below:

If you heat a gas, do the molecules move faster or slower?	faster / slower
If moving faster, do the molecules collide with the container walls more, or less, frequently?	more / less
If the molecules collide more frequently with the container walls, does the pressure increase or decrease?	increase / decrease
If you increase the container volume, are molecular collisions more or less frequent?	more / less
If the molecules collide less frequently, does the pressure increase or decrease?	increase / decrease

Clearly, all three gas properties are interconnected, but how? If we keep one property fixed, we can investigate the relationship between the other two. For example:

- If we keep the gas temperature fixed, we can see how changes in volume affect pressure.
- If we keep the gas volume fixed, we can see how changes in temperature affect pressure.

These two relationships were first investigated by Irish scientist, Robert Boyle (1662), and French chemist, Gay-Lussac (1701). From the above information, can you figure out what remaining relationship was investigated by French scientist, J Charles (1780)?

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A relationship between measurable quantities that is demonstrated experimentally and repeated in different ways over many years, can be said to be a physical law. Three scientists proved three relationships between the gas properties, leading to:

- Boyle's Law relating P and V.
- Gay-Lussac's Law relating P and T
- Charles' Law relating V and T

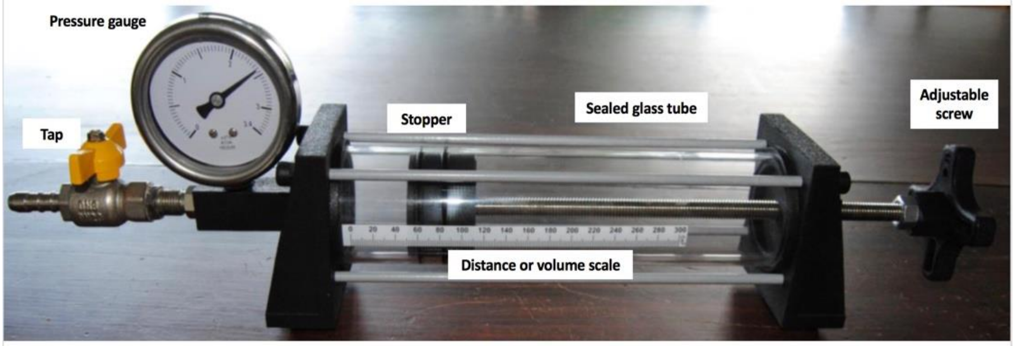
Since these three relationships are interconnected, we can combine them and we call the combined relationship ***the Ideal Gas Law***, which is given by:

$$PV = nRT$$

where the constant of proportionality is the product of two constants, nR, where n is the number of moles of gas atoms/molecules there are and R is the ideal gas constant.
Let's now test these ideas with two experiments.

Experiment 1: How the *pressure* of a gas changes when its *volume* is changed

Apparatus



- A pressure gauge, with a scale in units of pressure i.e. pascals (Pa).
- A sealed glass tube of gas (air), marked with a scale of distance (mm) or volume (ml).

Procedure

- Open the tap (by turning it to a position parallel to the tube). Note the pressure reading. This is your baseline pressure; the pressure of the air all around us.
- Twist the adjustable screw to move the stopper to about a fifth of the way along the tube (as shown in the picture). This is simply a practical starting point for the number of readings to be conducted within the timeframe for the experiment.
- Close the tap to define a fixed amount/mass of gas. Record the baseline pressure.
- Twist the adjustable screw so that the stopper reduces the volume that the gas can occupy within the tube. As you do, notice what happens to the pressure reading. Take readings of pressure as you reduce the volume. (If the tube is marked with units of ml you can write down the volume directly in these units. If the tube is not in these units, you can calculate the volume of the gas by assuming the radius of the tube is 1 cm.)
- Estimate the accuracy of your measurements of volume and pressure.
- Open the tap, to release pressure, and unscrew the stopper to return it to its original position.
- **Note: the equipment is only designed to work up to the maximum pressure on the scale. Keep below this pressure.**

Data

Volume (ml)	Pressure (Pa)

Estimate of error in Volume measurements (ml)	Estimated Error in Pressure measurements (Pa)

Do the following plots by hand on this page, or, use JagFit (see back of manual) and attach your two printed graphs to this page. Important: take care to label axes correctly and include units. *Note, your tutor will account for fitting where done by hand.*

Plot P along the y-axis, as a function of V along the x-axis:

Now plot P along the y-axis, as a function of $1/V$ along the x-axis:

From your graphs, describe how the gas properties are related. Is there a linear relationship between any two variables i.e., does a straight line fit to your points?

A straight-line graph is given by the equation $y = m\,x + c$, where m is the slope and c is the value of y where the line intercepts the y-axis i.e., where $x = 0$. Determine the slope and the intercept value, c, for your straight-line graph and give these values here, including units.

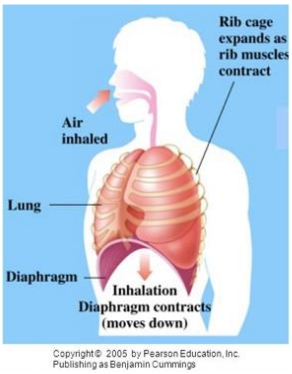
Do you expect the intercept to be at the origin where $P = 0$ and $V = 0$? Explain.

<u>Conclusion</u>

We investigated the relationship between pressure and volume, where temperature is held constant. This is Boyle's Law. From this experiment, briefly state this relationship in your own words and state if this is consistent with the Ideal Gas Law, for which $PV \propto T$.

<u>Implications</u>

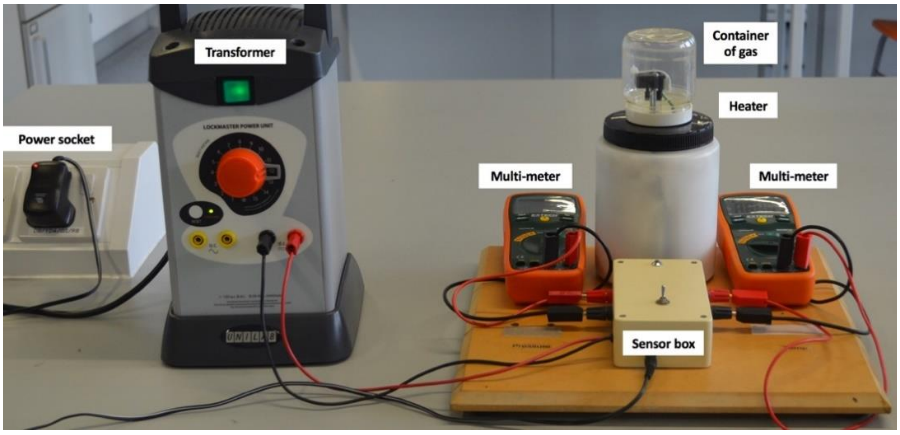
When we inhale, we lower the diaphragm muscle to increase the volume of our lungs. When we exhale, we raise the diaphragm to decrease the volume. Relate this to differences in pressure between the inside and outside of the lungs with the aid of Boyle's Law (the Ideal Gas Law).



Explain another everyday example that relates pressure and volume (for a temperature that's approximately fixed), using the Ideal Gas Law.

Experiment 2: How the *pressure* of a gas change when its *temperature* is changed

Apparatus



- A sealed container of gas (air), connected to a heater.
- A white box containing connections to temperature and pressure sensors.
- Two multi-meters, one to read pressure and one to read temperature.

Procedure

- Ensure all connections are in place (see picture).
- Turn the dial on the "pressure" multi-meter to V (volts), and press the "range" button until it is set to the millivolt (mV) range. You can record mV as a proxy for the units of pressure, Pascals (Pa). Set the "temperature" multi-meter to degrees Celsius (^{o}C).
- Turn on the sensors, by checking that the white box is plugged in and then flipping the switch so that its light comes on. Record the temperature and pressure, as per the multi-meters.
- Turn on the heater. For this, first check that the large transformer is plugged in and then press the on-switch. At this point the gas is being heated and you will notice the temperature readings will slowly increase.
- Take temperature and pressure readings at intervals of about 5 ^{o}C until the temperature reaches about 80 ^{o}C. Then immediately switch off the heater by pressing the green button.
- Estimate the accuracy of your measurements of temperature and pressure.
- Turn off all equipment, by returning switches to original positions and disconnecting power.

Data

Temperature (^{o}C)	Pressure (Pa)

Estimated error in Temperature measurements (^{o}C)	Estimated Error in Pressure measurements (Pa)

Results

Plot pressure, *P*, (y-axis) as a function of temperature, *T* in ^{o}C (x-axis).

Do this by hand on this page, or, use JagFit (see back of manual) and attach your printed graph to this page. Important: take care to label axes correctly and include units.
Note, your tutor will account for fitting where done by hand.

From your graph, describe how the gas properties of pressure and temperature are related. Is there a linear relationship between any two variables i.e., does a straight line fit to your points?

The curve of a straight-line graph is given by the equation $y = m\,x + c$, where m is the slope and c is the value of y where the line intercepts the y-axis i.e., where $x = 0$. Determine the slope and the intercept value, c, for your straight-line graph and give these values here, including units.

From your values of *m and c, d*etermine the value of temperature in ^{o}C for which P would extrapolate to being zero.

Describe what the molecules of the gas would be doing in everyday language at this temperature, T_0, for which $P = 0$?

<u>Conclusion</u>

We investigated the relationship between pressure and temperature, where volume is held constant. This is Gay-Lussac's Law. From this experiment, briefly state this relationship in your own words.

Explain how your measurements are consistent with the Ideal Gas Law, for which $PV \propto T$.

Implications

Car tyres increase in pressure by 3 x10^4 N/m^2 after driving for 20 mins. Explain this with the aid of the Ideal Gas Law

A jam jar can be easier to open after warming it up in a bowl of hot water. Explain this with the aid of the Ideal Gas Law.

Explain another everyday example that relates pressure and temperature (for a volume that's approximately fixed), using the Ideal Gas Law.

UCD Physics Laboratory: Investigating Conservation of Momentum

Student Name: ________________ **Student Number:** ____________
Lab Partner Name: ______________ **Demonstrator Name** ____________
Lab Date/Time: ______________

Goal

You will experimentally investigate the validity of a physical law. After this session, you will have more understanding of the process of experimental verification, and how the law you are testing is relevant to everyday experiences. You do not need prior knowledge of this topic to participate in this laboratory session.

Specifically, you will test the law of Conservation of Momentum, a law relating variables of mass and velocity, to explore the collision of two carts on a track. First, you will explore what happens when the carts have the same mass. Second you will explore what happens as you vary the mass of one of the carts.

Warmup exercises

We have an everyday understanding of the idea of momentum. It is a measure of how difficult it is to stop a moving object; the greater the momentum the harder it is to stop. We can appreciate that a truck moving at 30 km/s has more momentum than a small car moving at the same speed. Precisely, we define momentum, $\vec{p}$ as:

$$\vec{p} = m\vec{v}$$

where *m* is the mass, and $\vec{v}$ is the velocity. Momentum and velocity are vectors. A vector has a magnitude and a direction. For many objects, we can consider a combined (net) momentum and to do this we add up $m\vec{v}$ for each object.

In this laboratory, we consider motion in one direction only, and for this we are able to simplify the definition of momentum to the scalar relationship:

$$p = mv$$

where the values for *p* and *v* can be positive or negative to represent motion in the one direction or the other. We consider two colliding objects (carts) in our experiment. To find the combined (net) momentum for both carts, we simply add up the scalar value, mv for each cart.

A 10,000 kg truck is travelling eastwards at 100 km/s when it collides with a 1,000 kg parked car. Once they collide, the two vehicles travel together as a single unit. In which direction do they travel?

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The car and truck move together after the collision. Do you expect their velocity to be greater, less or the same as the velocity of the truck before the collision? Why?

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We find that the velocities of objects after a collision are not the same as beforehand, but we find that the combined (net) momentum after a collision, p_{after} is the same as that before the collision, p_{before}. This is called the law of Conservation of Momentum, and we can write this as:

$$p_{before} = p_{after}$$

Returning to the above question again, a 10,000 kg truck is travelling eastwards at 100 km/s when it collides head on with a 1,000 kg parked car. Once they collide, the two vehicles travel together as a single unit. In which direction do they travel and at what speed?

Hint: from considering Conservation of Momentum of motion in a straight line:

$$p_{before} = p_{after}$$
$$m_{truck}v_{before} = (m_{truck} + m_{car})v_{after}$$

Solve:

*Ans:*____________________

To be termed a physical law, a relationship between measurable quantities must be demonstrated experimentally and repeated in different ways over many years. In this laboratory session, we will have a go at testing this law by causing a collision between two carts.

Before the collision, we will record the mass and the velocity of each cart, and add them together to find the net momentum before the collision. After the collision, we will again record the mass and velocity of each cart, and add them together to find the net momentum after the collision. We will test if the momentum before the collision is equal to the moment after. In this way, we will be experimentally testing the Law of Conservation of Momentum.

Experiment: **Investigating Conservation of Momentum**

Apparatus

- Two carts, of mass 0.5 kg each, which can travel along a low-friction track
- A wooden block, for hitting the cart release mechanism
- Two photogates connected to a blue data-logger, which reports the cart velocity at the gates
- Two metal bars, of mass 0.5 kg each, which can be added to the carts to increase their mass

Fig 1

PART A. Measuring the velocity of cart A before the collision

Experimental set-up

i) Setting up the cart on the track:

- Make sure the track is level, so that gravity does not affect the speed of the carts. This is done via an adjustable leg at one end.
- Note that one cart (let's call it cart A) has a spring-loaded bung which can be depressed to one of two positions. Depress the bung so that it is fully inserted into the cart and clicks into place there. (This can be tricky and seems to work best when holding the cart vertical.)
- Place cart A on the track at the opposite end to the pulley wheel, such that the bung can snap out and hit the end wall bumper when you hit the knob on top. Use the wooden block to hit the knob (it is more accurate than using your hand), and see how the cart travels along the track.
- Insert the rectangular metal "flag" into the hole at head of the cart, with the largest surface facing you. Make sure the flag is secure and does not move. (This can be achieved by lifting it slightly out of the hole.) The role of the flag is to interrupt the light beam of the photogates (see below).

ii) Setting up the two photogates:

- In order to calculate momentum, we need values for mass and velocity. The cart mass is given as 0.5 kg. To calculate the velocity of the cart, we measure how long it takes the cart to travel a fixed distance between two points. The velocity is distance travelled divided by time taken. The distance between the two photogates is set using the ruler. The time taken is measured by the photogates.

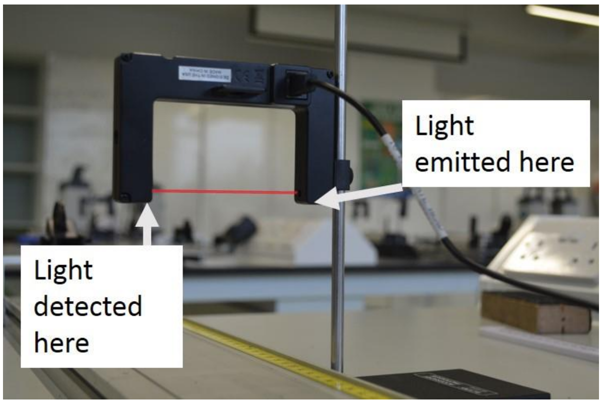


Fig 2

- The photogates comprise an infrared light source on one side, and a detector on the other, fig 2. Infrared light is invisible to the human eye, but is represented by the red line in the figure. When the beam is interrupted it sends a signal to the blue data-logger to start the timer. When the cart interrupts the beam of the second photogate, that gate sends a signal to stop the timer.
- The data-logger uses this timer information, and pre-recorded distance, to compute the cart velocity which it outputs on the screen. To use this feature of the data-logger, it must be set up correctly.

iii) Setting up the blue data-logger:

- Turn on the power supply at the socket. Turn on the blue data-logger. A screen will appear, select “photogate timing” and enter the flag length (0.0250 m) and photogate spacing (0.4000 m) by pressing ✓ to edit and again to confirm. Then press the home key. Press F2 to navigate to the table screen and then press ✓ twice and select “time between gates” to be visible.
- Check that the photogates work, by interrupting the light signal across the gate with your hand and checking that the red LED light on the gate blinks.
- Check that the data-logger reports a velocity each time the gate LED blinks. (Allow a slight delay in the data-logger response.)

Procedure

- Place the photogates at positions 40 cm and 80 cm on the track. In this way, the distance between the gates is 40 cm, which is the value we input during the data-logger set-up.
- On the data-logger, press ✓ to begin recording data, and again after the cart has completed a run.
- Release cart A, and record its velocity. Repeat the measurement three times to get a good estimate. This is the velocity of cart A before the collision.

Data

Run five trials and fill in the following table.

Measurements on Cart A before the collision
The mass of cart A = ______ kg

Trial number	Cart A velocity (m/s)	Cart A momentum *p* (kg m/s)
1		
2		
3		
4		
5		

Explain why you measure differing values for velocity (momentum) for each trial?

In the next part, cart A will be allowed to collide with a cart B which initially is stationary. In this case, the momentum of cart A before the collision constitutes the net (combined) momentum of both carts before the collision.

Using your above table of measurements, determine the following values for the net momentum before the carts collide:

The average net momentum, p_{av} (kg m/s)	The minimum net momentum, p_{min} (kg m/s)	The maximum net momentum, p_{max} (kg m/s)	Uncertainty, given as: +/- $(p_{max} – p_{min})/2$ (kg m/s)

Note:
The difference in values, $p_{max} – p_{min}$, is called the spread of values. From this spread, we provide an estimate of uncertainty written as +/- $(p_{max} – p_{min})/2$. For example, this might be something like +/- 0.3. Uncertainty can in principle be analyzed in a more sophisticated way than this. However, a more precise analysis of a random variation requires at least ten measurements of that variable, and preferably more than thirty; something we won't do in this laboratory.

You have now measured the initial momentum and we will use these values later.

PART B. Measuring the velocity of cart A and cart B after the collision

Experimental set-up

i) Setting up the cart on the track:

- Place cart B on the track. Assume the head of the cart is the end with the velcro (which we will not be using in our experiment). Ensure its flag is securely in the hole at the head of the cart, with the largest surface facing you. Position cart B so that its rear points towards cart A.

ii) Setting up the photogates:

- Move the first photogate to 50 cm and the second to 90 cm. We use a different technique to compute the velocity of the carts in this part of the experiment. In this part, the velocity is determined by how long it takes the metal flag to move past a given photogate. The data-logger measures how long the beam is interrupted for (i.e. time). It then uses the width of the flag (i.e. distance) to estimate the velocity of the cart. This is the reason we input the width of the flag (or flag length) when we first set up the data-logger. So the cart velocity is calculated from how long it takes its flag to pass through the photogate beam

iii) Setting up the blue data-logger:

- Switch the data logger off and on again. A menu should appear; select 'Collision Timer'. Ensure that 'Velocity 1' and 'Velocity 2' are set to visible. Navigate to the home screen and select 'Tables'. Press ✓ and set 'Velocity 1' to be displayed in column 1 and 'Velocity 2' to be visible in column 2. Press the ▶ button to begin recording data.

Procedure

Release cart A, allowing it to collide with the rear end of cart B. Cart B will trigger the second photogate while cart A will trigger the first photogate. For this to occur, the rear of cart B should be initially positioned just under the first photogate (at 45 cm) so that its flag is positioned after the photogate.

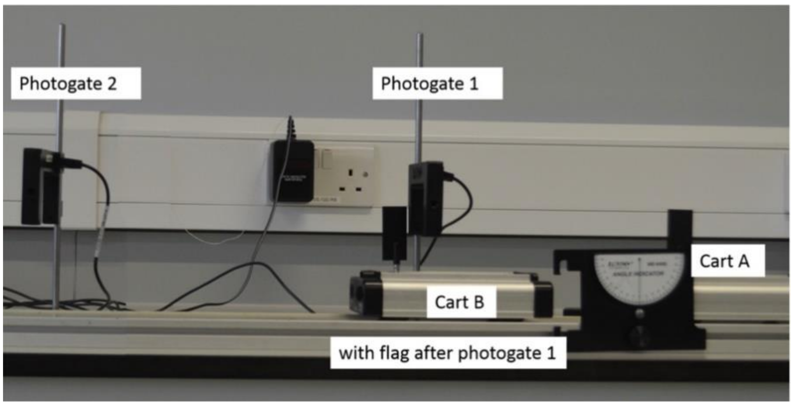


Fig 3

Data

Run five trials and fill in the following table with your velocity measurements for the two carts after their collision. Also calculate the net momentum after the collision for each trial i.e., the combined momentum of both carts.

Case 1. **After the collision, with cart A and cart B of the same mass**

The mass of cart A = ______ kg

The mass of cart B = ______ kg

Trial number	Cart A velocity (m/s)	Cart B Velocity (m/s)	Net momentum after collision, p (kg m/s)
1			
2			
3			
4			
5			

Determine the following three values from the above table:

The average net momentum, p_{av} (kg m/s)	The minimum net momentum, p_{min} (kg m/s)	The maximum net momentum, p_{max} (kg m/s)	Uncertainty, given as: +/- $(p_{max} - p_{min})/2$ (kg m/s)

Now add a metal bar to cart B to increase its mass, and then repeat the five trials.

Case 2. After the collision, with 1 metal bar added to cart B
The mass of cart A = ______ kg
The mass of cart B = ______ kg

Trial number	Cart A velocity (m/s)	Cart B Velocity (m/s)	Net momentum after collision, p (kg m/s)
1			
2			
3			
4			
5			

Determine the following three values from the above table:

The average net momentum, p_{av} (kg m/s)	The minimum net momentum, p_{min} (kg m/s)	The maximum net momentum, p_{max} (kg m/s)	Uncertainty, given as: $+/- (p_{max} - p_{min})/2$ (kg m/s)

Now add a second metal bar to cart B to increase its mass further, and then repeat the five trials again.

Case 3. After the collision, with 2 metal bars added to cart B
The mass of cart A = ______ kg
The mass of cart B = ______ kg

Trial number	Cart A velocity (m/s)	Cart B Velocity (m/s)	Net momentum after collision, p (kg m/s)
1			
2			
3			
4			
5			

Determine the following from the above table:

The average net momentum, p_{av} (kg m/s)	The minimum net momentum, p_{min} (kg m/s)	The maximum net momentum, p_{max} (kg m/s)	Uncertainty, given as: $+/- (p_{max} - p_{min})/2$ (kg m/s)

Results

Fill in the following tables.

Summary from part A:

Before collision	Average net momentum, p_{av},(kg m/s)	Uncertainty, given as: +/- $(p_{max} – p_{min})/2$ (kg m/s)

Summary from part B:

After collision	Average net momentum, p_{av} (kg m/s)	Uncertainty, given as: +/- $(p_{max} – p_{min})/2$ (kg m/s)
Carts of equal mass (case 1)		
1 bar added to cart B (case 2)		
2 bars added to cart B (case 3)		

From inspecting these tables, can you conclude that you have verified the Law of Conservation of Momentum? For this, consider if your measured net momentum before the collision matches that after the collision and consider the uncertainty in measurements.

As you increase the mass of cart B, does the total momentum after the collision change? Explain your answer.

Without altering your setup, how might you reduce the uncertainty in each value of average net momentum?

If plotting the velocity of cart B after the collision (y-axis) versus the mass of cart B (x-axis), what is the sign of the gradient for the graph? Zero, positive or negative? ____________

Explain:

Conclusion

We sought to experimentally verify the Law of Conservation of Momentum, which for any two objects, *A and B*, can be written as:

$$p_{before} = p_{after}$$
$$m_A u_A + m_B u_B = m_A v_A + m_B v_B$$

where *u* is the initial velocity, *v* is the final velocity, and *m* is the mass.

State the Law of Conservation of Momentum in your own words:

Implications

If your car was going to collide with an empty parked car, would you prefer the parked car to be heavier or lighter than your car? Why?

When a car crashes into a thick wall, we could say that it has momentum before the collision and that it is at rest after the collision. However, momentum must be conserved. Explain this apparent paradox by using the Law of Conservation of Momentum: $m_A u_A + m_B u_B = m_A v_A + m_B v_B$, and defining the variables for this case.

UCD Physics Laboratory: Investigation of Acceleration

Student Name: ________________ **Student Number:** ____________
Lab Partner Name: ______________ **Demonstrator Name** ____________
Lab Date/Time: ______________

Goal

You will experimentally investigate the validity of a physical law. After this session, you will have more understanding of the process of experimental verification, and how the law you are testing is relevant to everyday experiences. You do not need prior knowledge of this topic to participate in this laboratory session.

Specifically, you will test Newton's 2nd Law, a law relating three variables of force, mass and acceleration, using a cart on a track. To do this, you will keep one quantity fixed so that you can investigate how two other variables are related. In the first part you will keep the force in the direction of motion (along the horizontal) fixed and relate a horizontal acceleration to a mass. In the second part, you will keep the mass fixed and relate the acceleration down a slope to the component of the gravitational force directed down the slope.

Warmup exercises

Newton's second law is given by the vector relationship, $\overline{F} = m\overline{a}$, for which a force causes an acceleration and the constant of proportionality is mass, *m*. However, for motion confined to a straight line (one dimensional motion), we can simplify this law to the scalar relationship, $F = m\,a$, where F is the value of the net force acting on an object along its allowed direction of motion, and a is the value of acceleration in this direction of motion. We consider only motion in a straight line in this laboratory and so we are able to use this scalar form of the law.

If you throw a heavy ball with a force F and then throw a light ball with the same force, which ball gathers more speed? heavy/light Acting under constant acceleration, a cart starts from rest and has a horizontal velocity of 2 m/s due west after 5 s. What is the acceleration of the cart? _______________

Forces cause acceleration. For example if you kick a ball of mass m with a force 'F', its acceleration is 'a'; if you then kick the same ball with a force twice as big, '2F', then it accelerates at '2a'. In other words, the acceleration, a, is larger when the force, F, is larger:

$$a \propto F$$

The acceleration is larger when the mass, m, of the object is smaller:

$$a \propto \frac{1}{m}$$

We can combine these two relationships into one:

$$a \propto \frac{F}{m}$$

Isaac Newton (1687) provided experimental evidence of this relationship, and so it became a 'Law'. It is now called Newton's 2nd Law, and is more commonly written as:

$$F = m\,a$$

The unit of force is kg·m/s^2 which is called the Newton (symbol N), in honour of Isaac Newton.

If an apple falls from a tree, it speeds up until it hits the ground. So there must be a force which causes this acceleration. The acceleration due to the Earth's gravitational force field has been measured experimentally to be 9.8 m/s^2. We denote this as 'g' since its value is always the same, instead of generic acceleration 'a' (which can have many values). So the gravitational force is the product, mg.

To test Newton's 2nd Law, you will keep one quantity fixed so that you can investigate how two other variables are related. In the first part you will keep the force fixed and relate a horizontal acceleration to a mass which is varied. In the second part, you will keep the mass fixed and relate the acceleration to a force which is varied.

Apparatus

- One cart, of mass 0.5 kg
- A low-friction track, with a pulley wheel on one end
- A string, with a ring tied to one end and a hook to the other, threaded over the pulley wheel with the hook attached to the cart.
- Two photogates connected to a blue data-logger
- Three metal bars, of mass 0.5 kg each, which can be added to the cart to increase its mass

Where using a pulley, the string has an equal tension throughout. This simplifies our thinking, because we can consider the stage as being accelerated horizontally due to a constant horizontal force of magnitude, *F,* and we also consider *F* to be the magnitude of force exerted vertically between the string and the ring-weight. We return to this with an equation later.

Experiment 1: Acceleration from a constant force along a horizontal plane

Experimental set-up

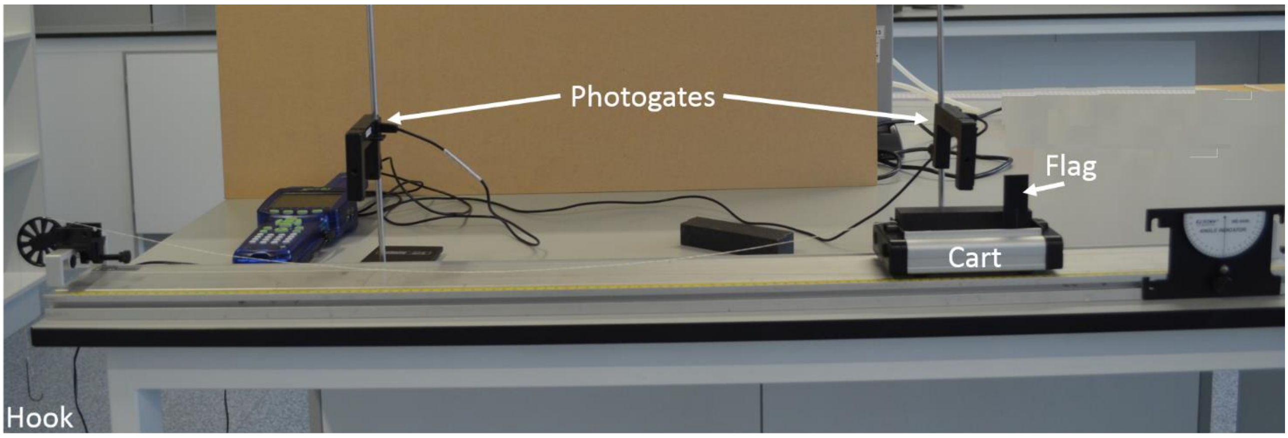


Fig 1

i) Setting up the cart on the track:

- Position the track on the laboratory bench in such a way that the pulley wheel hangs over one end of the bench.
- Ensure the track is level. This is done via an adjustable leg at one end.
- Place the cart on the track at the opposite end to the pulley wheel.
- You will find a string, with a ring tied to one end and a hook tied to the other. Attach the hook to the cart and thread the string over the pulley wheel so that the ring hangs down. The weight of the ring will accelerate the cart along the track.
- Insert the rectangular metal "flag" into the hole at head of the cart, with the largest surface facing you. Make sure the flag is secure and does not move. (This can be achieved by lifting it slightly out of the hole.) The role of the flag is to interrupt the light beam of the photogates (see below).

ii) Setting up the two photogates:

- The photogates comprise an infrared light source on one side, and a detector on the other, fig 2. Infrared light is invisible to the human eye but is represented by the red line in the figure. When the beam is interrupted it sends a signal to the blue data-logger.
- Place the photogates at positions 30 cm and 80 cm on the track. In this way, the distance between the gates is 50 cm.
- In order to calculate acceleration, we must measure the change in velocity in a given time interval.
- The velocity is determined by how long the cart's metal flag takes to move past a given photogate. The photogate is connected to a blue data-logger, which reports how long the beam is interrupted for (i.e. time). It then uses the width of the flag (i.e. distance) to estimate the velocity of the cart. For this reason, we must input the width of the flag (or flag length) when we set up the data-logger (below). The cart *velocity* is calculated from how long it takes its flag to pass through the photogate beam. To output these results, the blue data-logger must be set up correctly (see below).

- The cart *acceleration* is determined by computing the change in velocity between the two photogates.

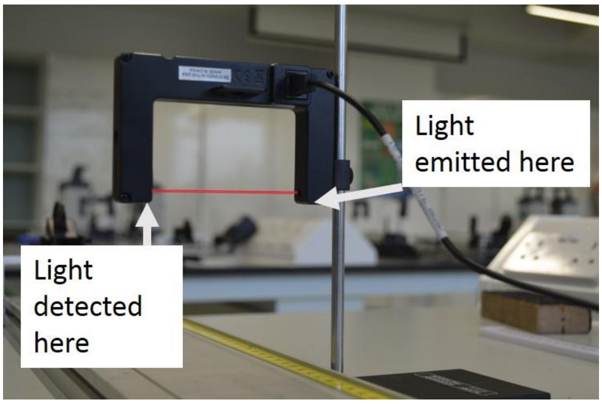


Fig 2

iii) Setting up the blue data-logger:

- Turn on the power supply at the socket. Turn on the blue data-logger. A screen will appear, select “photogate timing” and enter the flag length (0.0250 m) and photogate spacing (0.5000 m) by pressing to edit and again to confirm.
- Ensure that only ‘Velocity In Gate’ and ‘Time Between Gates’ are set to visible.
- Then press the home key.
- Press F1 or navigate to the graph section. Once on the graph screen, press F4 to open the graph menu. Navigate to ‘Two Measurements’ and press select.
- Press the select key and navigate to the ‘Y’ (i.e. y-axis), which should be visible on the right-hand side of the graph. Press select and choose ‘Time Between Gates’. This will now appear on the right of the graph. The left axis should already be displaying “Velocity in Gates”.
- You can now record data by pressing to begin and stop.
- On the graph screen, velocity will be displayed as a line and the time taken to travel between gates will be displayed as both a single point on the graph and as a numerical value along the right-hand side Y axis of the graph.
- To read the data from your completed run accurately, press F3 and select ‘Smart Tool’. Use the navigation buttons to see the precise values for the points on the graph.
- To save your experimental data, use the arrow keys to highlight your data file in the RAM memory and press “F4 files”. Select the “copy file” option and then choose the external USB as the destination for the file, and press “F1 OK”. Transfer the USB data stick to the lab computer and create a graph.

<u>Procedure</u>

- On the data-logger, press to begin recording data, and again after the cart has completed a run.
- Record the total mass being accelerated (i.e. the mass of the cart, the metal block on the cart and the ring). Release the cart and record its velocity and time as it passes each photogate.
- Add a metal bar to the cart to increase its mass and repeat the above steps.
- Repeat until you have added three metal bars. Be sure that the metal bars are not stacked too high i.e. that they do not trigger the photogate.

Data:

Mass of ring, m_{ring} (kg)	Mass of cart, m_{cart} (kg)	Velocity 1, v_1 (m/s)	Velocity 2, v_2 (m/s)	Time 1, t_1 (s)	Time 2, t_2 (s)	Acceleration, a (m/s^2)

- Calculate the acceleration (i.e. the change in velocity during a given time interval):

$$a = \frac{v_2 - v_1}{t_2 - t_1}$$

- On the blue data-logger, use the arrow keys to highlight your data file in the RAM memory and press "F4 files". Select the "copy file" option and then choose the external USB as the destination for the file, and press "F1 OK". Before transferring the USB data stick to the lab computer to create a graph, we must decide what to put on the x and y axes (see below).

<u>Results</u>

If Newton's 2nd Law is indeed, $F = m\,a$, it will plot as a straight line i.e., it will take the form:

$$y = k\,x + c$$

where *k* is the gradient (slope), and *c* is what we will call the intercept (the value of *y* where *x* is zero). Here we refer to *k* instead of the traditional *m* for the gradient of a straight line, because we have already used *m* to mean mass.

In this investigation, we kept the force constant and increased the mass in order to investigate how acceleration changes. Therefore, we put mass on the x-axis and acceleration on the y-axis. How can we rearrange Newton's 2nd Law into the mathematical format of a straight line graph, where the x-axis is the mass and the y-axis is the acceleration?

We could rearrange $F = m\,a$ into the format $y = k\,x + c$ as follows:

$$\frac{1}{a} = \frac{1}{F}\,m$$

where *a* is acceleration, *F* is force, *m* is mass and *c* = 0

We know *m* is mass, but which mass? (Circle the correct answer below) i) $m = m_{cart}$ ii) $m = m_{ring}$ iii) $m = m_{cart} + m_{ring}$ iv) $m = m_{cart} - m_{ring}$

The cart and ring are connected together and so they have the same magnitude of acceleration, *a*, and the net mass moving is $m_{cart} + m_{ring}$. Thus, we can more usefully rearrange our equation as follows:

$$\frac{1}{a} = \frac{1}{F}\left(m_{cart} + m_{ring}\right)$$
$$= \frac{1}{F}\, m_{cart} + \frac{1}{F} m_{ring}$$

Now, for this case where $\frac{1}{a}$ is the y-axis and m_{cart} is the x-axis, which term is the slope of this graph? And which term is the intercept i.e., the value of *y* where *x* is zero?

___

___

Plot your experimental data, with $\frac{1}{a}$ as the y-axis and m_{cart} as the x-axis. If the graph is a straight line, then you have verified Newton's 2nd Law.

Plot your graph by hand on this page and make your best estimate for a straight line fit to your data. *Note, your tutor will account for your fitting by hand*
Important: take care to label axes correctly and include units.

You can now find a value for *F* in two separate ways and compare them for accuracy, as follows:

From your graph determine the slope, and hence calculate *F*.

From your graph determine the intercept, and hence calculate *F*.

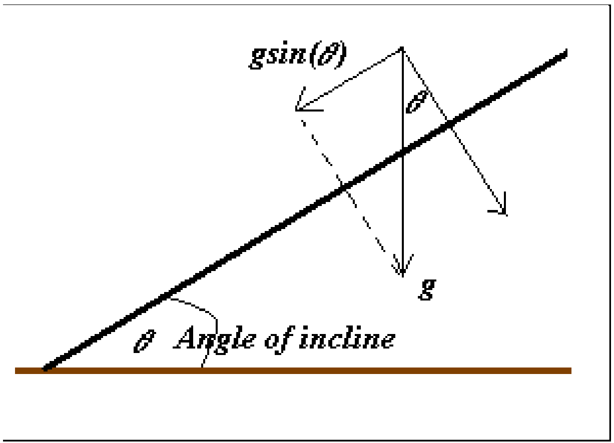
Compare your value of F determined in the two different ways above, determine the best value of F and estimate the uncertainty on your resulting value for *F*.

From the value you found for *F,* calculate the acceleration due to gravity, g. How does it compare to the generally accepted value of g?

Hint: because we use a pulley, the force, F *also acts vertically on the ring. The vertical motion of the ring can therefore be considered under solely this tension force F and the force due to gravity,* $m_{ring}g$*.*

Experiment 2: Acceleration of a constant mass down an inclined plane

The apparatus should be set up as in the picture. Raise one end of the track using the wooden block in place of the elevator. The carts can be released from rest at the top of the track.



The cart will experience a gravitational force, given by $F_g = m \cdot g$ directed vertically downwards towards the earth, where the acceleration due to gravity is g directed vertically downwards (see diagram). By taking components of a vector, it is possible to show that the component of the gravitational force directed along our permitted direction of motion down the slope, is $F_g \cdot sin\theta$, which is then equal to m$g \cdot sin\theta$. This force causes the cart to accelerate and roll down the slope. From our warmup exercises in this script, we were saying that for Newton's second law, $F = m\ a,$ where F is the value of the net force acting on an object along its allowed direction of motion, and a is the value of acceleration in the object's direction of motion. And so, from Newton's Second Law, we can write:

$$F_g \cdot sin\theta = \mathrm{m}g \cdot sin\theta = ma$$

where a is the component of the object's acceleration parallel to the inclined plane.

By cancelling m, this simplifies to: $a = g \cdot sin\theta$ (as shown in the diagram)

In keeping with intuition then, the acceleration of the cart depends on the angle of the incline. For example, $a = 0$ where $\theta = 0$, and $a = g$ where $\theta = 90^{\circ}$.

<u>Procedure</u>
Vary the angle of the incline, taking measurements using the data-logger for at least four different angles, and determine the accelerations for the cart in the same way as was done in investigation 1.

Data:

Angle of incline	Sine of angle	v_1 (m/s)	v_2 (m/s)	t_1 (s)	t_2 (s)	Acceleration down the incline, a (ms^{-2})

Since we predict that the acceleration down the incline is $a = g\sin\theta$, we expect there to be a linear dependence of *a on* $\sin\theta$.

Make a graph with $\sin\theta$ as the *x-axis* and *a* as the *y* axis to see if this is the case.

What does the slope represent?

What value do you expect (theoretically) for the intercept?

Plot your graph by hand on this page and make your best estimate for a straight line fit to your data. *Note, your tutor will account for your fitting by hand.*
Important: take care to label axes correctly and include units.

What value do you measure for *g*?

What value do you measure for the intercept?

Comment on your results. How could you improve on your measurements of *g*?

Conclusion

We sought to experimentally verify Newton's 2nd Law, $F = m\,a$. State Newton's 2nd Law in your own words:

Implications

If you simultaneously drop a bowling ball and a billiard ball, they will hit the ground at the same time. This means that they were both accelerated at the same rate. What is this rate?

Does the bowling ball experience a larger, smaller or the same force as the billiard ball? Use Newton's 2nd Law to justify your answer.

The single scalar form for Newton’s second law is helpful to consider for straight line motion. For more general motion in three dimensions, for example along *x, y and z axes*, the vector form of Newton’s Second Law yields three scalar relationships:
$F_x = m\,a_x$, $F_y = m\,a_y$ and $F_z = m\,a_z$. In this way, we are able consider motion in each orthogonal direction as being independent.

Give a common example for which in principle we need to consider the vector form of Newton’s second law. *Hint: can you think of a common motion that is generally isn’t in a straight line?*

UCD Physics Laboratory: Investigation of Rotational Motion

Student Name: ________________ **Student Number:** _____________
Lab Partner Name: _______________ **Demonstrator Name** _____________
Lab Date/Time: _______________

What should I expect in this experiment?

This experiment introduces you to some key concepts concerning rotational motion. These are: torque (τ), angular acceleration (α), angular velocity (ω), angular displacement (θ) and moment of inertia (*I*). They are the rotational analogues of force (F), acceleration (a), velocity (v), displacement (s) and mass (m), respectively.

Pre-lab assignment

What is the angular velocity of a spinning disk that completes 2 full revolutions in 10 seconds?

Introduction:

The equations of motion with constant acceleration are similar whether for linear or rotational motion:

Linear	Rotational	
$v_{average} = \dfrac{s_2 - s_1}{t_2 - t_1}$	$\omega_{average} = \dfrac{\theta_2 - \theta_1}{t_2 - t_1}$	**Eq.1**
$v_{average} = \dfrac{v_1 + v_2}{2}$	$\omega_{average} = \dfrac{\omega_1 + \omega_2}{2}$	**Eq.2**
$v_2 = v_1 + at$	$\omega_2 = \omega_1 + \alpha t$	**Eq.3**
$s_2 = v_1 t + at^2/2$	$q_2 = w_1 t + at^2/2$	**Eq.4**

Furthermore, just as a force is proportional to acceleration through the relationship *F=ma*, a net torque changes the state of a body's (rotational) motion by causing an angular acceleration.

$$\tau = I\alpha \qquad \textbf{(Eq.5)}$$

The body's moment of inertia is a measure of resistance to this change in rotational motion, just as mass is a measure of a body's resistance to change in linear motion. The equation $\tau = I\alpha$ is the rotational equivalent of Newton's 2nd law $F = ma$.

You will use two pieces of apparatus to investigate these equations. The first lets you apply and calculate torque, measure angular acceleration and determine an unknown moment of inertia, ***I*** of a pair of cylindrical weights located at the ends of a bar. The second apparatus lets you investigate how ***I*** depends on the distribution of mass about the axis of rotation and lets you determine the value of ***I***, already measured in the first part, by a second method. You can then compare the results you obtained from the two methods.

Investigation 1: To measure the moment of inertia, I, from the torque and angular acceleration.

Place cylindrical masses on the bar at their furthest position from the axis of rotation. The bar is attached to an axle which is free to rotate. The masses attached to the line wound around this axle are allowed to fall, causing a torque about the axle

The value of the torque caused by the falling masses is $\tau = Fr$ where *F* is the weight of the mass attached to the string and *r* is the radius of the axle to which it is attached. Calculate the value of τ.

Mass, m attached to string (kg)	
Force, F = m . g (N)	
Radius, r of axle (m)	
Torque, τ = F $\times$ r (Nm)	

In this session, you will calculate the angular velocity, ω, and the angular acceleration, α. Distinguish between these two underlined terms.

Wind the string attached to the mass around the axle until the mass is close to the pulley. Release it and measure the time for the bar to perform the first complete rotation, the second complete rotation, the third, fourth and fifth rotation. Estimate your experimental uncertainties.

Number of Rotations	θ (rad)	Time (s)
0	0	0
1		
2		
3		
4		
5		

Since you have the angular distance travelled in a given time you can use Eq. 4 to find the angular acceleration α. Explain how you can do this and find a value for α.

α =

Using Eq.1, calculate the average velocity, $\omega_{average}$, during each rotation and fill in the table below.

If angular acceleration is constant, then $\omega_{average}$ is equal to the instantaneous velocity at the time half-way between the start and the end of a rotation, t_{mid}.
Can you understand this? Explain.

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Enter the values in the table below and **make a plot** of $\omega_{average}$ on the y-axis against $\boldsymbol{t_{mid}}$ on the x-axis.

Number of Rotation	$\omega_{average}$ (rad / s)	t_{mid} (s)
1		
2		
3		
4		
5		

Since this graph gives the instantaneous velocity at a given time, Eq. 3 can be used to find the angular acceleration, α.

What value do you get for α?

Now you know τ and α, so work out I from Eq. 5.

Create your graph of $\omega_{average}$ on the y-axis against t_{mid} on the x-axis.

Do the following plot by hand on this page, or, use JagFit (see back of manual) and attach your printed graph to this page. Important: take care to label axes correctly and include units. *Note, your tutor will account for fitting where done by hand.*

I*nvestigation 2:* *To determine how the moment of inertia, I, depends on the distribution of mass in a body.*

Take the metal bar on the bench and roll it between your hands. Now hold it in the middle and rotate it about its centre so that the ends are moving most. Which is easier? Which way does the bar have a higher value of *I*?

Attach the weights and the bar to the rotational apparatus known as a **torsion axle**. This consists of a vertical axle connected to a spring which opposes any departure from the angle of rotational equilibrium.

Note: The apparatus is delicate. So as not to damage the spring, please keep the rod to within half a rotation from equilibrium.

When you rotate the bar, the spring causes a torque about the axis of rotation which acts to restore the bar to the equilibrium angle. Usually the bar overshoots, causing an oscillation to occur. This is exactly analogous to the way a mass on a linear spring undergoes simple harmonic motion. The period of the oscillations, *T,* is determined by the restoring torque in the spring, *D*, and the moment of inertia, *I*, of the object rotating, in this case the bar and cylindrical weights. They are related by:

$$T = 2\pi\sqrt{\frac{I}{D}}$$

The value of D is written on each torsion axle. Note it here.

To investigate the influence of mass distribution vary the position of the cylinders along the torsion bar, measure the period of oscillation, T, and use the equation above to calculate the moment of interia, I for the combined system of cylinders plus rod. (To improve the precision with which you measure T take the average over 10 oscillations.)

r – Position of the cylinders along rod (m)	T – Period of oscillation (s)	I for the combined system of cylinder + bar (kgm^2)	I for the cylinders (kgm^2)
0.05			
0.10			
0.15			
0.20			
0.25			

Just as you can simply add two masses together to get the total mass (e.g. if the mass of a cylinder is 0.24kg and the mass of a bar is 0.2kg, then the mass of cylinder plus bar is 0.44kg) you can also add moments of inertia together. Given that the moment of inertia of the bar is 0.00414 kgm^{-2}, will let you fill in the fourth column in the table above.

Plot the value of $I_{cylinder}$ against the position r.

Plot the value of $I_{cylinder}$ against the position r^2.

What do you conclude?

Create a graph of $I_{cylinder}$ against the position, *r*.
Do the following plot by hand on this page, or, use JagFit (see back of manual) and attach your printed graph to this page. Important: take care to label axes correctly and include units. *Note, your tutor will account for fitting where done by hand.*

Create a graph of $I_{cylinder}$ against the position, r^2.
Do the following plot by hand on this page, or, use JagFit (see back of manual) and attach your printed graph to this page. Important: take care to label axes correctly and include units. *Note, your tutor will account for fitting where done by hand.*

The last measurement in the table above, with r = 0.25m, returns the bar + cylinders system to the orientation used in your first investigation. You have thus measured the moment of inertia of the bar + cylinder system in two independent ways. Write down the two answers that you got.

I from investigation 1:

I from investigation 2:

How do the two values compare? Which is more precise?

Appendix 1. Graphing

Many of the experiments in the 1st Year laboratory involve the plotting of a graph. Graphs are very important in Physics as they provide a rich display of the results obtained in an experiment. One third of the human brain is devoted to images, and so we are well optimised to interact with graphs rather than with tables of numbers.

Plotting graphs by hand:

(1) *Scale:* It is important to choose the scales so as to make full use of the squared page. The scale divisions should be chosen for convenience; that is, one unit is either 1, 2 or 5 times a power of ten e.g. 0.5, 5, 100 etc., but never 3, 7, 9 etc.

(2) *Marking the points:* Readings should be indicated on the graph by a ringed dot ⊗ and drawn with <u>pencil</u>, so that it is possible to erase and correct any unsatisfactory data.

(3) *Joining the points:* In the case of a straight line which indicates a direct proportion between the variables, the ruler is positioned so that the line drawn will pass through as many points as possible. Those points which do not lie on the line should be equally distributed on both sides of the line. A point which lies away from this line can be regarded as 'doubtful' and a recheck made on the readings. In the case of a curve, the individual experimental points are <u>not</u> joined with straight lines but a smooth curve is drawn through them so that as many as possible lie on the curve.

(4) *Units:* The graph is drawn on squared page. Each graph should carry title at the top e.g. Time squared vs. Length. The axes should be labelled with the name and units of the quantities involved.

(5) In the case of a straight-line graph, the equation of the line representing the relationship between the quantities x and y may be expressed in the form

$$y = mx + c$$

where m is the slope of the line and c the intercept on the y-axis. The slope may be positive or negative. Many experiments require an accurate reading of the slope of a line.

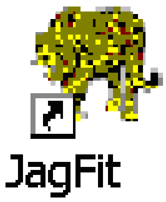
Using JagFit

In the examples above we have somewhat causally referred to the ***'best fit'*** through the data. What we mean is, the curve which comes closest to the data points having due regard for the experimental uncertainties.

We can judge this really quite well by eye, but to so isn't quantitative or reproducible between people necessarily, and so doing this manually isn't always the best way.

We can determine a straight line fit to data that varies due to random fluctuations using so-called 'least square fitting', but this requires a calculator/computer and sufficiently large data sets. At least 10 measurements are required to be usefully quantitative in this way, and more typically more than 30 measurements are needed.

A computer can make a difference where data sets are large enough then, and a plotting program called Jagfit is installed on the computers. Jagfit is freely available for download from this address:
http://www.southalabama.edu/physics/software/software.htm



If you are to use it, then double-click on the JagFit icon to start the program. The working of JagFit is fairly intuitive. Enter your data in the columns on the left.

- Under Graph, select the columns to graph, and the name for the axes.
- Under Error Method, you can include uncertainties on the points.
- Under Tools, you can fit the data using a function as defined under Fitting_Function. Normally you will just perform a linear fit.

Three of the experiments in this manual were initially developed by the Physics Education Group, CASTeL, Dublin City University.

Appendix 2. Grading scheme

Grading is consistent with the UCD grade scale:

Net lab Score	UCD level	UCD description
0 - 2	NG - G	wholly unacceptable
2 - 4	F - E	unacceptable - marginal
4 - 6	D – C	acceptable - good
6 - 8	B - A	very good - excellent
8 - 10	A+	excellent - exceptional

Demonstrators are asked to discuss with the 1st year labs academic coordinator, Ian Mercer, if they think their grading varies significantly from this reference.

Feedback

The net grade comprises three components for a report, the beginning, the middle and the end. Demonstrators mark this net grade as an integer (whole number) on the front of a report and also mark the three component grades within a report. The component grades are:

	Component of Report	Grade
1	Beginning – 'Data and Preparation'	between 0 and 4
2	Middle – 'Results'	between 0 and 4
3	End – 'Conclusions and Implications'	between 0 and 2
	Net grade	**integer** between 0 and 10

Demonstrators are not asked to otherwise annotate reports. Instead, the demonstrator feeds back to the class on say three main areas to improve at the start of the following lab session. Also, demonstrators respond to questions raised by individuals about their last graded report either during or after the lab session in which the report is returned.

The demonstrator submits the net (integer) grades for their class to the physics admin office immediately after their return of scripts/grades to a class, using the template excel sheet provided by the physics school admin office. Net grades are then uploaded by the school office within an additional week so as to be visible to students in their online grade centre.

Where unable to take a lab, the scheduled demonstrator finds a replacement aided by the lab manager, Thomas O'Reilly. The scheduled demonstrator primes their replacement for interaction with students on their recently graded report.

Three graded components

1. Preparation and data (the beginning)

A grade of between 0 and 4 awarded for a cumulative performance across the following:

- **Warm up**. Intro exercise/s.
- **Setup procedure**. Follow guided procedure to first useful data.
- **Method and range**. Take data in an appropriate manner and over a range of parameter space so as to allow for the most robust conclusions. This involves some critical thinking by the student and may for example involve checks or repetitions that expose hysteresis or a weakness in the apparatus.
- **Ordered data**. Record data in a clear and ordered way using the tables provided.

A grade of 4 is awarded for an exceptional performance only.

2. Results (the middle)

A grade of between 0 and 4 awarded for a cumulative performance across the following:

- **Plot** (distil) data. Plot, or otherwise distil as guided, all useful data from tables.
- **Clarity** of plot. Include axes labels, scale and correct units.
- **Slope and intercept**. Determine slope and intercept for a linear relationship. This generally involves assigning a straight line/s by eye, or by using 'JagFit' (see appendix 1). Either method is fine and the grader accounts for a reasonable fit by eye.
- **Relate to physical law**. Relate these variables to a physical law with consideration of errors where helpful. Where appropriate, systematic uncertainty and possible imperfections in an apparatus should also be considered.

A grade of 4 is awarded for an exceptional performance only.

Consider uncertainty in measurements. Use units correctly and consistently.

Whilst plotting is the main means of distilling data in our experiments, the Momentum experiment requires the distillation and interpretation of information by other means which include estimations of measurement uncertainty. The first three grades for this component are attributed to this.

For labs in this semester, we don't expect the student to propagate random errors by adding in quadrature. We do expect some critical thinking about the extent and source of errors.

3. Conclusions and implications (the end)

A grade of between 0 and 2 awarded for a cumulative performance across **conclusions** and **implications**.

A grade of 2 is awarded for an exceptional performance only. This may require the demonstration of some independent and critical thinking on the impact of measurement uncertainty on conclusions.

Tutor discretion

1. Reward diligence or critical thinking

It may be that exceptional diligence and/or critical thinking has led directly to students not completing a lab. To account for this, 2 net grade units can be awarded at the tutor's discretion. It remains that the overall student performance is considered in keeping with the UCD grade scale (see above).

By critical thinking, we mean thinking about the exercise that goes beyond regurgitation of material in the lab manual or delivered during the class. Generally, this is the mark of the stronger student.

2. PHYC10180

This module contains less maths than some others. For experiments such as gases and rotation, there are two parts. If students have been diligent but there is not enough time to complete both parts then the first part is sufficient.

3. Electrical experiments

These are designed as enquiry based and credit should be given for testing of even erroneous models for circuits. The grade should be awarded for addressing questions across the script and should be broadly in keeping with the UCD grade scale (see above).

4. PHYC20080

Whilst the style of these experiments varies, the grading distribution remains as given above. Where the intro contains no questions, the first component of grade is given for preparation to first useful data, range and ordered recording of data.