EXPLORING PHYSICS

YEAR 12 - EXPERIMENTS, INVESTIGATIONS & PROBLEMS

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SCIENCE TEACHERS' ASSOCIATION OF WESTERN AUSTRALIA

YEAR 12 ATAR

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Practical skills: Measurement and uncertainties

The *maximum* uncertainty of a measurement is usually ± 1 scale division. Thus, on a ruler that measures to 1 mm, a reading of 14.5 cm would be shown as **14.5 ± 0.1 cm**. On a *digital* instrument (stopwatch, balance) this is the best you'll get.

On an *analogue* instrument (ruler, thermometer, measuring cylinder) a skilled user may be able to estimate to less than this. For example, a thermometer having a fairly big spacing between the degree markings might be readable to ± 0.2 degree, if you were good at using it, or to ± 0.5 degree if you are not so skilled.

Other factors such as the reliability of the instrument itself are also important.

Example:

- Use a ruler to measure this page to ± 0.1 cm.
- Now measure it to the best (most accurate) value that you can, and show your result accordingly.
- How can we show which of these measurements has the lesser uncertainty (i.e. is 'more accurate')?

Adding or subtracting uncertainties:

If you *add* two measurements, you also add their uncertainties. Thus,

4.5 ± 0.1 cm + 5.5 ± 0.1 cm = **10.0 ± 0.2 cm**.

(Note that a simple rule about significant figures does not apply here; 2 SF + 2 SF but the answer is to 3 SF. *Significant figures give a general idea of uncertainties* instead of the more thorough treatment of uncertainties shown here.)

If you subtract measurements, you also add the uncertainties. Thus,

5.5 ± 0.1 cm - 4.5 ± 0.1 cm = **1.0 ± 0.2 cm**.

If you *multiply or divide* measurements, you convert to % uncertainty, then add these.

Example:

1. A toy car travelled 6.25 ± 0.05 metres in 22.51 ± 0.01 seconds. The speed is distance divided by time. So, we convert to % uncertainty:

$$\frac{\pm 0.05}{6.25} \times 100 = \pm 0.8\%$$

so we can now write the distance as 6.25 cm ± 0.8% .

The % uncertainty in the time is:

$$\frac{\pm 0.01}{22.51} \times 100 = \pm 0.04\%$$

So we can now write the time as **22.51 s ± 0.04%**.

Then when we calculate the average speed of the car, we can show an estimate of the uncertainty of the speed in the answer.

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{6.25\ \text{m}}{22.51\ \text{s}} = 0.27765\ldots \text{m s}^{-1}$$

$$\text{uncertainty} = 0.8 + 0.04 = \pm 0.84\%$$

$$0.84\% \text{ of } 0.27765 \ldots = 0.002$$

$$\text{thus the speed is } 0.278 \pm 0.002 \text{ m s}^{-1}$$

Note that a significant figure 'rule of thumb' works in this case. But note also that for actual measurements, showing the uncertainty estimate is much better than just blindly following a rule.

Exercise: Use your measurements of this page (above) to calculate its area, and show the result with an estimate of the uncertainty.

Practical skills: Measurement and uncertainties

Minimising uncertainties by making repeat measurements:

You can reduce the uncertainty in a measurement by making lots of measurements of the same thing, each independent of the others, then finding the mean value and the standard deviation of the distribution. The uncertainty in this case is ± the standard deviation. Another name for standard deviation is 'standard error of the mean'.

For example, a group of students measuring "g" got the following:

Run	1	2	3	4	5	6	7	8	9	10
Value (m s^{-2})	9.36	9.67	9.64	9.41	9.88	10.21	9.55	9.74	9.96	9.92

Calculate the mean and the standard deviation of these values, and hence quote "g" with an estimate of the experimental uncertainty.

Using a spreadsheet to calculate the mean and standard deviation, we get:

Mean = 9.734

St dev = 0.250

We would quote the mean value to be:

9.7 ± 0.2 m s^{-2}, or 9.7 ± 0.3 m s^{-2}; note that either way, the "expected" value of 9.8 m s^{-2} falls within the experimental uncertainty.

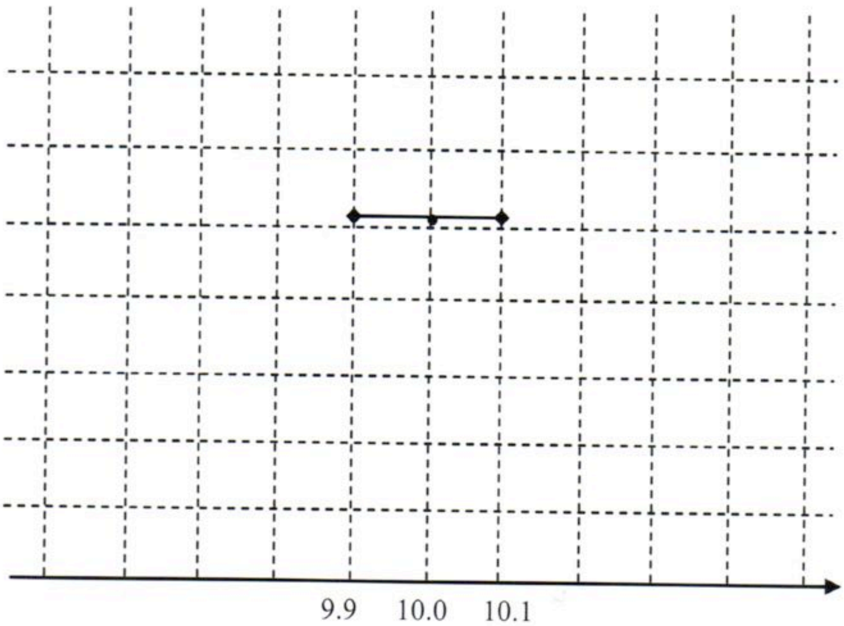
The more values you include, the more likely it is that your mean is close to the expected or actual value.

Why does this reduce the experimental uncertainty? Try using any two or three consecutive values in this table to calculate an average value for "g" and then compare it with the expected value. Note that the standard deviation is a feature of large samples and is not a valid measure for small samples, eg two or three.

Showing uncertainties on a graph:

You can graphically represent uncertainty in a measurement by plotting the value, and then adding 'error bars' that extend along the axis to show the ± values.

For example you would graph a value of 10.0 ± 0.1 m s^{-1} as a dot at 10.0, with a bar extending 0.1 unit in the positive direction (to show that the value could be as high as 10.1) and a bar extending in the negative direction (to show that the value could be as low as 9.9).



When drawing a line of best fit, it is worth keeping in mind that the central dot is not the measurement – anywhere along the bars could be correct. That is what an uncertainty means. A line of best fit should reflect your understanding of the physics of the situation.

Practical skills: Significant figures

A quick and relatively easy way to imply the uncertainty of a measurement is to express it to an appropriate number of significant figures. The number of significant figures (SF) or digits in a measurement is thus an indication of its accuracy or certainty.

The general rule is: Digits that are certain should be expressed; uncertain digits must not be expressed. Leading zeros (e.g. the zeros in 0.0001) and rounding zeroes (e.g. the zeroes in 20,000) do not count as significant figures. A zero to the right of both a non-zero digit and a decimal point is significant. Thus, while the numbers 0.02 and 200 are both expressed to one significant figure, the number 200.0 is expressed to four significant figures.

To count the number of SF, it helps to express the number in scientific notation. This is in the form of a significant (non-zero) digit followed by a decimal point and other SF as needed, and multiplied by the appropriate power of ten. This is routinely used to express small numbers (< 0.001) or large numbers (>1000).

For example, 0.00023 is written in scientific notation as 2.3×10^{-4}; 54,000 is written as 5.4×10^{4}. Both of these are expressed to two SF. However 34,050 m (3.405×10^{4} m) is expressed to four SF.

When reporting measurements or giving the answer to a calculation, express only those digits that you are certain of. That is, round off (or expand) the measurement or the calculated answer to an appropriate number of SF.

Significant figures in calculations

When multiply or dividing, always round off the final answer to the least number of significant figures. Remember that the display on your calculator is not your friend. Working out how to write your final answer is your responsibility.

For example: find the area of a book cover when its length is 28.5 cm (3 SF) and its width is 9.5 cm (2 SF).

Your calculator shows the area (length × width) as 270.75 cm^2. How should you write the answer?

Because the third digit in the width is not given, it is uncertain and this makes the third, fourth and fifth digits in the answer uncertain. Try recalculating the area with small variations in the width (e.g. try 9.49 cm, 9.52 cm etc.) You will see that a small variation in the width, eg, 9.52 instead of 9.50, gives a different value in the third digit of your answer, while the first two (the 2 and the 5) are stable. Thus, the third and subsequent digits in the calculated answer are uncertain, i.e. not significant. The best answer is 270 cm^2 or 2.7×10^{2} cm^2 which shows an accuracy of 2 SF. If you write the answer as 271 or 270.8 or 270.75 cm^2 you are claiming false accuracy.

Thus, the number of SF in a final calculated answer is limited by the number of SF in the least accurate measurement - in this case, the width limits the answer to two SF. Most of the calculation problems in this book give data expressed to three SF, so that the final answers should be to three SF.

Note that many calculations you will do will involve working out a value that you then use in a second calculation. Do not use a rounded value in the second calculation step - round off only the final answer.

Practical skills: Estimating quantities

It is useful to be able to estimate measurements and answers to calculations, and when we do, we express the answer to one or at most two SF.

For example, a typical school science laboratory is about 10 m wide.

Estimating a quantity usually involves doing a calculation with one or more measurements missing or unstated. To produce a reasonable answer, you have to assume a reasonable value for any missing measurement. Reasonable assumptions align with real-life values. For example, a person is likely to be between 1 and 2 m tall, but not 10 cm or 10 m tall; a car travelling on a freeway is likely to be moving at between 70 km h^{-1} and 110 km h^{-1}, and so on.

When estimating a quantity, you must state clearly the assumptions that you have made, and give the final answer to one or two SF.

Example: A car is travelling along a freeway. Estimate how far the car will travel in 20 minutes.

Thinking: the relevant equation in this case is $v_{av} = s/t$. We have the time, t (20 minutes = 1200 s) and need to work out the distance, s. We will need to assume the speed and that this speed is constant. On the freeway, let's say 100 km h^{-1} or about 28 m s^{-1}.

Working:

$v_{av} = s/t$

so $s = v_{av} \times t$

$= (27.7778 \times 1200)$ m

$= 33\ 333.333$ m

But wait - the calculator display is not your friend. None of the data given is accurate beyond one SF (a car might travel along a freeway at a speed between 70 and 110 km h^{-1}). The final answer should therefore be given only to one SF. The estimate is thus 30 000 m or 3×10^4 m or 30 km.

Gravity and Motion

Develop a deeper understanding of motion, its causes and the field theory of gravity through investigations.

Use Newton's Laws of Motion and the gravitational field model to analyse:

- **motion on inclined planes,**
- **the motion of projectiles, and**
- **satellite motion.**

Investigate to develop skills in relating graphical representations of data to quantitative relationships between variables, using lines of force to represent vector fields, and interpreting interactions in two and three dimensions.

Explore the ways in which models and theories are related to gravity and motion by investigating contexts including technologies, such as artificial satellites, navigation devices, and related areas of science and engineering, such as sports science, amusement parks, ballistics and forensics.

$$\Delta x = \frac{1}{2}(v_0 + v_f)(t)$$

$$\hat{H} = \sum_{n=1}^{N} \frac{\hat{p}_n^2}{2m_n} + V(x_1, x_2, \ldots x_N)$$

$$v_f^2 = v_0^2 + 2a\Delta x$$

World records and fun fairs

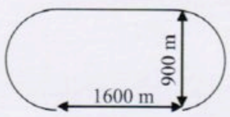
In weight-lifting, the bench press is performed while the weight-lifter lies on his or her back. The weight-lifter lowers the weight to chest level, then lifts it until the arms are straight and the elbows locked (or nearly so). In 2003, an Irish weight-lifter set a new benchmark for bench presses by lifting an accumulated total of 138 480 kg (that's over 138 tonnes) in one hour.

Roller coaster design also seems to be about pushing the boundaries. The table shows the relationship between maximum speed and the completion date for a number of famous roller coasters in the USA and Japan.

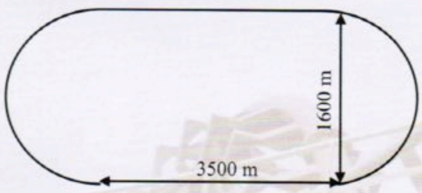
Completion Date	Maximum Speed (km h^{-1})
1996	130
2000	145
2001	170
2003	190
2005	205

Completed in 2005, a roller coaster in California called Kingda Ka offers extreme thrills. The steepest part of the track allows a vertical drop, and the passenger-bearing train exceeds 200 km h^{-1} in sections of the ride – a world record speed. The Kingda Ka also boasts the biggest vertical descent of any roller coaster yet built, with over 127 vertical metres separating the highest and the lowest parts of the track.

Pylon racing is not for the faint-hearted pilot. Up to eight racers at a time fly their aircraft at very low level around a closed circuit. For "Formula One" racing aircraft this 5.0 km long, with straight legs of 1.6 km length and curved ends 900 m in diameter. The aircraft that completes eight laps in the fastest time wins.



Formula One pylon racing circuit



Unlimited pylon racing circuit

The unlimited Red Bull pylon races pit individual pilots against the clock. Often, the pilot who can withstand the most 'g' during turns gets the fastest circuit time. Pilots are subjected to 9g or more for very brief periods (two or three seconds) during extremely tight turns. High g has potentially hazardous effects on a pilot. For example, at 3g every part of the pilot seems to weigh three times what it normally weighs, so even the slightest movement requires extraordinary effort. The heart has to work harder to pump blood, that suddenly weighs three times what it normally does, to the head. The result of high g can be loss of consciousness ('blackout') which at low level and high speed can be catastrophic. In general, the higher the g loading, the faster blackout takes hold.

Both players and officials are more interested in the progress of a cricket game than in irrelevant details – any ball that goes over the boundary without bouncing first, earns the batsman six runs. Thus, while a number of cricket batsmen have hit balls that obviously travelled 100 m or more before touching the ground, there is no official longest recorded distance for a 'six'. Wikipedia reports, perhaps unreliably, that Yuvraj Singh of India hit a 'six' that travelled 128 m from the bat before coming to ground. If we assume that the ball was struck one metre above the ground, and that air resistance had no significant effect on the ball's flight, we can calculate that the lowest speed the ball could have had as it left Mr Singh's bat was 35.3 m s^{-1}. In reality, the special conditions required to allow this are most unlikely, and the ball's initial speed was almost certainly significantly higher than calculated.

At 400 km h^{-1}, a competitor experiences a continuous centripetal acceleration of almost 3g when swinging around the curved ends (where $g = 9.8$ m s^{-2}). The record speed for "Formula One" class pylon racing, over a 5.0 km course, stands at 423.5 km h^{-1}. "Unlimited" class pylon racing allows the use of larger and much more powerful aircraft, most of which were designed as fighters for World War II, and are over fifty years old. A typical "unlimited" race circuit is 12 km long, and the speed record for this event is an eye-popping 801 km h^{-1}.

Comprehension questions

1. Which do you think would be an advantage in doing bench presses - long arms or short arms? Explain your answer.

2. a) Estimate the power at which the record-setting bench presser operated when lifting 138 tonnes in one hour. State clearly any assumptions you have to make.

   b) One horsepower is equivalent to 0.746 kW. Express the bench presser's power in horsepower.

3. Construct a graph of completion date vs maximum speed for recently-constructed roller coasters. Use the graph to predict the maximum speed of a roller coaster to be completed in the year 2030. Is this prediction reliable? Explain.

   a) Calculate the speed that a roller coaster train could attain from a standing start if it dropped 127 m vertically.

   b) Compare your answer to (a) with the information given about the Kingda Ka roller coaster. Explain any discrepancies.

4. Some newly-built roller coasters have the steepest part of the journey at an angle greater than 90° to the horizontal. Would this make the train go faster than if it descended at 90°? Explain.

5. a) Consider Mr Singh's cricket ball, which travelled a large horizontal distance while dropping vertically for a very short distance. In general, the ball should leave the bat at a particular angle in order to maximise range for a given initial speed. To a close approximation, this angle is 45°. Verify that, based on the data supplied, the minimum initial speed of the ball must have been about 35.3 m s^{-1}.

   b) Sketch the shape of the ball's trajectory, assuming that air resistance is negligible.

   c) Determine the maximum height above the ground reached by the ball in its journey.

   d) Calculate the initial speed of the ball if it travels 128 m horizontally, but leaves the bat at an angle of 30°.

6. a) Show that, at 400 km h^{-1}, the centripetal acceleration on a Formula One pylon racer is almost 3g.

   b) Calculate how long it takes a Formula One pylon racer to turn through 180° at 400 km h^{-1}. This is the length of time for which the pilot continuously experiences high g.

7. a) Determine the centripetal acceleration on an Unlimited pylon racer completing a circuit at 800 km h^{-1}.

   b) For what time period does the Unlimited pylon racer experience high g?

   c) Why is the track for Unlimited pylon racing longer than the track for Formula One?

Vectors explained

Notes

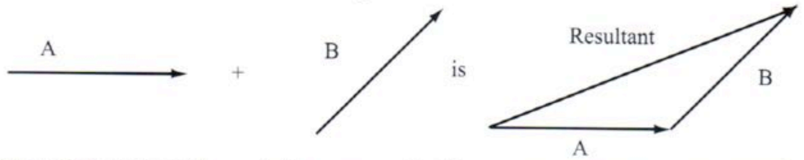
Remember the following important principles

You can represent a vector quantity with an arrow, where the length of the arrow represents the magnitude and the arrowhead represents the **direction**.

You can add or subtract scalar quantities arithmetically but you must **add or subtract vector quantities geometrically.**

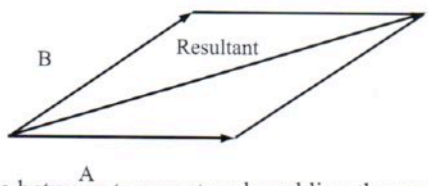
You can add vector quantities by putting the tail of one vector arrow at the arrowhead of the second vector arrow. The sum, or resultant, is a vector that begins at the tail of the first vector you added and ends at the arrowhead of the last vector you added. The diagram shows an example.

Adding vectors



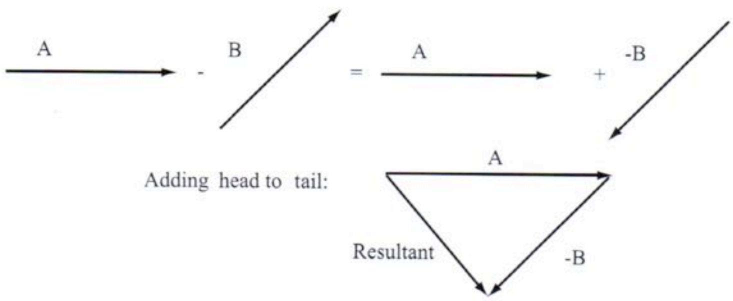
You can add vectors that act through the same point, known as **concurrent** vectors, by completing a parallelogram. The diagonal then gives the resultant, as illustrated.

Concurrent vectors

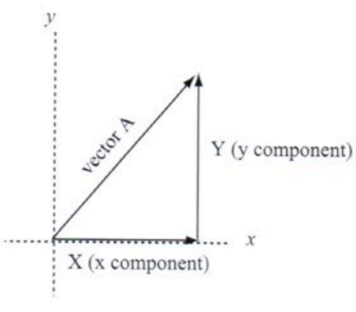


You can find the **difference** between two vectors by adding the negative vector of the vector you are subtracting. A negative vector is one of equal magnitude but opposite direction. You can represent the difference between two vectors A and B as shown below:

Difference BetweenVectors



A vector quantity can have an effect in directions other than that vector's direction. You can express any vector quantity as two vectors at right angles to one another, as long the sum of those two vectors is equal to the original vector. We call such vectors **rectangular components** of the original vector. For example, vector A can have components Y and X. You can convert (resolve) any vector into an infinite number of sets of mutually perpendicular components. Note that a vector has no components perpendicular to itself.



Background

You can resolve or break down a single force into two forces at right angles to one another. The two resolved forces or components when added together will give the original force.

In this experiment you will measure a force, the tension, and its vertical component, the weight, and the horizontal component, the thrust in the boom.

Aim

To show that a single force can be resolved into components at right angles to one another.

Equipment

- large retort stand with 2 boss heads and clamp
- 2 pieces of 10 mm diameter dowel or metal rod about 50 mm long, one with an eye hook in the end and the other with a short piece of plastic tube partly pushed onto one end
- dowel - 8 mm diameter, 400 mm long with an eye hook at one end and a nail in the other end. (A level bubble attached to the boom is an easy way to make sure the boom is level)
- string or fishing line about 500 mm long
- large protractor
- 2 spring balances (10 N)
- a set of slotted masses (e.g. 10 × 50 g)

Pre-lab

Draw tables similar to Tables 1 and 2 shown below.

	Trial 1	Trial 2	Trial 3
Angle between string and boom			
Tension T (N)			
Weight W (N)			
Thrust P (N)			

Record the weight (W) in newtons in Table 1.

	Trial 1	Trial 2	Trial 3
Vertical component of tension ($T_V = T \sin \theta$)			
Horizontal component of tension ($T_H = T \cos \theta$)			
Difference between T_V and W			
Difference between T_H and P			

Table 2

Notes

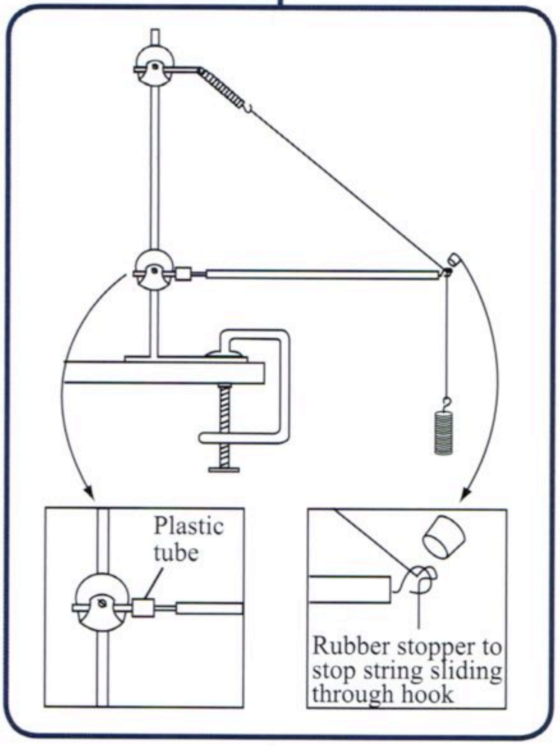


Figure 1.1:Set up

Experiment 1.1: Resolving forces

Notes

Lab notes

- Adjust the upper balance and string length until the boom is horizontal and the string is at an angle of between 40° and 65° to the boom.
- Measure and record the angle θ between the string and the boom.
- Attach the spring balance to the end of the boom and slowly pull it horizontally until the nail in the boom just moves free inside the plastic tube. Measure and record the horizontal force to achieve this. This is the thrust (P). Measure and record the tension (T) in the string.
- Repeat the experiment using two other values of the angle.

Processing of results

- For each set of readings, complete the calculations set out in Table 2.
- Represent one of these situations graphically by selecting one set of results and drawing an accurate scale diagram showing all forces acting in this situation.

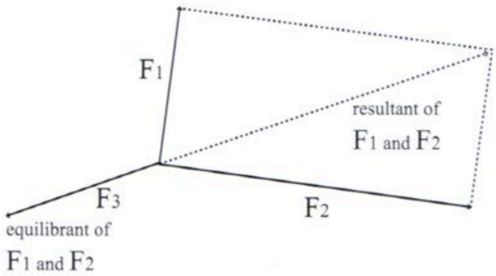
Post-lab discussion

1. On the basis of your results, write a general conclusion relating a vector to its components.
2. What happens to the tension in the string and the thrust on the boom as the angle is made smaller?
3. The weight of the beam in this experiment was ignored. Is this reasonable? Explain.
4. List the major sources of errors in this experiment.
5. Express the average difference between T_V and W as a percentage of W. Do the same for T_H and P compared to P. Are these errors acceptable?
6. Describe a practical situation you have seen that uses the principles examined in this experiment.

Background

We define the resultant as the net force experienced by an object when two or more forces act at the same point on the object.

We call the single force that will balance the combined effect of the two or more forces, the equilibrant. Remember, forces are vector quantities so we can add them geometrically and since you will be investigating concurrent forces you may add the vectors by completing a parallelogram as shown below.



Determining the resultant force vector

Notes

Aim

In this experiment you will measure three concurrent forces then compare the resultant of two of the forces with the third force. This third force is the equilibrant.

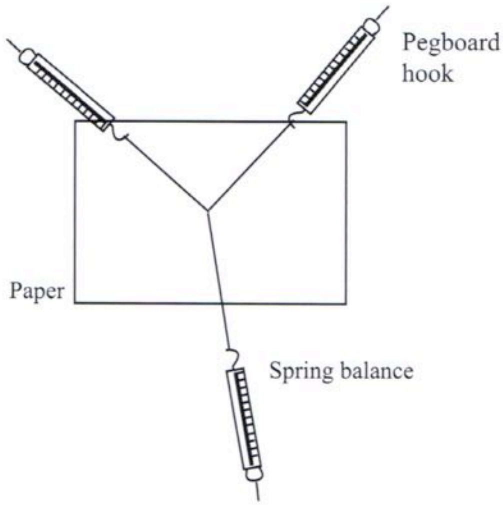
You will need to find the resultant and equilibrant of two forces acting at an angle to each other, and work out the relationship between them.

Equipment

- force table or pegboard approximately 1 m × 1 m
- three pegboard hooks
- three spring balances (10 N or 20 N)
- 1 m of string or fishing line
- protractor
- paper
- rule

Pre-lab

- Place the pegboard on a flat bench
- Connect the three spring balances using the string or fishing line as shown.
- Arrange the three balances so that each balance reads more than half the full scale reading and each reading is different from the others. You will find this easier if you first position two of the balances then adjust the position of the third.
- Arrange a sheet of paper under the strings so that the knot joining the strings is in the middle of the sheet. Carefully mark the point at which the strings meet and the other end of each string.

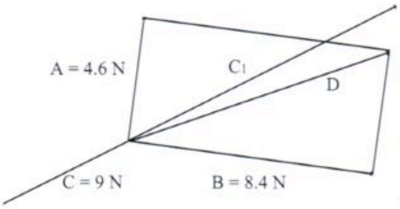


Lab notes

- Using a pencil and rule, you can now join the points to show the positions of the strings. Label the lines A, B and C in any order and write the balance reading near each string.
- Using a new piece of paper for each set of readings, change the position of the balances so you can measure three additional sets of results.

Experiment 1.2: Adding forces

Processing of results



Relationship between the resultant and the equilibrant forces

Notes

- For each of your four sets of results select a suitable scale and draw a vector diagram to represent the forces you measured. Make sure you measure and draw the angles between the forces accurately.
- Add vectors A and B by constructing a parallelogram as shown in the example. Then draw D, the resultant of A and B.
- You can now draw the equilibrant of C and label it C_1. The equilibrant has the same magnitude as C but is in the opposite direction.
- Complete the table below using your results from each trial.

	Trial 1	Trial 2	Trial 3	Trial 4
Magnitude of A (N)				
Magnitude of A (N)				
Magnitude of D = A + B (N)				
Difference in magnitude of C_1 and D (N)				
Angle between D and C_1				

Post-lab discussion

1. From your results state the relationship between the resultant and equilibrant for forces acting concurrently on a stationary object.
2. Choose one set of results. Add A and C using the same method used above. Compare the sum of these with B. Does the evidence support your conclusions?
3. Under what circumstances would A, B and C be equal in magnitude? Show this in a scale diagram.
4. Explain why differences exist between C_1 and D, and why the angle between C_1 and D is not always zero.
5. List the main sources of error in your experiment. How does each source of error contribute to the variation in your results?
6. From the context you are studying choose two examples where two forces act concurrently.
   a) Describe each example and draw a vector diagram to show the force vectors and the resultant in each case.
   b) For each example indicate whether the resultant force is unbalanced or not.

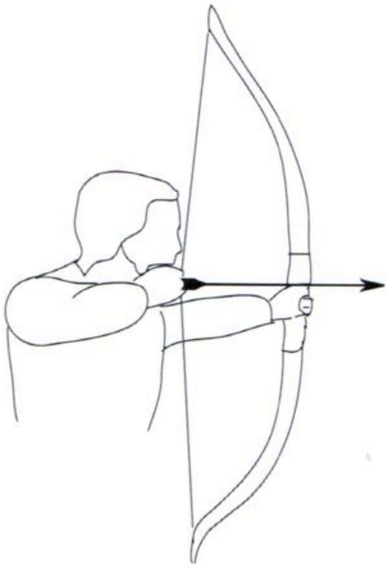
Problem Set 1: Vector addition, subtraction and resolution

Notes

1. Explain why it is essential to describe both magnitude and direction of a quantity such as velocity.

2. A hockey player runs from fullback directly up the field for 15.0 m in an easterly direction to intercept the ball. He then dribbles the ball for 10.0 m in a northerly direction before passing the ball to a team-mate 20.0 m to the west.
   (a) Calculate the player's displacement.
   (b) Calculate the ball's displacement.

3. An archer stretches a bow so the string makes angles of 45° to the arrow. If the tension in the string is 208 N, what force is exerted on the arrow at the time of release?



4. A swimmer can achieve a speed of 1.50 m s^{-1} in still water. She heads directly across a rip in which the water is moving at a velocity of 3.50 m s^{-1} west. Determine her resultant velocity.

5. A canoeist can paddle a slalom kayak for short bursts at a speed of 2.70 m s^{-1} in still water. He wants to cross a stream in which a 2.00 m s^{-1} current flows.
   (a) At what angle to the current must he point his canoe if he wants to land on the other bank directly opposite to where he started? Assume he paddles at top speed throughout his crossing.
   (b) Calculate his resultant velocity if he heads directly across the stream at top speed.
   (c) The stream is 40.0 m wide. How far downstream will he land on the opposite bank?

6. A cross country skier uses a compass to determine direction. She leaves a ski village and skis 3.0 km east, then 8.0 km south, then 10.0 km east, then 5.0 km south, then 3.0 km west, then 6.0 km north, and finally 4.0 km west. She wants to return to village by the most direct route.
   (a) Draw a diagram to an appropriate scale and work out how far from the village she is.
   (b) In what direction should she head to return to the village if the terrain will allow her to travel straight to the village?

7. A netball player is standing still when she catches a ball that is moving at about 5 m s^{-1}. Estimate the ball's change in velocity.

8. A tennis player serves a ball at 80 km h^{-1} towards his opponent, who returns it directly back to the server at 90 km h^{-1}. Calculate the ball's change in velocity.

9. In a game of squash a player strikes the ball so that hits the side wall at 25 m s^{-1} at an angle of 45° to the wall. It rebounds at 20 m s^{-1} at an angle to the wall of 45° on the opposite side of the normal. Calculate the ball's change in velocity.

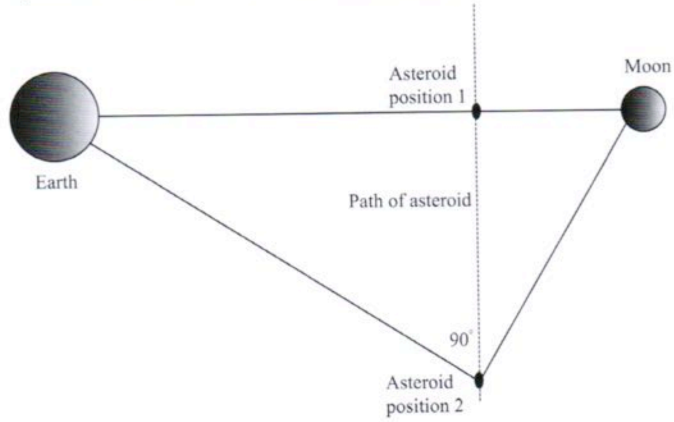
10. Two ice skaters hold one arm each of a third skate and each pulls with a force of 150 N. Calculate the resultant force pulling the third ice skater forward if the angle between his arms is a right angle.

11. A batter hits a cricket ball at right angles to its original direction. The bowler bowled the ball at 30.0 m s^{-1}. If the ball leaves the bat at 30.0 m s^{-1}, determine the ball's change in velocity.

Problem Set 1: Vector addition, subtraction and resolution

Notes

12. A small asteroid passes between the Earth and the Moon.



The Earth attracts it with a force of 480 N and the Moon attracts it with a force of 53.2 N when the asteroid is in position 1. The forces of attraction are 359 N and 13.1 N respectively when the asteroid is in position 2. Work out the net force on the asteroid in positions 1 and 2.

13. An archer fires an arrow with a velocity of 45 m s^{-1} at an angle of 18° to the horizontal. Estimate its velocity in the horizontal direction.

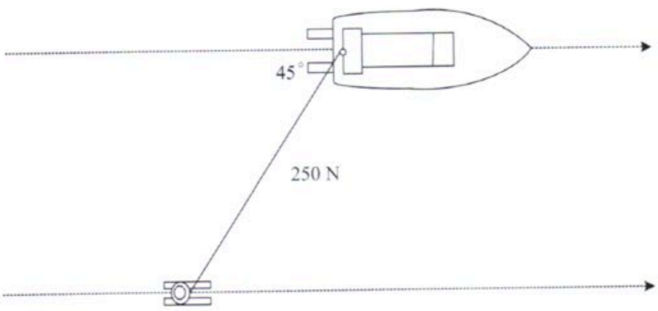
14. A marathon runner is running at constant velocity. A spectator looking eastwards notices that the runner is moving northwards at 1.40 m s^{-1}. At the same time another spectator looking northwards notes that the runner is moving eastwards at 1.10 m s^{-1}. Determine the runner's actual velocity.

15. A two person bobsled crew push the sled, one from each side, at an angle of 12.0° to the track with a force 600 N each.
    (a) How much force do they apply to the sled parallel to the track?
    (b) What is the force with which each crew member pushes against the other?

16. A golfer hits a ball with a velocity of 25.0 m s^{-1} at an angle of 35.0° to the horizontal. Immediately after she hits the ball, at what rate does it rise and at what rate does it move towards the pin?

17. A roller skater starts down a slope inclined at 25.0° the horizontal. The skater is not significantly affected by frictional forces. Determine the skater's acceleration.

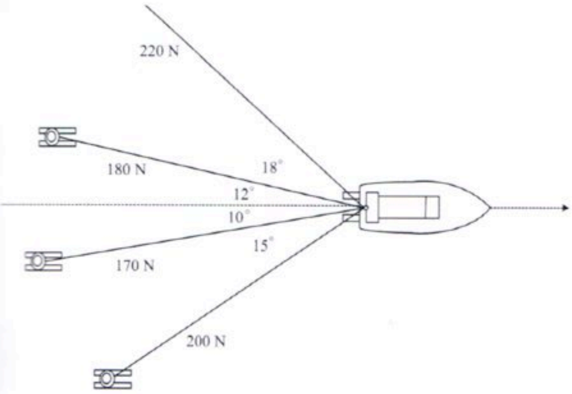
18. Rachael reaches a constant speed of 35.0 km h^{-1} while sliding down a water slide inclined at an angle of 30.0° to the horizontal. How long does she take to descend a vertical height of 12.0 m once she reaches this speed?



19. A power boat tows a water skier. The skier is situated well to one side of the boat, but is travelling in the same direction as the boat. The tension in the rope is 25.0 N and the rope makes an angle of 45.0° to the direction of both boat and skier. Determine the minimum force the skier must apply to the water to maintain this path.

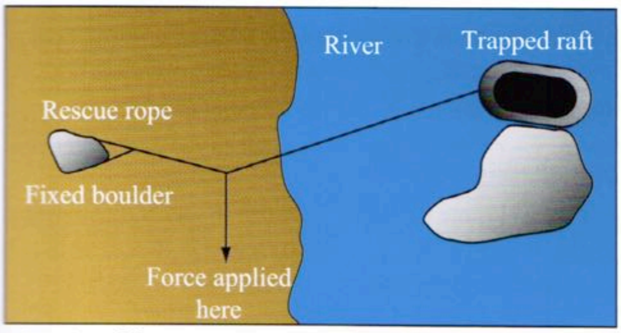
20. During a football game a player kicks the ball eastward at a constant horizontal velocity of 13.0 m s^{-1} directly toward a team-mate 45.0 m away. There is a crosswind blowing from the north at 8.50 m s^{-1}.
   (a) How much time does the team-mate have to get into position to catch the ball?
   (b) How far does the team-mate have to run in a southerly direction to catch the ball?

21. A truck driver supported a plank horizontally by its two ends. He then loaded bricks on its centre and found that the weight of 166 kg of bricks was just enough to break the plank. He wanted to use an identical plank as a ramp to load a full fuel drum of total mass 197 kg onto a truck.
   (a) Explain why the driver could still use this plank to load the fuel drum.
   (b) What is the minimum angle to the horizontal at which he could still use the plank to load the drum?



Question 22

22. A ski boat is towing four skiers. The diagram below shows the tow ropes tensions and angles. Calculate the total force the skiers apply to the boat.



Question 23

23. A vector pull is a very simple method rescuers use to increase the force on a rescue rope during river rescues. Use a diagram with an appropriate scale to show that the force applied to the trapped raft is very much larger than the force applied by the rescuers.

Notes

Moments and equilibrium explained

Notes

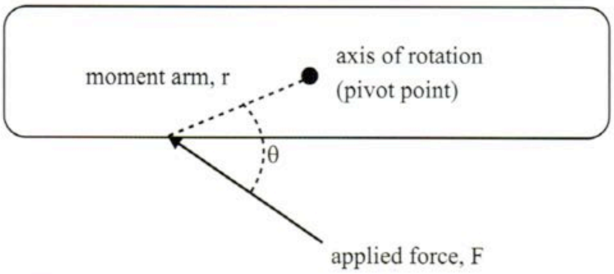
Remember the following important principles

The centre of mass of an object is the point at which all of the mass of the object appears to be concentrated. Depending on the shape of the object, the centre of mass can be within the object, or at some external point, as is the case with a horseshoe.

A moment of a force or torque results when you apply a force to an object in such a way that it is not directed through its centre of mass. As a result, the mass will change its speed of rotation.

The magnitude of this turning effect depends on the magnitude and direction of the force and how far its point of application is from the axis of rotation. An example of this principle is the fact that it is difficult to open a door if you push close to its hinges.

The turning effect of a force is called the moment or torque exerted by that force. The size of a torque depends on: the size of the applied force, the moment arm (the distance between the point of application of the force and the axis about which the object will rotate), and the angle between the line of action of the force and the moment arm.



Mathematically, we can write

$$\boldsymbol{\tau} = \mathbf{r\ F\ sin\ \theta}$$

where:

τ is the torque, in N m
r is the distance (in m) between the line of action of the force and the axis of rotation
F is the applied force (in N)
$\boldsymbol{\theta}$ is the angle between the line of action of the force, and the moment arm

Note that the formula for torque simplifies to $\boldsymbol{\tau} = \mathrm{r\ F}$ in the special case when the angle between the applied force and the moment arm is 90°.
The units of torque are (metres × newtons) or m N (note the space between m and N, otherwise this would be mN = millinewtons). To avoid confusion this is often written as N m.

Conditions for Equilibrium

If a body is at rest or in a state of uniform straight line motion, then it follows that there are no unbalanced forces acting on it. In this case the vector sum of all forces in any direction acting on the body is equal to zero.

$$\Sigma F = 0$$

Even with this condition satisfied a body can still undergo rotational acceleration in the case where the lines of action of two opposing parallel forces of equal magnitude do not coincide. For rotational equilibrium to exist, the algebraic sum of the moments of the forces about any axis must be zero.

$$\Sigma M = 0$$

This is known as the principle of moments. The expression we use to solve problems where a body is in equilibrium under a system of coplanar forces is:

$$\Sigma(\text{anti-clockwise moments}) = \Sigma(\text{clockwise moments})$$

Experiment 2.1: Parallel forces

Aim

Notes

In this experiment you will be able to test the principle of moments for yourself. In a number of simple equilibrium situations that you set up with the equipment provided you will be able to

- find the values for the clockwise and anticlockwise moments in each case you set up
- verify the principle of moments
- make predictions of where to hang masses on the apparatus in order to balance it
- calculate the mass of the metre rule that you use, by using the method of moments

Equipment

- one metre rule with holes drilled at the 25 cm, 50 cm and 75 cm mark
- two sets of slotted 50 g masses
- 50 mm long bolt with a diameter of approximately 5 mm
- retort stand, boss head and clamp
- 0–10 N spring balance
- electronic pan balance
- wire or string for suspending masses from the metre rule
- two bulldog clips or similar could also be used to support masses

Pre-lab

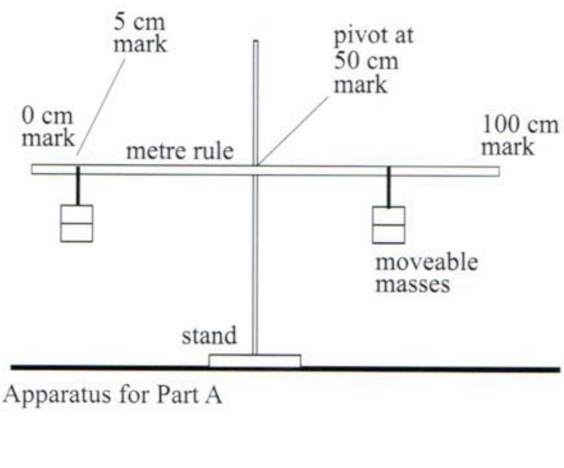
Part A: Balancing a constant moment

- In this part of the experiment you will balance a constant moment produced by a constant weight that is at a fixed distance from the pivot. To do this you will need to use different masses at varying distances from the pivot.
- Set up the equipment as shown by first placing the bolt through the rule, then clamping the bolt with the boss-head. Make sure the rule balances horizontally before you add any weights.
- Adjust the height of the pivot so that when the rule is balanced the weights are a few centimetres above the bench top.

Note: If the metre rule represented is balanced in the horizontal position, the 100 g mass provides an anticlockwise moment about the bolt. The moveable masses provide an equal magnitude moment in a clockwise direction on the other side of the pivot. When the anticlockwise moment cancels the clockwise moment about the bolt, the rule and the masses will be in equilibrium.

Fixed Mass Data	
Mass in grams (g)	100 g
Mass in kilograms (kg)	
Distance from pivot (cm)	45.0 cm
Distance from pivot (m)	
Weight in newtons (N)	
a c moment about pivot (Nm)	

Table 1



Apparatus for Part A

Experiment 2.1: Parallel forces

Notes

Lab notes

- Hang a 100 g mass between the 50 cm mark and the 100 cm mark in a position so that the metre rule is balanced in the horizontal position.
- Use the scale on the metre rule to measure the distance from the pivot to the point where you hung the second 100 g mass and record this value in table 2 as shown below, in the column labelled 'Distance to weight (cm)'.
- Add successive 50 g masses and repeat steps 2 and 3 for all mass values shown in the first column of table 2.

Post-lab discussion

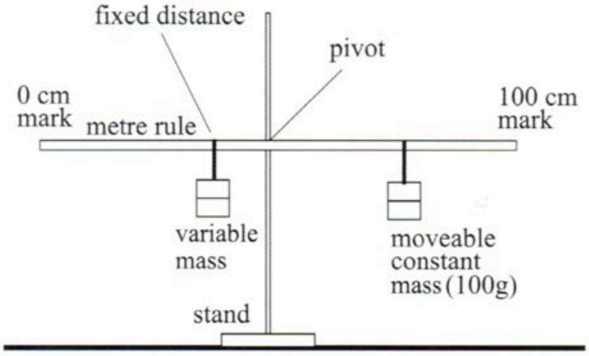
Mass used (g)	Mass used (kg)	Weight used (N)	Distance to weight (cm)	Distance to weight (m)	weight × distance (N m)
100					
150					
200					
250					
300					
350					
400					
450					

Table 2

Fill in the remaining blank spaces in table 1 and table 2.

1. Comment on any regularity in the values you obtain in the last column of table 2.
2. Compare the average value in table 2 to the value of the anticlockwise moment in table 1.
3. Write a statement about moments that summarises your findings in this part of the experiment.
4. Why is the mass of the rule ignored in your experiment?
5. Comment on how the length of the lever arm for the clockwise moment changes as you add more weights at a fixed distance to the left of the pivot. Explain your reasoning.

Pre-lab



Apparatus for Part B

Part B: Balancing a variable moment

In this part of the experiment you will balance a changing moment produced by a changing weight that is at a fixed distance from the pivot. To do this you will need to shift a constant mass to varying positions from the pivot.

Set up the equipment as in Part A with a 100 g mass at the 40 cm mark on the rule. This will be at the fixed distance of 10 cm from the pivot for this part of the experiment. See the diagram (*left*).

Lab notes

- Position a 100 g mass at the 40 cm mark and balance the rule by hanging a 100 g mass on the other side of the pivot. Record the distance to the pivot of the second mass in table 3.

Values for Constant Measurement	
Mass of movable constant weight (g) Weight of movable constant (N) Distance from pivot of variable mass (cm) Distance from pivot of variable mass (m)	100 g 10.0 cm

Table 3

- Add a further 50 g mass to the first one at the 40 cm mark and balance the rule by moving the 100 g constant mass. Record the new balance position.
- Repeat steps 2 and 3 for each of the mass values shown in the first column of table 4.

Mass used at fixed distance (g)	Weight used at fixed distance (N)	Distance to pivot for constant weight (cm)	Distance to pivot for constant weight (m)	Moment for constant weight (N m)	Moment for variable weights (N m)	Difference between ACM and CM (N m)
100						
150						
500						
250						
300						
350						
400						
450						

Table 4

Post-lab discussion

1. Fill in all the remaining blank spaces in table 3 and table 4.
2. Comment on any regularity in the values you obtained in the last column of table 4.
3. Write a statement about moments that summarises your findings in this part of the experiment.
4. Why can you ignore the mass of the rule in your experiment?
5. Comment on how the length of the lever arm for the clockwise moment changes as you add more weights at a fixed distance to the left of the pivot. Explain your reasoning.

Notes

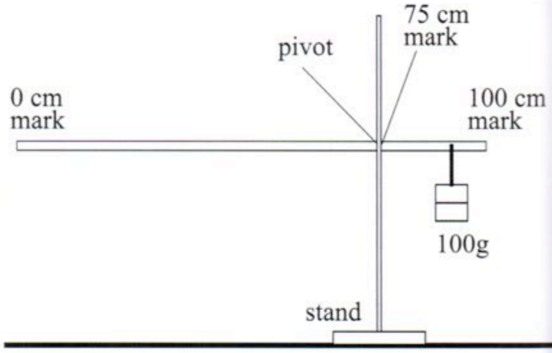
Experiment 2.1: Parallel forces

Notes

Pre-lab discussion

Part C: Weighing a metre rule

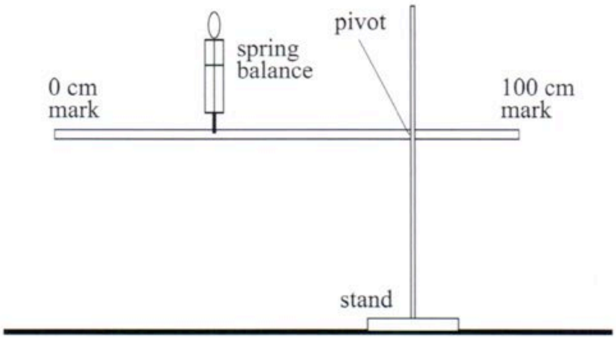
- In this part of the experiment you will calculate the weight of the metre rule by using the principle of moments when the rule is balanced. To do this you will need to change the pivot point of the rule.
- Set up the equipment as shown by placing the bolt through the rule at the 75 cm mark.



Apparatus for Part C

Lab notes

- Hang a 100 g mass at a point on the rule so that the rule comes to rest in a horizontal position. Record the distance to the pivot of the 100 g mass.
- Mark on the diagram the position of the ruler's centre of mass and all the forces acting on the rule.
- Use your knowledge of moments to calculate the weight of the rule. Record this value.
- Remove the 100 g mass and use a spring balance to support the rule horizontally from its 30 cm mark as shown.



Using a spring balance

- Mark on the diagram all the forces acting on the rule.
- Use the reading from the spring balance to calculate the weight of the rule. Record this value.
- Dismantle your apparatus and weigh your rule on an electronic balance. Record this value.

Post-lab discussion

1. Compare the two values you obtained for the weight of the rule and comment on any differences.
2. Would the reading on the spring balance change if the rule was not supported horizontally? Explain your answer.
3. If the pivot in "Using a spring balance" was replaced by another spring balance, what reading would it show? Use the measured weight of the rule you found from the electronic balance to calculate your answer.

Experiment 2.2: Forces and torques in equilibrium

Aim

Notes

In this investigation you will verify the conditions you need for a body to be in equilibrium. You will do this by investigating the relationship between

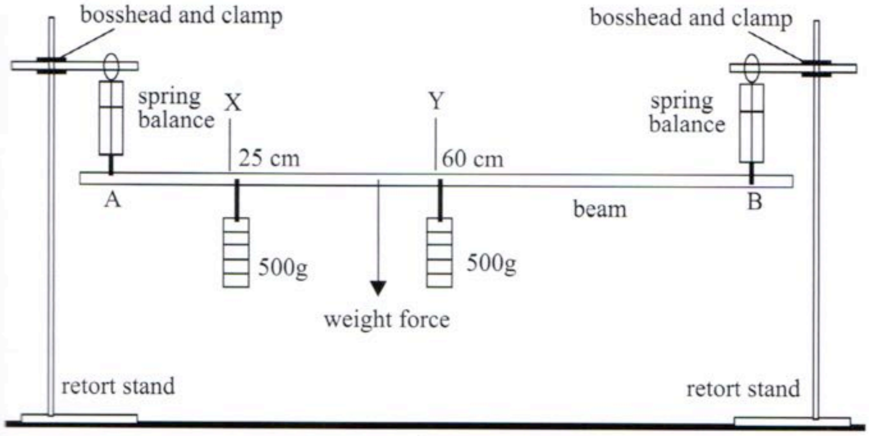
- forces that act on a body that is in equilibrium
- moments that act on a body that is in equilibrium

Equipment

- one metre rule to act as a beam
- two sets of slotted 50 g masses
- two retort stands with boss heads and clamps
- two 0-10 N spring balances
- wire, string or paper clips for suspending masses from the metre rule and beam from spring balances

Pre-lab

- In this experiment you will use two spring balances to support a beam on which you hang two weights at different points along its length.
- Measure the weight of the beam using one of the spring balances and record your value in the table.



Apparatus for Experiment 5.2

- Set up the equipment as shown with attention to the following points:
  a) Position the retort stands with the longer parts of their bases towards each other.
  b) Position the spring balances on the clamps so that a vertical line through them passes within the area of the base of the stand. The spring balances should be near to and equidistant from each ends of the beam.
  c) The spring balances must hang vertically before you take a reading.
  d) Make sure the beam balances horizontally before you take a reading.

Experiment 2.2: Forces and torques in equilibrium

Lab notes

- Once the beam is in equilibrium record the reading on each spring balance and the position of the weights in the table below. Record the weights in newtons and the positions in metres measured from the spring balance at A.
- Change the positions and sizes of each weight to obtain another two sets of measurements. Use different weight values for the two weights in both trials.
- Complete the column for trial 1 in table 1. The distances should be measured from the position Y.

Note: The spring balances exert upward forces on the beam while the slotted weights and the weight of the beam exert downward forces.

Weight of beam = ___________g				
Measurements taken	Symbol	Trial 1	Trial 2	Trial 3
Upward force at A (N)	F_A			
Upward force at B (N)	F_B			
Distance from A to B (m)	b			
Downward force at X (N)	F_X			
Distance from A to X (m)	x			
Downward weight force of beam (N)	F_W			
Distance of centre of gravity from A (m)	cg			
Downward force at Y (N)	F_Y			
Distance from A to Y (m)	y			
Distance from Y to B (m)	B			
Distance of centre of gravity from Y (m)	CG			
Distance from X to Y (m)	X			
Distance from Y to A (m)	A			

Table 1

Post-lab discussion

1. For *each* trial calculate $F_A + F_B$ and $F_X + F_y + F_W$ and record your results in table 2. What do you notice about these values in each trial?
2. For *each* trial calculate the sum of the clockwise moments about A and the anticlockwise moment about A and record your results in table 2. What do you notice about these values in each trial?
3. For *trial 1 only*, calculate the clockwise moment about Y and the sum of the anticlockwise moments about Y and record your results in table 2. What do you notice about these values?
4. Write a statement about vertical forces that summarises your findings in this experiment.
5. Write a statement about moments that summarises your findings in this experiment.
6. Write a statement about the position on the beam about which moments can be taken when a system is in equilibrium.
7. Explain why the spring balances have to be attached equidistant from the ends of the uniform beam.
8. What assumption did you make about the centre of mass of the beam in this experiment?
9. Explain why it is important to position the retort stands with the longer ends of their bases towards each other.
10. Explain why the spring balances must be positioned over the bases of the stands.
11. Explain why the spring balances must both be vertical when you take readings from them.

Measurements taken	Symbol	Trial 1	Trial 2	Trial 3
Sum of upward force on beam (N)	$F_A + F_B$			
Sum of downward force on beam (N)	$F_X + F_Y + F_W$			
Sum of clockwise moments about A (N m)	$\Sigma\ CM_A$			
Anticlockwise moment about A (N m)	$\Sigma\ ACM_A$			
Clockwise moment about Y	$\Sigma\ CM_Y$			
Sum of anticlockwise moments about Y (N m)	$\Sigma\ ACM_Y$			

Table 2

Experiment 2.3: Bridges

Aim

To measure the forces within a Bridge system, to assist in understanding static and rotational equilibrium.

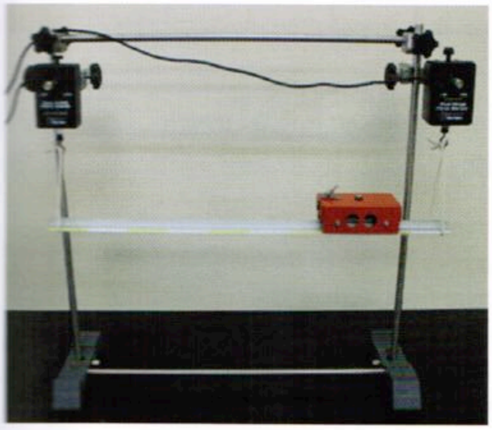
Equipment

- data logging software
- 40 cm Ruler or small plastic track with cart
- large protractor
- slotted masses (20 g – 100 g)
- 2 force probes (0-50N)
- 2 retort stands
- string and scissors
- scale (0-200 g)

Lab notes

A bridge or painting system

1. Measure the mass of the track and cart.
2. Set up the apparatus as shown below. Ensure that force probes and string are all vertical and try to ensure that the ruler is level.



3. Load the data logging software and ensure that you change to sample rate to 20 samples per second for 10 seconds.
4. Place the cart below one of the force probes.
5. Roll the cart from one aide of the bridge to the other side. Record the force vs time graph for the system 1. Print this graph. This can be done by manually recording the position of the cart and force from the two probes.
6. Add a 40 g slotted mass at the 10 cm mark on the ruler or track.
7. Place the cart below one of the force probes.
8. Roll the cart from one aide of the bridge to the other side. Record the force vs time graph for the system 2. Print this graph. This can be done by manually recording the position of the cart and force from the two probes.
9. Change the height of one of the sides of the bridge by 5 cm. This will now make the bridge uneven. Ensure that the string and force probes are still in a vertical plane.
10. Place the cart below one of the force probes at the top of the slope.
11. Roll the cart from one aide of the bridge to the other side. Record the force vs time graph for the system 3. Print this graph. This can be done by manually recording the position of the cart and force from the two probes.

Results

Mass of Cart:_______________

Mass of the Track: _______________

Notes

Experiment 2.3: Bridges

Notes

System 1

Cart Position (cm)	0	5	10	15	20	25	30	35	40
Force 1									
Force 2									

System 2: 40 g Mass attached at: _______________

Cart Position (cm)	0	5	10	15	20	25	30	35	40
Force 1									
Force 2									

System 3

Cart Position (cm)	0	5	10	15	20	25	30	35	40
Force 1									
Force 2									

Post-lab discussion

1. From your graph for System 1, how do you know that the cart is in the middle of the bridge?
2. Will the sum of the two forces from the two supports always be the same value? Prove using a simple Forces up = Forces down calculation.
3. From your graph from System 2, how is it different from System 1?
4. Will the sum of two forces from the two force probes always be the same?
5. From your graph from System 3, how is it different from System 1?
6. How did changing the slope change the relationship between Forces up = Forces down in the system?
7. Will the sum of two forces from the two probes always be the same?
8. What errors are present in the system?

Experiment 2.4: Non-parallel forces

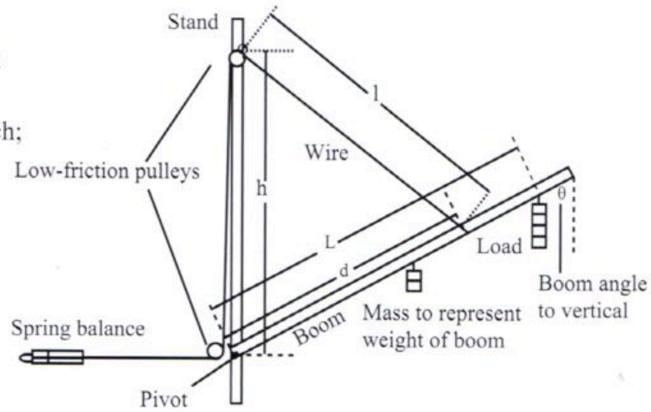
Aim

In this investigation, you will use the conditions for equilibrium to study the effect on forces acting at a pivot when a cantilevered object is supported at various angles. You will calculate the reaction at the pivot by resolving the measured values of the tension in a supporting wire when the object is in different positions.

Equipment

- one metre rule with holes drilled at 50 cm, 60 cm and 95 cm mark
- two sets of slotted 50 g masses;
- sturdy retort stand and appropriate clamp for attaching it to a bench;
- bossheads and clamps;
- 0 – 20 N spring balance;
- wire or string for suspending masses from the metre rule;
- wire or strong string for supporting boom;
- pivot for boom;
- 2 low friction pulleys with appropriate mountings;
- protractor;
- method for securing spring balance with reading

Note: a 360° protractor attached at the 100 cm end of rule and a plumb line would make the boom angle easier to measure.



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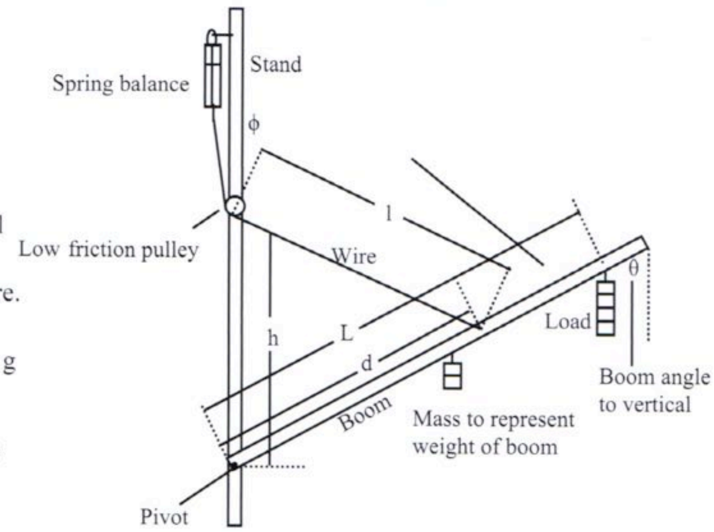


Pre-lab

In this experiment, you will use a metre rule to represent a boom, and a wire to represent a tie as in a crane. Using the equipment as in the figure you will measure the tension in the tie for various angles of the boom. From these and other measurements you will calculate the reaction at the pivot.

- With the help of a partner arrange the quipment as in the figure.
- Attach a 55 g mass to the boom at the 95 cm mark, and a 150 g mass at the 50 cm mark.
- This second mass is to give the boom some weight so that the small weight of the rule can be ignored in your calculations.

Lab notes

- Position the upper pulley so that the wire passes over it at a height of 70 cm above the pivot.
- Attach the wire to the 60 cm mark on the boom and pass it over the pulleys to the spring balance.

Use the information below to check that you have used the correct values in your set up.

Boom and other variables						
Length to load, L (cm)	C of mass from pivot, c (cm)	Distance to tie, d (cm)	Mass of boom (kg)	Load (kg)	Height of tie above pivot, h (cm)	Acceleration due to gravity, g (m s^{-2})
95.00	50.00	60.00	0.15	0.50	70.00	9.80

Experiment 2.4: Non-parallel forces

- Adjust the boom so that it makes an angle of 20° with the vertical and record the tie tension reading T on the spring balance on the results table. Record also the length l of the tie and the angle ϕ the tie makes with the stand.
- Change the angle of the boom and complete the first three columns of the results table *(below)*.

Boom angle to vertical, θ	Tie length, L (cm)	Angle between tie and stand, ϕ	Tension in tie, T (N)	Vertical component, T_v (N)	Horizontal component, $T_h = R_h$ (N)	Vertical reaction, R_v (N)	Reaction of pivot, R (N)	Reaction angle to horizontal γ
20								
40								
60								
80								
90								
100								
120								
140								
160								

Post-lab discussion

1. Draw a diagram showing all forces acting on the boom. Use the following labels in your diagram.
   T = tension in tie
   T_h = horizontal component of tension in tie
   T_v = vertical component of tension in tie
   W_b = weight of boom
   W_l = weight of load
   R = reaction at pivot
   R_h = horizontal component of reaction at pivot
   θ = angle of boom to vertical
   ϕ = angle of tie to vertical
   γ = angle of reaction to horizontal (above horizontal is positive, and below horizontal is negative)
2. For one angle only of the boom show your working for 3 to 7 below.
3. For one angle of the boom use the tension in the tie and the angle the tie makes with the stand nto calculate the vertical component of the tension. You can use $T_v = T \cos \phi$ to find the vertical component.
4. Compare the value you calculated for T_v with the sum of the downward forces due to the mass of the boom and the load. Note; you should find that T_v is less than the sum of the weight of the boom and load. The difference in these values is the vertical reaction at the pivot.
5. Find the vertical reaction R_v at the pivot by using the relationship: $\Sigma F_{up} = \Sigma F_{down}$. That is $R_v + T_v = W_b + W_l$. What is implied by a negative value for R_v?
6. Find the horizontal reaction R_h at the pivot. You can use the relation $R_h = T_h = T \sin \phi$ to find the horizontal component since the only horizontal force applied to the boom is R_h.
7. Use the values of R_v and R_h that you calculated above to find the reaction R. find also the angle that the reaction force makes with the horizontal. If R_v is negative, then the reaction is angled below the horizontal then you can assign a negative value to γ when recording its value in the table.

8. Enter the values for the remaining boom values in the results table.

9. On the same axis plot R, R_v and R_h against the boom angle on the x-axis. Extrapolate your graphs to boom angles of 0° and 180°.

10. Plot a graph of reaction angle on the y-axis vs boom angle on the x-axis.

11. Based on your measured and calculated results write a general conclusion relating to resolved components and the vector sum of the forces on a system in equilibrium.

12. What happens to the tension in the tie as the boom is raised? Give an explanation for this in terms of moment arm lengths.

13. Select a boom angle and calculate from theory the corresponding reaction. Compare this with the values in your table.

14. List the major sources of error in this experiment. Can you suggest any improvements?

15. From your graphs find the angle of the boom that produces the maximum horizontal reaction. Explain why the maximum will always be at this angle on a boom supported in this way.

16. Why is the horizontal reaction zero at 0° and 180°?

17. From your graph of reaction angle determine the boom angle that produces an horizontal reaction force. How will this angle change if a larger load is placed on the boom? Give an explanation for your answer.

18. At what angle of the boom is the tie longest?
How can this affect the performance of a crane?

19. Suggest a reason why the tension in the tie does not change uniformly with the angle of the boom.

Notes

Further investigations

Use the apparatus to investigate what happens with the point of attachment of the tie is altered on the stand and on the boom.

Experiment 2.5: Cantilevers

Notes

Aim

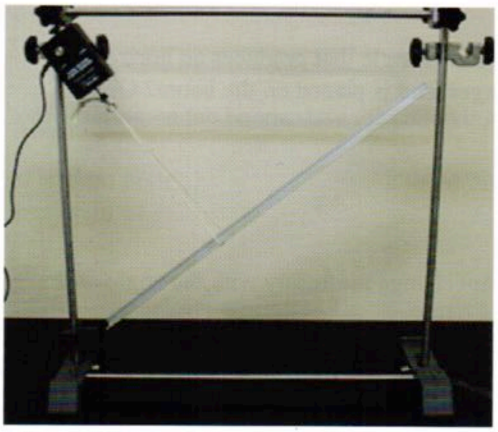
To measure the forces within a cantilever system. Assist in understanding static and rotational equilibrium

Equipment

- data logging software
- force probes (0-50N)
- 40 cm ruler
- 2 retort stands
- large protractor
- sticky tape, string and scissors
- slotted masses (20 g – 100 g)
- scale (0-200 g)

Lab notes

1. Measure the mass of the ruler.
2. Set up the apparatus as shown. For this first system try to keep the string at right angles to the ruler. Ensure that force probes and string are in all aligned and record the angle between the ruler and horizontal.



3. Add a 100 g slotted mass to the end of the 40 cm ruler. Record the tension from the force probe.
4. Progressively move the 100 g mass from the end of ruler to the pivot. Record the tension in the string every 5 cm.
5. Graph force vs position for system 1.
6. Change the positon of the string and force probe. Move the string to possibly 25 cm on the ruler and ensure that force probes and string are in all aligned and record the angle between the ruler and horizontal.
7. Repeat the process of moving the 100 g mass from the end of the ruler to the pivot. Ensure you determine new perpendicular distance for the tension in the string.
8. Graph force vs position for system 2.

Results

System 1

Mass of ruler: ______________

Angle between the ruler and horizontal: ______________

perpendicular (m) for string: ______________ (m)

Cart position (cm)	0	5	10	15	20	25	30	35	40
Force 1									
Force 2									

System 2

Mass of ruler: ______________

Angle between the ruler and horizontal: ______________

perpendicular (m) for string: ______________ (m)

Cart position (cm)	0	5	10	15	20	25	30	35	40
Force 1									
Force 2									

Notes

Post-lab discussion

1. How do you know that the system is in rotational equilibrium?
2. Prove that the system is in rotational equilibrium with a sum of moments calculation for one of your results.
3. What trend or relationship do you observe in the graph of tension vs position?
4. How did changing the orientation of the string in the second system change the graph of tension vs position?
5. Determine the reaction force provided by the pivot for 2 different positions.
6. What errors are present in the system?

Investigation 2.6: Cranes

Notes

Background

Construction sites often feature cranes such as the one illustrated below. They are used to lift heavy loads into place.

The task

What stops the crane from tipping over when a heavy load is attached to the boom?

What is the purpose of the short boom on the right of the crane, behind the operator's station?

How does the crane operator compensate for the moment created by a load as it moves toward the end of the long boom on the left?

Cranes like this one can be made taller by adding more modules underneath the operator's station. What additional problems must be overcome as the crane gets taller? How are these problems solved?

Problem Set 2: Moments and equilibrium

Notes

1. What is the difference between m N and mN?

2. Mario, a construction worker, is using a large wrench to tighten bolts joining two steel girders. He holds the wrench at a point that is 750 mm from the bolt and applies an average force perpendicular to the wrench of 160 N. Find the torque he applies to the bolt.

3. Louise uses a torque wrench to tighten the cylinder head bolts on her car. A torque wrench has a dial that allows you to preset the torque you want, then gives you a warning sound when you reach this set torque. Louise sets her wrench to warn her when she exceeds 88.0 N m. If the handle of the wrench is 400 mm long how much force does she need to apply to the handle before she hears the warning?

Question 3

4. Explain why buses and trucks usually have much larger diameter steering wheels than normal passenger cars have, while racing cars usually have smaller diameter steering wheels than normal passenger cars have.

5. While hiking through the bush carrying a heavy backpack, Michael finds himself leaning forward as he walks. Why does he do so?

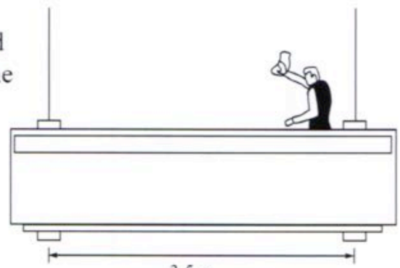
6. While playing in the park with his two children a father sits on the see-saw at a point 1.60 m from pivot point. Amanda tries to balance him by sitting at the opposite end, which is 2.50 m from the pivot.
   (a) Amanda has a mass of 24.0 kg and father's mass is 60.0 kg. Show that they cannot achieve a balance.
   (b) Ben balances the see-saw by sitting 0.5 m front of Amanda. Estimate Ben's mass.

7. When Jackie replaced the standard tyres on her sports car with a set of low profile tyres, the car seemed more powerful and was able to achieve greater acceleration. Explain how this was possible. (Low profile tyres reduce the overall diameter of a wheel.)

8. A plumber carries a long 36 kg pipe on his shoulder finds that he must pull down on the pipe with his outstretched hand 450 mm in front of his shoulder to keep the pipe balanced. He discovered later that the centre of mass of the pipe was actually 120 mm behind him. Calculate:
   (a) the downward force that his hand has to exert while he carries the pipe in this way; and
   (b) the upward force that his shoulder has to exert while he carries the pipe in this way.

9. A uniform wooden bench type seat has a mass of 25.0 kg and a length of 1.90 m. The legs of the bench are 400 mm from each end. A person sits on the end of the bench, their weight acting at a point 100 mm from the end of the bench. What is the maximum mass of a person who can on the bench in this way without causing it to tip up?

10. John works on tall buildings as a window cleaner and stands on a horizontal platform suspended at its ends vertical cables P and Q. The 3.50 m long platform has mass spread uniformly along its length and weighs 280 N. On a particular occasion the tensions in the cables P and Q are 320 N and 590 N respectively.
    (a) Determine John's weight.
    (b) How far he is standing from the centre of the platform?



Question 10

Problem Set 2: Moments and equilibrium

11.`The front wheels of Janet's car support 8000 N of its weight, while the rear wheels support the remaining 7000 N. She wanted to find out how far the centre of gravity was from the front wheels, so she measured wheelbase (distance between the front and rear wheels) of her car and found it was 3.20 m. How far was her car's centre of gravity from its front wheels?

12. Ralph is building a bridge. He needs to lift a long, non-uniform tree trunk weighing 48.0 kN into a horizontal position onto two supports, using a crane with a maximum lifting capacity of 30.0 kN. If the crane operates at maximum load when it lifts the first end into position, find:
(a) the lifting force the second operation at the other would need,
(b) the distance to the centre of mass of the log from its heavier end.

13. Engineers design racing cars with a low centre of mass and widely spaced wheels to improve their high speed cornering ability. Explain, using moments, the physics on which they base this design.

14. At the end of a long day of painting his two-storey house Keith finds that he can't quite reach a part of the external wall near a balcony. He decides to improvise and use a heavy plank that is about 4.00 m long and has a mass of 37.5 kg.
(a) How far beyond the edge of the balcony will he be able to stand if he arranges the plank so its centre of mass is 750 mm in from the balcony edge? Keith's mass is 73.5 kg.
(b) Describe a simple way Keith could use to increase this distance.

Notes

15. A bridge has a weight of 3.15×10^5 N and two piers, 29.7 m apart, support it. The bridge's mass is uniformly distributed along its length. When a truck weighing 5.30×10^4 N is 10.7 m from the far end of the bridge and a car weighing 1.25×10^4 N follows 11.4 m behind it, find the weight supported by each pier.

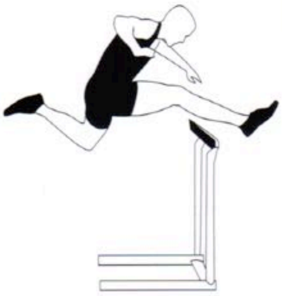
16. In a science experiment several students tried to touch their toes while they stood with their backs to the wall. They found that this was not possible if their heels were touching the base of the wall and they kept their legs straight. Explain why none of the students could perform this apparently easy task.

Question 17

17. By inverting your body to a handstand position your centre of mass moves much closer to the ground. A lower centre of mass should give you more stability. Why is it therefore more difficult to remain in a handstand position than to stand upright as normal?

18. Explain why you can not avoid swaying from side to side when you try to walk along a straight line with your arms folded.

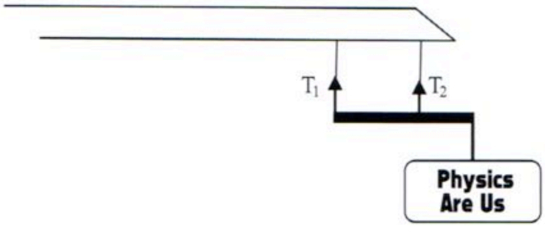
19. Good hurdlers have a distinctive action as they clear each hurdle in a race. You may have noticed that they lean their upper bodies well forward close to horizontal as they stride over each hurdle. Can you suggest why this action improves an athlete's performance in this event?



Question 19

Notes

20. A uniform sign hangs from a beam outside a shop as shown in the diagram below. The beam has a mass of 30.0 kg, is 3.00 metres long and is suspended from the eaves of the shop by two identical wires, that are under tensions T_1 and T_2 respectively.

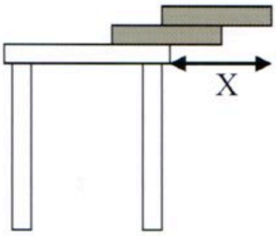


$T_1 = 110.0$ N

$T_2 = 260.0$ N

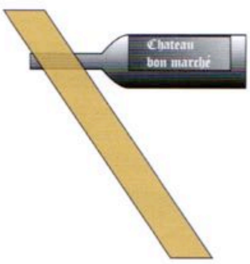
Calculate the mass of the sign and the distance along the beam where the second supporting wire is attached.

21. Two identical wooden planks, each of length 80.0 cm are positioned so that they hang over the end of a table as shown below.



What is the maximum possible distance, x such that the planks do not topple over?

22. Below is a diagram of a novelty one-bottle wine rack. It consists of a flat piece of wood 80.0 mm wide, 15.0 mm thick, and 200 mm long. An angled hole at one end fits the neck of a bottle. The rack, when holding a bottle, is quite stable if you stand it on a flat table as shown. Explain the critical factor in its design. Would one design suit all bottles?

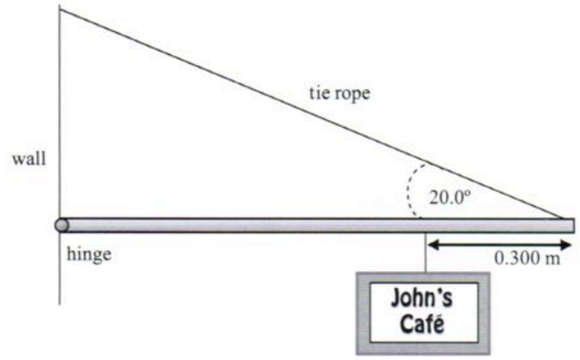


23. A door, 2.40 m high and 0.900 m wide, weighs 206 N. Its centre of mass is located at its geometric centre. Hinges attached 0.300 m from its top and bottom support the door.
   (a) Assuming that the door's weight is supported entirely by the upper hinge, find the magnitude and direction of the force that the lower hinge exerts on the door.
   (b) If instead each hinge supports half the weight of the door, find the magnitude and direction of the force that each hinge exerts on the door.

Problem Set 2: Moments and equilibrium

Notes

24. A shop sign has mass 45.0 kg and hangs from a uniform 12.0 kg beam as shown. The beam is 1.60 m long.



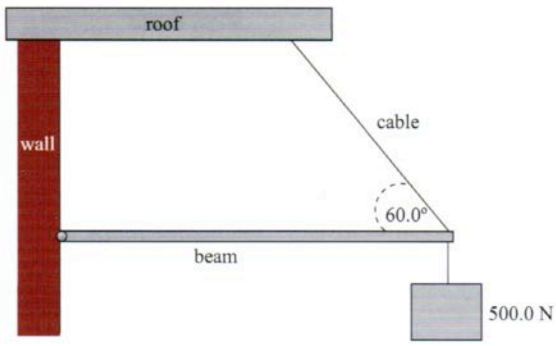
Determine

(a) the tension in the tie rope

(b) the vertical and horizontal components of the force acting on the beam at the hinge

(c) the magnitude and direction of the force acting on the beam at the hinge.

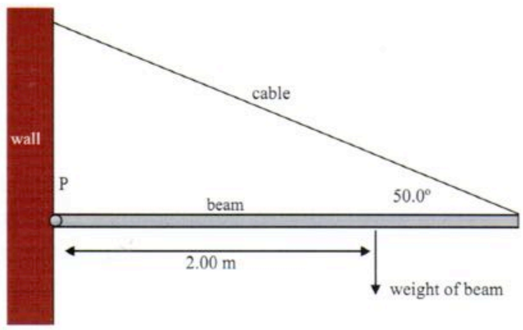
25.



The diagram shows a uniform beam, 1.40 m long and of mass 35.0 kg, that is hinged at the wall. A 500 N mass hangs from the unhinged end. This end is supported by a cable attached to the roof above.

Calculate the tension in this cable, and hence the size and direction of the force that the hinge exerts on the beam.

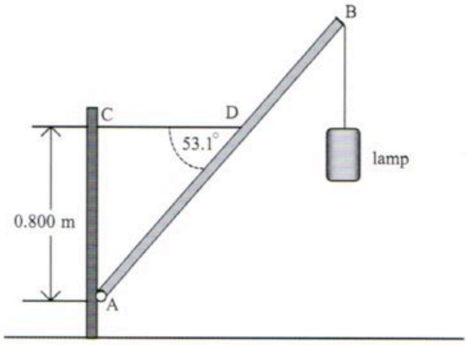
26. A non-uniform beam of mass 50.0 kg has its centre of mass located 2.00 metres from the pivot point P. The beam is supported by a cable connected 2.40 metres from P as in the diagram bel A man of mass 75.0 kg stands at P, then begins to walk out on the beam.



If the breaking strain of the cable is 1.36×10^3 N, how far out can he walk before the rope breaks?

Notes

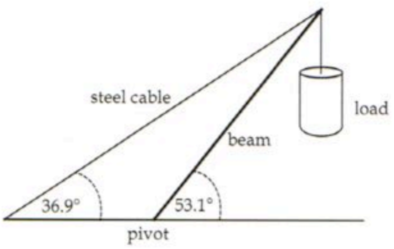
27. A lamp hangs from the structure shown in the diagram below.



The uniform support AB is 1.70 m long and has mass 5.00 kg; the lamp's mass is 10.0 kg. Find

(a) the tension in the light horizontal cable CD,
(b) the horizontal and vertical components of the forces that the pivot A exerts on the pole AB, and hence
(c) the magnitude and direction of the force exerted by the pivot A on the pole.

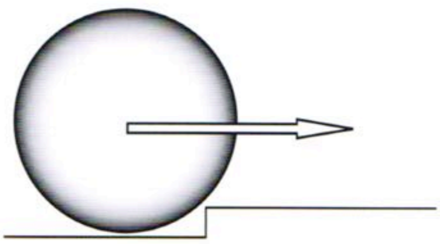
28. A simple crane is made from a 2.00 tonne beam that is pivoted at the ground. Its centre of mass is one third of its length from the bottom. The beam is supported by a steel cable, and the crane has a 5.00 tonne load attached, as shown below:



Determine

(a) the tension in the steel cable
(b) the magnitude of the reaction force exerted on the beam by the ground.

29. In order to roll a metal wheel of radius 50.0 cm up over a kerb 0.200 m high, Max has to pull horizontally at the axle with a force of 240 N.



Calculate

(a) the mass of the wheel
(b) the size and direction of the minimum force which, applied at the axle, could roll the wheel up over the same kerb.

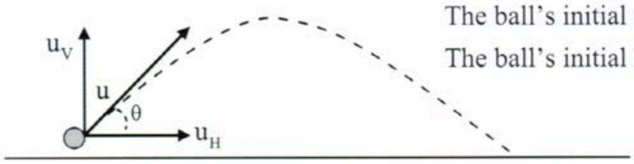
Projectile motion explained

Notes

Remember the following important principles

A projectile, such as a cannon ball, a javelin, or a body rolled off the edge of a cliff has a complex motion that carries the projectile in both the vertical and the horizontal directions.

We must separate the projectile's motion into horizontal and vertical components before we can analyse it. Consider a soccer ball kicked with a velocity u (m s^{-1}) at an angle θ to the ground as shown. To work out how far it will travel and how high it rises, we first have to resolve the initial velocity into its horizontal and vertical components.



The ball's initial vertical velocity, $u_v = u \sin \theta$
The ball's initial horizontal velocity, $u_H = u \cos \theta$

Applying the rectilinear equations of motion ($v = u + gt$, $v^2 = u^2 + 2gs$ and $s = ut + \frac{1}{2}gt^2$) to the vertical component of the ball leads to expressions for the maximum height reached, s_v (m) and its time of flight, t (s) assuming that air resistance is negligible.

$$s_v = \frac{(u \sin \theta)^2}{2g}$$

$$t = \frac{2u \sin \theta}{g}$$

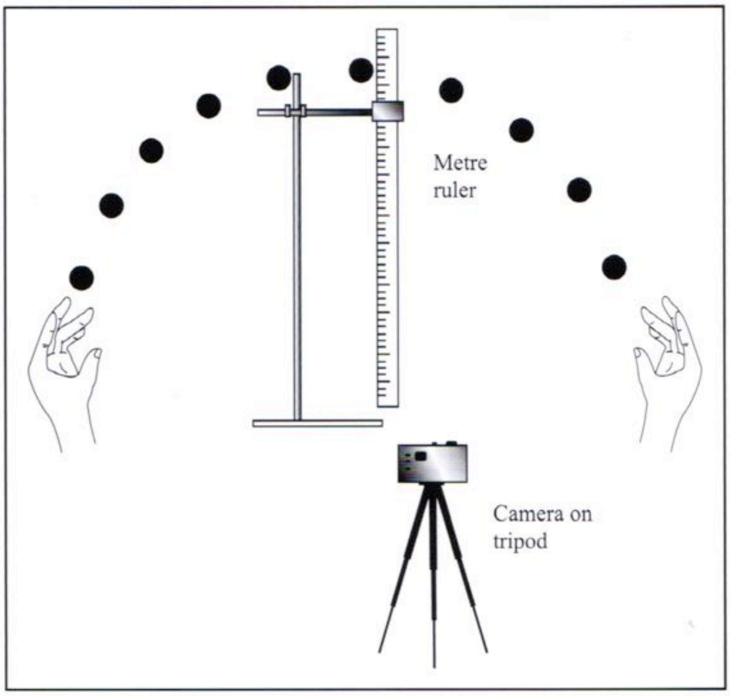
Since there are no horizontal forces acting on the ball, its horizontal velocity component remains constant and an expression for its range, s_h (m) can be determined using:

$$s_h = (u \cos \theta)t$$

Note that the gravitational acceleration term g does not appear in the horizontal motion equation. Note also that the time of flight, t is the same whether we consider the ball's horizontal motion component or its vertical component.

If we take account of air resistance, then the actual values for height, time of flight and range will all be less than those previously stated, and the flight path of the projectile will also change, decreasing the horizontal range.

Investigation 3.1: Video analysis of projectile motion



Aim

To study the motion of a projectile.

Equipment

- video analysis software
- webcam or digital camera
- metre ruler
- tennis ball
- basketball

Lab notes

1. Setup a simple projectile system by throwing a tennis ball in an arc upwards. Practise throwing the tennis ball so that it reaches a maximum height of approximately 2 m and that it lands around 3 m away.
2. Setup the digital movie camera to capture the side view of the throw. This ideally is around 4-5 m perpendicularly away from the plane of motion. You will need a scale within the movie and use either the height of the person throwing the ball or a metre ruler placed within the view.
3. Record a short 3.00 second movie of the ball in motion.
4. Check to see if your data-logging software allows for you to capture a movie using a webcam. If you do not have access to a data logging program then you will need to do a frame by frame conversion of movie to a horizontal time graph and then a vertical time graph.
5. View the horizontal displacement vs time graph. Draw a line of best fit on the graph.
6. View the vertical displacement vs time graph. Draw a line of best fit on the graph or alternatively do a quadratic curve fit for the data.
7. View the horizontal velocity vs time graph. Draw a line of best fit on the graph.
8. View the vertical velocity vs time graph. Draw a line of best fit on the graph.
9. Determine the acceleration due to gravity from the vertical velocity vs time graph.
10. Determine the vertical displacement by determining the area on the vertical velocity vs time graph.
11. Repeat the procedure for arrange of different systems:
    (a) Throwing the tennis ball horizontally and allowing the ball to fall downwards. Practise throwing it from a height of 2 m horizontally so that it lands around 5 m away.
    (b) Throwing the basketball on the oval. Practise throwing it so that it lands as far away as possible. Try to maximise the displacement horizontally.
    (c) Throwing the basketball on the oval. Practise throwing it so that it lands as high as possible. Try to maximise the displacement vertically.

Results

Samples of the expected type of graphs are shown in Figures 3.1.1 and 3.1.2. If you do not have this data you may wish to use the sample graphs to assist you in answering the questions.

Notes

Notes

Figure 3.1.1: A displacement vs time graph for System 1

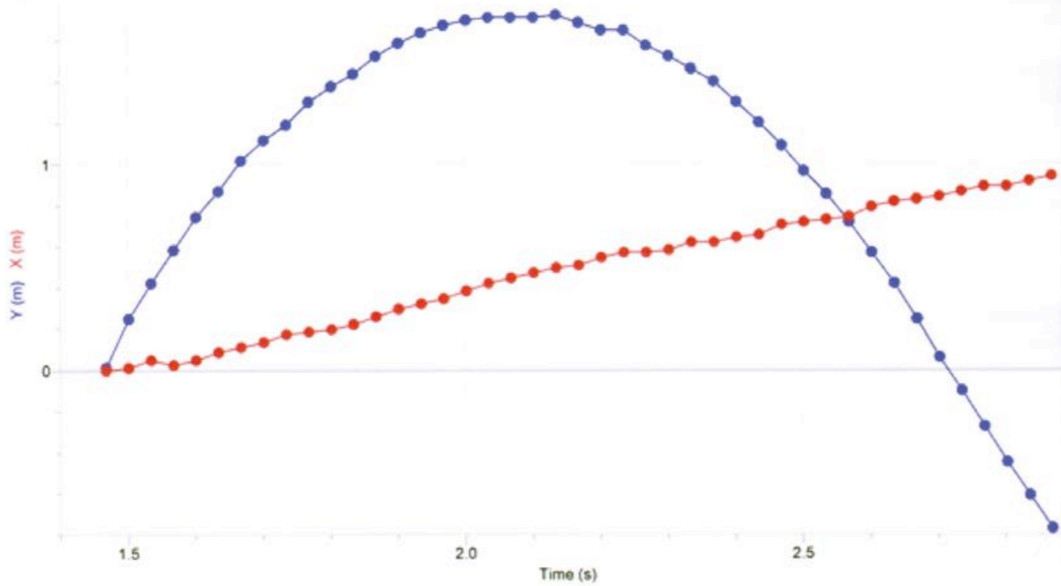
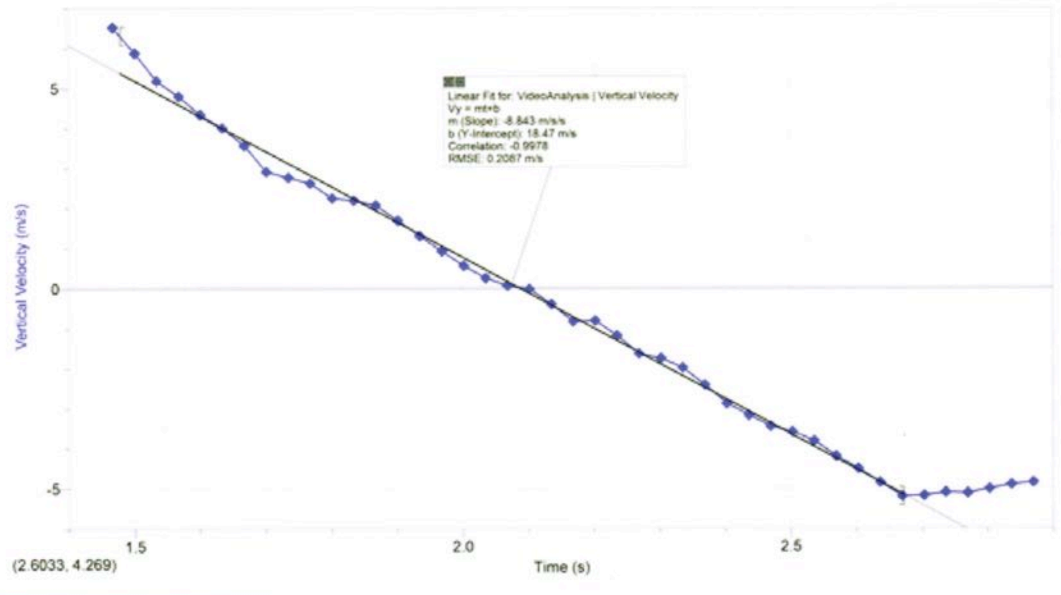


Figure 3.1.2: A vertical velocity vs time graph for System 1



Post lab discussion

1. Did the acceleration due to gravity change for the different systems?
2. What was your displacement vertically and horizontally for all systems?
3. What was your maximum height for all systems?
4. Can you identify the horizontal velocity at maximum height for the systems?
5. Can you determine the final velocity (magnitude and direction) the instant before the ball hits the ground?
6. Can you determine the initial velocity (magnitude and direction) the instant after the ball has been released?
7. What errors are present in the system?

Investigation 3.2: Projectile motion and air resistance

Background

We usually make a number of assumptions before we describe the path of an object projected into the air. These assumptions include that air resistance is negligible, that the acceleration due to gravity is constant, that the Earth's surface is flat and that the Earth does not rotate.

In particular, the shape of the object (strictly speaking, its drag coefficient) and wind or other movement of the air can significantly affect the path of a projectile over relatively short distances.

The task

Repeat the procedures for Experiment 3.1, using first a small, dense projectile such as a ball bearing, and secondly a larger, less dense projectile such as a ping pong ball or a ball made of expanded polystyrene.

Report on the effect that air resistance can have on a projectile. Compare your findings to those of Experiment 3.1.

Notes

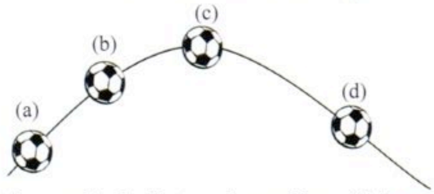
Problem Set 3: Projectile motion and air resistance

Notes

1. If you want to throw a ball as far as is theoretically possible the best angle to throw it is 45° above the horizontal. Explain why this gives the maximum range.

2. A fielder on the boundary of a cricket oval returns the ball to the wicketkeeper. Why does the force of gravity not affect the horizontal velocity of the ball?

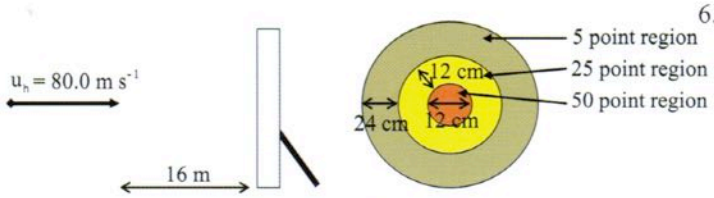
3. The figure below shows the flight path of a soccer ball. It is shown at four positions:
   (a) just after it is kicked,
   (b) as it rises,
   (c) when it is at the top of its path
   (d) and as it falls



   Show with an arrow the resultant force acting on the ball at each position. If there is no resultant force, write 'no force'. You may ignore the effects of air resistance.

4. A high-board diver jumps horizontally away from the diving tower. Draw a diagram to show the path she will take as she dives into the pool. On the diagram draw arrows to show her vertical, horizontal and resultant velocities at the top, middle and near the bottom of her dive.

5. In a shooting competition the target is 1000 m from the competitors. The shooters set the sights on their rifles so they aim a certain distance above the target. Explain why the bullet still manages to hit the target.



side and front views of target

6. An inexperienced archer in a competition aims his bow and arrow at the centre of a target. He stands 16 m from the target. The bow is capable of firing the arrow at 80.0 m s^{-1}.

   Assuming that there is no air resistance, and the archer always fires the arrow at its maximum speed and it leaves his bow horizontally, what score will the archer achieve?

7. A long jumper jumps at an angle of 16.5°. If he launches with a velocity of 7.90 m s^{-1}, how far should he jump?

8. At a fun fair your friend and you decide to try your hand at a 'knock-em-down' game. The target is a stack of empty cans about four metres away at head height. You have four foam rubber balls to use. Your friend tells you to throw the balls as fast as possible. The operator advises you that throwing them more slowly may be better. Explain how each method could successfully knock down the stack of cans.

9. A gymnast dismounts from a beam by leaping into the air doing a somersault and then landing on the floor in a standing position. If she takes off from the beam in a standing position with a velocity that has a vertical component of 4.00 m s^{-1} upwards, how long is it before she lands on the floor? The beam is 1.10 m above the floor.

10. A baseball player pitches the ball at an angle of 10.0° above the horizontal with a speed of 22.5 m s^{-1} towards the batter who is 19.4 m away. If the pitcher throws the ball from a height of 1.50 m from the ground, at what height does the batter hit the ball?

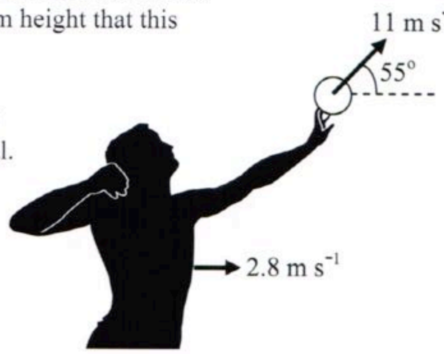
11. Brett kicks a football with an initial velocity of 18.0 m s^{-1} at 35.0° to the horizontal.
   (a) How much time does Peter have to get to a position where he can catch the ball at the same height off the ground as Brett kicks it?
   (b) How far does Peter have to be from Brett to catch the ball in this way?

12. An athlete can throw a javelin with a maximum velocity of 28 m s^{-1}. If she uses angles of projection between 25° and 40° above horizontal, estimate the longest throw that she can achieve.

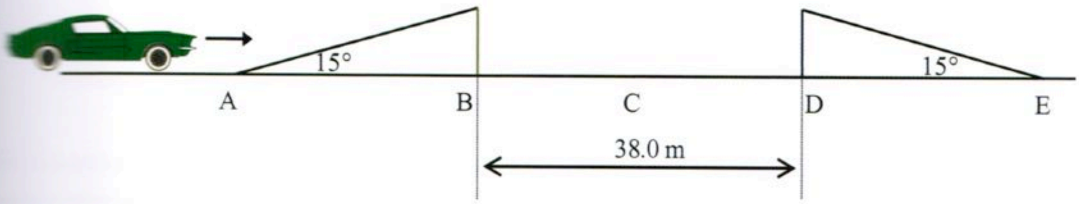
13. A springboard diver leaves the board 3.00 m above the water with a velocity of 2.30 m s^{-1} at an angle of 110° to the board. At what horizontal distance from the end of the board will the diver enter the water?

14. Helicopters are often used to drop water onto small bush fires. A helicopter approaching a bush fire horizontally at a speed of 21.0 m s^{-1} must release the water no closer than 160 m from the fire and then turn quickly away to avoid flying over the fire. What is the minimum height that this helicopter can fly to ensure that the water reaches the fire?

15. The shot-putter shown in the diagram throws his shot forward with a velocity of 11.0 m s^{-1} with respect to his hand, in a direction 55.0° above the horizontal. At the same time, the shot-putter's body is moving forwards horizontally, with a velocity of 2.80 m s^{-1}. At the moment of release, the shot is 2.40 m above the ground.
   (a) Calculate the vertical and horizontal velocity of the shot putt at the moment it is released.
   (b) Calculate the shot putt's maximum height above the ground.
   (c) Calculate the throw (horizontal range) the shot-putter achieves.



16. A stunt woman is attempting to jump her car across a pair of ramps that are 38.0 m apart. To successfully complete the jump she must drive her car at a minimum constant speed up the ramp.



   (a) If she leaves the ramp with an initial speed of 108 km h^{-1}, calculate (in m s^{-1}) the vertical and horizontal components of her velocity.
   (b) Will there be a point during the flight of the car where the stunt woman and her car experience zero acceleration? If so where?
   (c) What will be the velocity of the car at its highest point? You must justify your answer.
   (d) At what point A, B, C, D, or E in her journey will she have the greatest speed? Why?
   (e) At what minimum speed must she leave the ramp so as to make it to the other side?

Notes

Problem Set 3: Projectile motion and air resistance

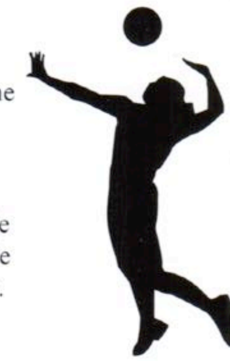
Notes

17. A cricket batsman is hitting the bowlers all over the ground. One shot that he makes just clears the fence on one part of the ground.

(a) Sketch, using a solid line, the path the ball follows if it just clears the fence. Ignore air resistance.
(b) Sketch, using a dotted line, the path the ball follows if it just clears the fence, this time taking air resistance into account. Show the forces acting on the ball at its highest point.
(c) Another shot he hits goes straight back over the bowler's head. The fence is 64.0 m away and 1.40 m high. If he hits the ball with a velocity of 28.0 m s^{-1} at an angle of 35.0° to the ground, will he clear the fence? Assume that he strikes the ball at ground level, and ignore air resistance.

18. An archer fires an arrow horizontally towards a target with a velocity of 83.0 m s^{-1}. He fires the arrow from a position 1.35 m above the ground and it hits the bottom of the target, that is 0.450 m above the ground. Determine the distance between the archer and the target.

19. A basketball player shoots successfully at goal from a horizontal distance of 5.30 m to the centre of the goal-ring. She releases the ball at an angle of 48.0° to the horizontal and 1.20 m below the height of the ring.
Calculate the ball's speed as it left her hands.



20. Marc returns a volleyball from near the floor as he stands on the middle of the baseline. He hits the ball with a velocity of 13.0 m s^{-1} at an angle of 48.0° above the horizontal directly towards his opponents' base line. The court is 18.0 m long and the ceiling in the gymnasium is 6.00 m above the floor.
(a) Show that the ball does not hit the ceiling.
(b) Show that the ball lands in the court if his opponents fail to touch it before it lands.

21. Very fast sprinters are often also very good at long jump. Explain why this might be so.

Chapter 4: Circular motion

Circular motion explained

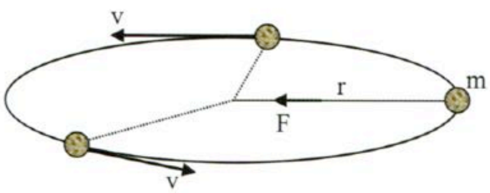
Remember the following important principles

Rectilinear motion describes the path of an object moving in a straight line. We can think of circular motion as the movement of a body in a series of very short, straight lines, that gradually change direction as it progresses.

That is,  is approximately equivalent to 

Suppose an object is travelling at constant velocity. If you then apply a force at right angles to its direction of motion, its direction of motion will change. If this force is constant in magnitude and always at right angles to the object's motion, then the path of the object will be a circle. The deviating force points towards the centre of the object's circular path. The object's acceleration is also directed toward the centre of the circle. The object's velocity at any time has a constant magnitude and its direction is tangential to its circular path.

As an example, consider a mass, m being whirled around a horizontal circle on the end of a length of string. Even though it may be travelling with a constant speed, its **velocity** is changing since the direction in which the mass is moving is constantly changing.



The circular path described by the mass has an effective radius, r equal to the length of the string.

The direction of motion of the mass at any point is given by the tangent to the circular path at that point, as shown. Since its velocity is changing, then the mass must be accelerating, which means that there must be a resultant force, F acting on the mass. In this situation, the force is the tension in the string and, as for any object having circular motion, its direction is 'centre-seeking'. Such forces are called centripetal forces.

A centripetal force has a magnitude given by the mathematical relationship: $F_c = \frac{mv^2}{r}$

Where:

- **F** is the centripetal force (in newtons)
- **m** is the mass in kilograms (kg)
- **v** is the speed in metres per second (m s^{-1})
- **r** is the radius of the circular path in metres (m)

The acceleration is also directed toward the centre of the path.

Newton's second law tells us that the magnitude of the centripetal acceleration, a_c is $a_c = \frac{v^2}{r}$

Other situations where a centripetal force is evident

Situation	What provides the centripetal force
Earth orbiting the Sun	Gravitational force of attraction between the Earth and the Sun
An object on the Earth's surface	Force of gravity on the object (its weight)
Car rounding a bend on a road	Frictional force between the tyres and the road

Notes

Circular motion explained

Notes

To find the speed of an object moving in a circle use:

$$v = \frac{\text{distance travelled}}{\text{time}} = \frac{2\pi r}{T}$$

Where:

T is the period (time taken to complete one revolution) in seconds (s)

The frequency is the number of revolutions an object completes in one second. It is the reciprocal of the period:

$$f = \frac{1}{T}$$

Where:

f is the frequency, in hertz (Hz)

Non-uniform circular motion

If an object moves in a circle that has a vertical plane then you must take the weight force of the object into account.

Consider someone whirling an object in a vertical circle on the end of a string. The speed of the object is not constant because at the top of the loop the object has gravitational potential energy as well as kinetic energy, while at the bottom of the loop its potential energy is converted into extra kinetic energy.

As it travels around the vertical circle, the object has two forces acting on it: the force exerted by the string tension; and the object's weight force, which always acts downward. The centripetal force is always the resultant of these two forces.

At the top of the circle the resultant centripetal force acts downward, and its magnitude is given by:

$$F_c = \frac{m v^2}{r} = F_1 + m g$$

where F_1 is the force supplied at right angles to the motion (e.g. tension in the string) that keeps the object moving in a circular path. In this case, both F_1 and mg act in the same direction, so we can treat both as positive.

In the special case where the object travels across the top of the circle at minimum speed, F_1 is zero and the centripetal force is supplied entirely by the gravitational force mg.

At the bottom of the circle the resultant centripetal force is directed upward and its magnitude is given by:

$$F_c = \frac{m v^2}{r} = F_2 - m g$$

In this case, F_2 and mg acts in opposite directions, so we cannot treat both as positive. Thus if F_2 is taken as positive then mg must be negative.

Experiment 4.1: Going around in circles

Background

An unbalanced force must act on an object if that object is to accelerate.

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

Acceleration is the rate of change of velocity. Change of velocity can be either change of speed, change of direction, or both. Thus, a driver can make a car accelerate by turning it around a corner just as much as by pushing harder on the accelerator or brake. As it turns it is accelerating. Therefore, a net or unbalanced force is required to make the car go around the corner.

Aim

To study the relationship between some variables for an object moving in a circular path.

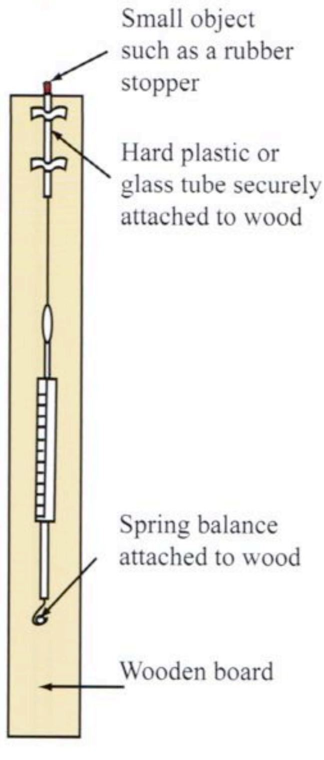
Equipment

- a piece of hollow glass or hard plastic tubing - (150–250 mm)
- large rubber stopper
- fishing line or strong thin cord (1.5 m)
- metre rule
- stop watch
- sticking tape or alligator clip
- spring balance or set of 20 g or 50 g masses

Pre-lab

- Using the equipment shown in the diagram you can investigate the effect on the centripetal force of changes you make to the radius of the circular path, the mass of the object or its speed.
- Note that you can carry out both qualitative (observation-based) and quantitative (measurement-based) investigations using this equipment.
- The glass tubing should be prepared by fire polishing the ends and then wrapping it in cellulose or plastic tape to help prevent it from cutting the line, or cracking and shattering.
- 20 or 50 g masses or large, identical washers and a paper clip can be used instead of a spring balance.
- Be careful. This experiment requires a good deal of space and so should be done outside. It is also advisable to practise whirling the stopper around so that you can control it when you are trying to record your results. Make sure the stopper is securely tied to the fishing line or cord.

Notes



Equipment for Experiment 4.1

Experiment 4.1: Going around in circles

Notes

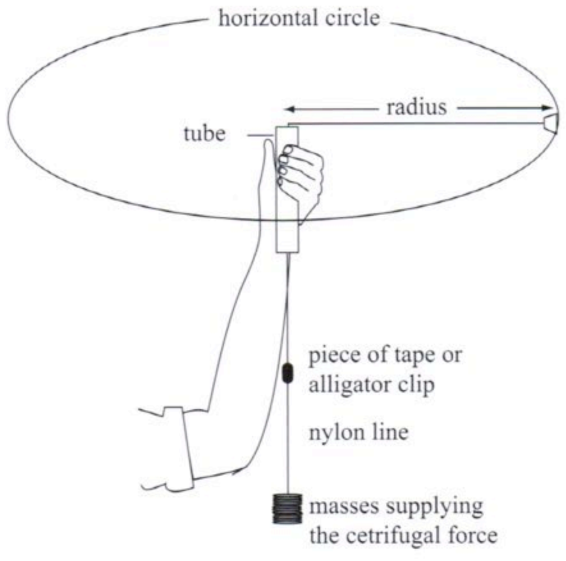
Lab notes

Part A: Variable force with constant radius

- Prepare a data table similar to the one below.

Mass providing centripetal force (kg)	Centripetal force (N)	Time for 20 turns		Average time per turn (s)	Velocity v ($m\ s^{-1}$)	Velocity^2 v^2 ($m^2\ s^{-2}$)
		Trial 1 (s)	Trial 2 (s)			
0.200						

- Measure the mass of the rubber stopper accurately, and record the value.
- If you are using washers and a paper clip instead of slotted masses, measure and record the masses of these as well.
- Use an alligator clip or tape to mark the fishing line below the glass tubing so that you can measure the radius of circle of the revolving rubber stopper. The mark will help you to keep the radius constant.
- Attach a 200 g mass or an appropriate number of washers to the end of the fishing line. *This weight force will provide the centripetal force.*
- Whirl the stopper around so that it is revolving in a horizontal circle of radius 600 mm. You can do this by whirling the stopper with increasing speed until the alligator clip or tape is level with, but not touching, the bottom of the glass tubing.
- Record the time for 20 revolutions in the data table. Repeat to obtain several more results.
- Repeat the experiment with masses of 250 g, 300 g, 400 g and 450 g in the place of the 200 g mass. For each of these, keep the radius of the circular path constant at 600 mm.



Part B: Variable radius with constant force

- Prepare a data table similar to the one below.

Radius (m)	Time for 20 turns		Average time per turn (s)	Velocity v (m s^{-1})	Velocity^2 v^2 (m^2 s^{-2})
	Trial 1 (s)	Trial 2 (s)			
0.20					

- Use the same rubber stopper as in Part A and place a mass of 250 g on the end of the fishing line. You will use this throughout this Part.
- Reset the alligator clip or tape so the radius is 200 mm.
- Whirl the stopper at the speed required for it to revolve at a radius of 200 mm. Record the time for 20 revolutions. Repeat to obtain two sets of data.
- By increasing the speed of revolution, measure the time for 20 revolutions for radii of 400 mm, 600 mm, 800 mm, 1000 mm and 1200 mm. Repeat these measurements to obtain two readings for each radius. In each of these keep the 250 g mass on the end of the fishing line. For each trial, you should reset the alligator clip or tape.

Processing of results

For each set of results calculate the quantities listed in the tables, using $v = \dfrac{2\pi r}{T}$

- For the constant radius set of data, plot
  a) centripetal force vs velocity, and
  b) centripetal force vs velocity squared.

- For the constant force set of data, plot
  a) radius vs velocity, and
  b) radius vs velocity squared.

Post-lab discussion

1. Using the mass of the rubber stopper and any line of data from one of your results tables check the equation for centripetal force,

$$F_c = \frac{mv^2}{r}$$

2. Determine the slope of the graph of centripetal force vs velocity squared. What does this slope represent? Compare it to the value obtained using the mass of the stopper and the radius of revolution.

3. Determine the slope of the graph of radius vs velocity squared. What does this slope represent? Compare it to the value obtained using the mass of the stopper and the centripetal force.

Notes

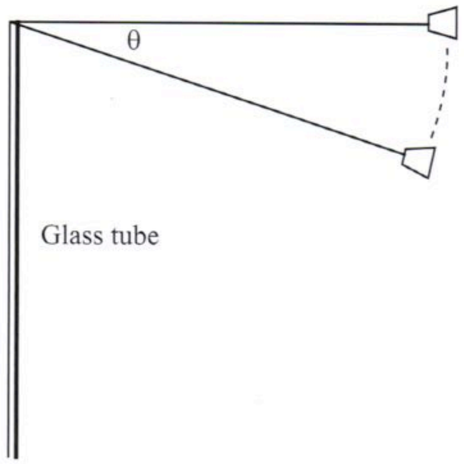
Notes

4. Describe the uncertainties in this experiment. Estimate the percentage uncertainty in the expression:

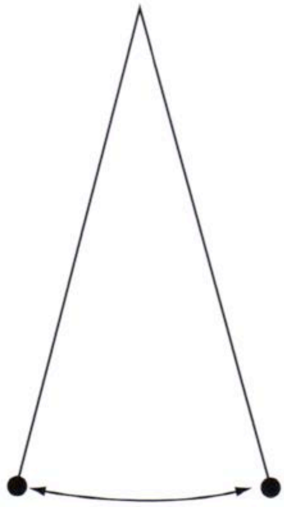
$$\frac{v^2}{r}$$

5. Does the fact that the string holding the stopper is not exactly horizontal affect the relation between F and v? Explain.

6. Determine the relation between F and v in terms of the angle (θ) between the string and the horizontal.



7. The bob of a pendulum swings through a circular arc of constant radius. At what point of the swing does the cord holding the bob exert the greatest centripetal force on the bob? Explain.



Conclusion

State the relationship you have obtained between the variables being investigated in each part of this experiment.

Investigation 4.2: Video analysis of horizontal circular motion

Aim

To graphically analyse horizontal circular motion in a horizontal plane

Equipment

- video analysis software
- webcam or digital camera
- metre ruler and stopwatch
- tennis ball and string
- force probe (0-10N)
- scale to measure mass (0-200g)

Lab notes

1. Setup a simple horizontal circular motion system using the tennis ball. Ensure the string is firmly attached to the tennis ball.
2. Aim to use a string length of approximately 50 cm. Practise moving the ball in a horizontal plane. Alternatively use a horizontal CM kit but just ensure that the small spheres are visible in the camera.
3. Setup the digital movie camera to capture the side view of the plane of motion. This ideally is around 2–3 m perpendicularly away in the same horizontal plane of motion. You will need a scale within the movie and use either the metre ruler placed within the view or the length of the string.
4. Record a short three second movie of the ball in constant motion.
5. View the horizontal displacement vs time graph. Determine the radius of rotation and the period from the graph.
6. View the horizontal velocity vs time graph.
7. Repeat the procedure for two different systems such as one that uses a different mass and length.
8. If you have a force probe incorporate and measure the tension vs time graph for the tennis ball as it moves through a rotation.

Results

System	Period (s)	Radius (m)	Mass (kg)	Angle	Velocity (ms^{-1})	Centripetal acceleration (ms^{-2})	Centripetal force (N)	Tension in string (normal force)
1								
2								
3								

Notes

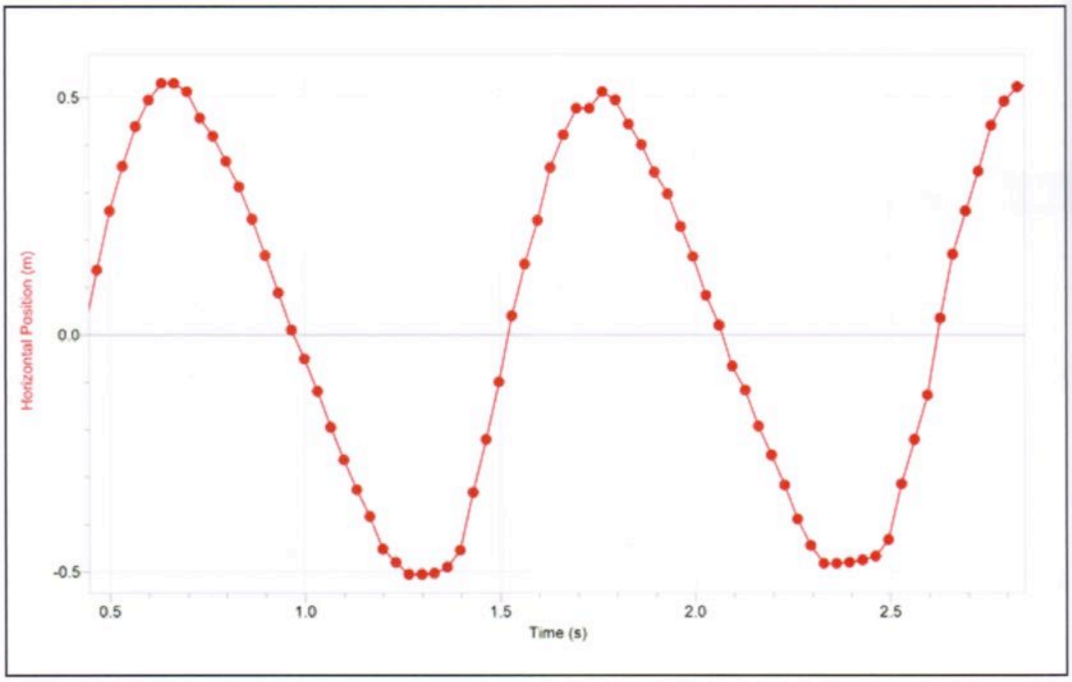
Investigation 4.2: Video analysis of horizontal circular motion

Notes

Post lab discussion

A sample of the expected type of graph is shown in Figure 4.2.1. If you do not have this data you may wish to use the sample graphs to assist you in answering the questions.

Figure 4.2.1: A horizontal position vs time graph for System 1



1. Draw the free body diagram for the system.
2. Derive $v^2 = rg \tan \theta$
3. Derive a formula for determining the tension in the string.
4. Determine the tension in the string.
5. What was the 'loss' of energy in the system from one rotation to the next? (Hint: kinetic energy)
6. What errors affected your results?

Investigation 4.3: Video analysis of vertical circular motion

Aim

To graphically analyse vertical circular motion in a horizontal and a vertical plane

Equipment

- video analysis software
- webcam or digital camera
- metre ruler and stopwatch
- tennis ball and string or a Hotwheels ™ loop track
- force probe (0-10N)
- scale to measure mass (0-200g)

Lab notes

1. Setup a simple vertical circular motion system using either the tennis ball and string or the Hotwheels ™ loop track. Ensure that the string is firmly attached to the tennis ball.
2. Aim to use a string length of approximately 50 cm. Practise moving the ball in a vertical plane. Ensure that the centre of the swing does not oscillate or move around too much.
3. Setup the digital movie camera to capture the side view of the plane of motion. This ideally is around 2-3 m perpendicularly away from the plane of motion. You will need a scale within the movie and use either the metre ruler placed within the view or the length of the string.
4. Record a short 2.00 second movie of the ball in constant motion.
5. Check to see if your data-logging software allows for you to capture a movie using a webcam. If you do not have access to a data logging program then you will need to do a frame by frame conversion of movie to a horizontal time graph and then a vertical time graph.
6. View the horizontal displacement vs time graph. Determine the radius of rotation from the graph.
7. View the vertical displacement vs time graph. Determine the period of rotation.
8. View the horizontal velocity vs time graph. Identify the points where the tennis ball is at the top and bottom of the loop. Determine the kinetic energy change that the ball experiences from the base to the top of the loop.
9. View the vertical velocity vs time graph. Identify the points where the tennis ball is at the sides of the loop.
10. Repeat the procedure for two different systems such as one that uses a different mass and length.
11. If you have a force probe incorporate and measure the tension vs time graph for the tennis ball as it moves through a rotation. Identify the positions where the force is a maximum and minimum.

Results

System	Centripetal Acceleration	Centripetal Force	Tension in string (normal force)
1			
2			
3			

Post lab discussion

Samples of the expected type of graphs are shown in Figures 4.3.1 and 4.3.2. If you do not have this data you may wish to use the sample graphs to assist you in answering the questions.

Notes

Investigation 4.3: Video analysis of vertical circular motion

Notes

Figure 4.3.1: A horizontal velocity vs time graph for System 1

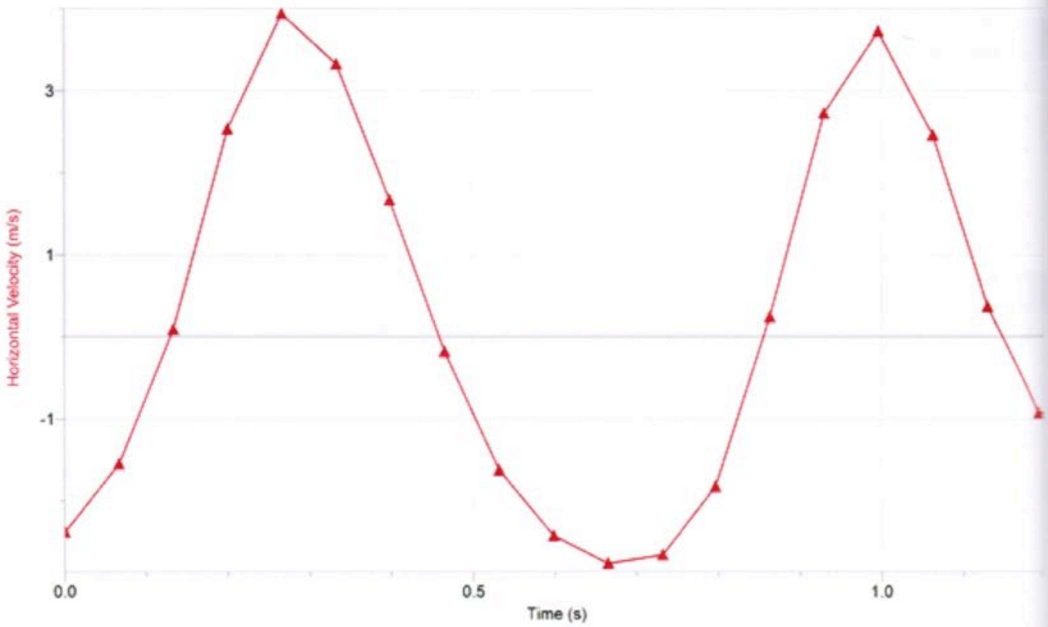
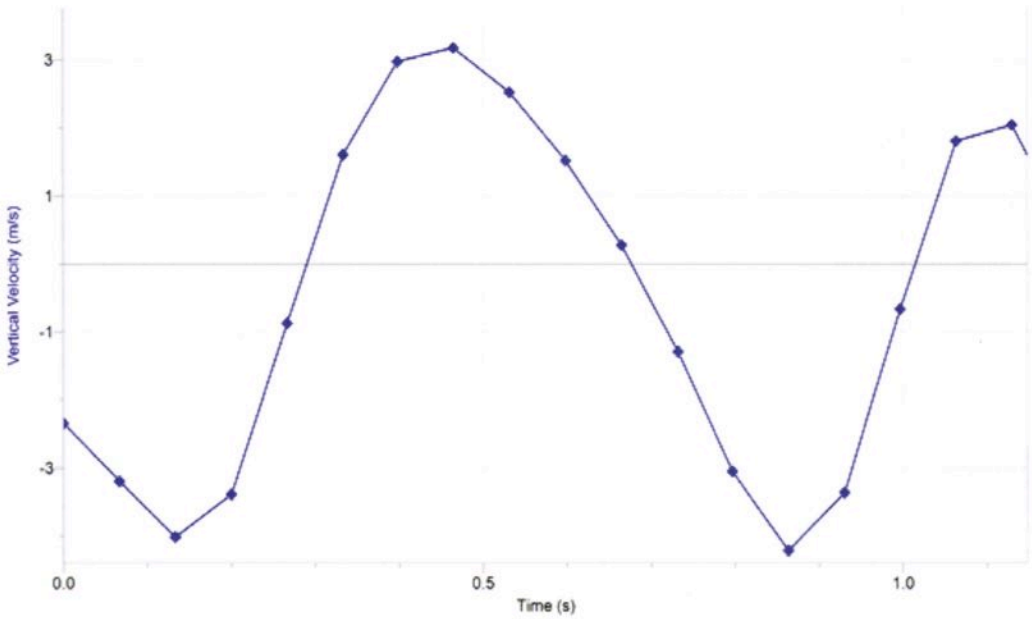


Figure 4.3.2: A vertical velocity vs time graph for System 1



1. Draw the free body diagram for the system.
2. Derive $v^2 = rg\tan\theta$
3. Derive a formula for determining the tension in the string.
4. Determine the tension in the string.
5. What was the 'loss' of energy in the system from one rotation to the next? (Hint: kinetic energy)
6. What errors affected your results?

Investigation 4.4: Centripetal forces

Background

There are a number of everyday situations where centripetal forces producing horizontal circular paths are evident – cars turning a corner, athletes running the bend of a race track, high speed trains turning on banked tracks, aircraft banking, etc.

The task

Use diagrams and appropriate mathematics to explain the origin of the centripetal force in three different situations (i.e. do not do an athlete running around a track and a cyclist negotiating a race track, as these are predominantly the same example).

Notes

Problem Set 4: Circular motion

Notes

1. An Olympic hammer thrower whirls the hammer, which is a round metal ball on the end of a short steel wire, rapidly in a circle in preparation for the throw. If the athlete wants the hammer to travel due west, at what point should the athlete release the hammer? A diagram may help when you explain your answer.

2. Why does a sprinter running in a 200 m event lean towards the centre of the curve he is rounding?

3. A roller skater coasts around a curve at constant speed on a horizontal surface. What provides the centripetal force?

4. Use a diagram to clearly explain why engineers design banked curves on roads that have high speed limits.

5. An ice skater glides around a curve of radius 15.0 m at a constant speed of 3.50 m s^{-1}. What is the skater's acceleration?

6. A baseball player swings a 0.585 kg bat in a horizontal arc so that its centre of mass moves in a curved path of radius 1.25 m at a constant speed of 11.5 m s^{-1}. Determine the magnitude of the force with which the player must grip the bat.

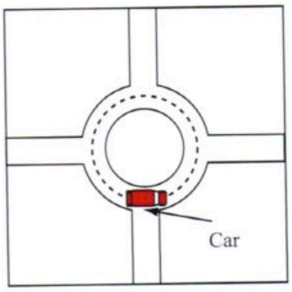
7. A playground roundabout takes 15.5 s to make a complete revolution.
   (a) Calculate the speed of a child sitting on the roundabout 3.80 m from its centre.
   (b) Calculate the centripetal force on the child if her mass is 28.0 kg

8. A civil engineer has to design a road in which there is a curve with a radius of 300 m. The road will have a maximum speed limit of 110 km h^{-1}. At what angle should the road bank on the curve so that no frictional force is needed by a vehicle, travelling at the speed limit, to move round it?

9. Susanna swings on a 4 m long maypole chain with enough speed to swing in a circle of radius 2.5 m.
   (a) Estimate the tension in the chain.
   (b) Estimate her period of revolution.

10. A 1250 kg car follows a circular path around a roundabout of radius 18.0 m at a constant speed of 24.0 km h^{-1}.
    (a) Is the car accelerating? Explain.
    (b) Find the average force provided by the friction between the tyres and the road to maintain this circular path.
    (c) At what angle would the curved road need to be banked for there to be no need to rely on friction to maintain the circular path?

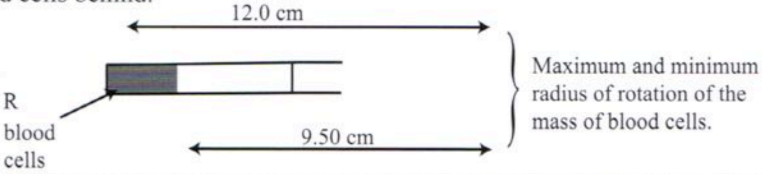
Question 9



Question 10

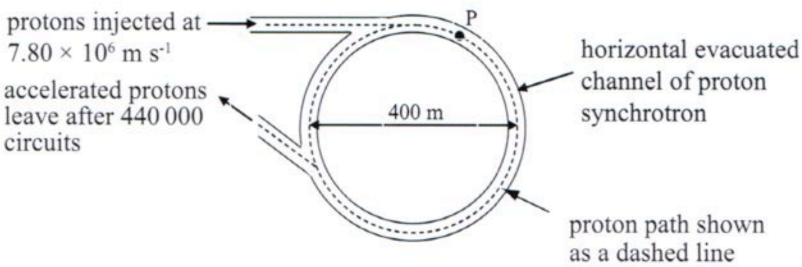
11. The banked track at a velodrome has a radius 70.0 m. Estimate the minimum speed that a cyclist must maintain in order to stay on the track without relying on friction.

12. Red blood cells are separated from plasma using a centrifuge. Little test-tubes of blood are loaded into the centrifuge and then rotated at high speed. The test tubes swing outwards and the red blood cells move into the ends of the test-tubes. The plasma is poured off, leaving the red blood cells behind.

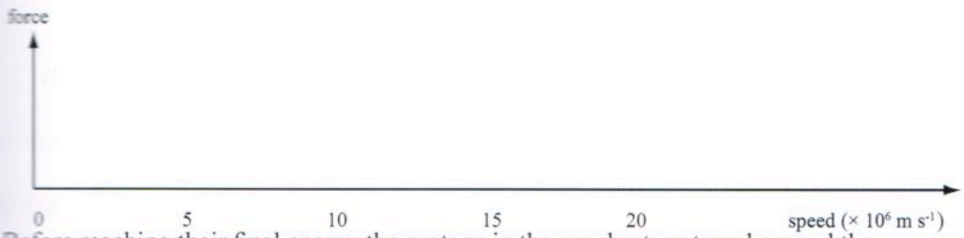


(a) If the centrifuge in the diagram is rotating at 3800 revolutions per minute, determine the minimum speed of the red blood cells in the test tubes.
(b) Calculate the maximum centripetal acceleration of the red blood cells in the test tubes.
(c) A red blood cell has a mass of approximately 98.0 ng. Red blood cells break if subject to a force greater than 8.20 mN. Determine the maximum rotational frequency of this centrifuge if the cells are not to be damaged.

13. The diagram below shows the schematic diagram (as viewed from above) of a proton synchrotron. This is a device for accelerating protons to high speeds in a horizontal circular path.



In the synchrotron the protons of mass 1.70×10^{-27} kg are injected, as shown in the diagram, at a speed of 7.80×10^{6} m s^{-1}. The diameter of the path taken by these protons is 400 m.
(a) Show on the diagram the direction of the force required to make a proton move in the circular path when it is at the position marked P.
(b) Calculate the force that has to be provided to produce this path for this proton.
(c) Sketch, on the grid below, a graph that shows how this force will have to change as the speed of the proton increases over the range indicated on the x-axis. Include an appropriate scale on the force axis.



Before reaching their final energy the protons in the synchrotron travel around the accelerator 440 000 times in 2.50 s.
(d) Calculate the total distance travelled by a proton in the 2.50 s time interval.
(e) What would happen to the vertical displacement of the proton in this time?
(f) Consider your answer to e) above; what must be added to the synchrotron?

Notes

Problem Set 4: Circular motion

Notes

14. A string just supports a hanging brick without breaking. Explain why the string breaks if you set the brick swinging.

15. (a) Estimate the minimum speed required to spin a bucket of water at arm's length in a vertical loop without spilling the water.
    (b) Explain why the water does not fall out if the bucket traverses the top of its path at this or greater speed.
    (c) Does the bucket travel at a constant speed throughout its circular path? Explain.

16. A pilot flies her aeroplane in a vertical loop of diameter 1.60 km.
    (a) How fast is the aeroplane travelling at the top of the loop if the pilot feels no force from either the seat or the straps?
    The pilot cuts the engine at the top of the loop.
    (b) Ignoring air resistance, what is the speed of the aeroplane as it emerges from the bottom of the loop?

17. An aeroplane flies in a vertical loop of radius 650 m. At the top of the loop, the pilot experiences a downward reaction force, from her the seat, equal to one fifth of her weight. Estimate the aeroplane's speed at this instant.

18. A model car of mass 2.00 kg moves in a vertical circle of radius 5.00 m. If its speed at the lowest point is 20.0 m s^{-1} and at the highest is 10.0 m s^{-1}, calculate
    (a) the force that the track exerts on the car at the lowest point;
    (b) the force that the track exerts on the car at the highest point.

19. You strap into a safety harness and take a roller coaster ride. In one part of the ride, the roller coaster car goes through a vertical loop at a speed of 14.0 m s^{-1}.
    (a) Calculate the radius of the loop of track if you feel "weightless" as you pass through the top of the loop.
    (b) Describe what would happen to you if the car went through the loop faster than 14.0 m s^{-1}. Explain your answer.
    (c) Describe what would happen to you if the car went through the loop slower than 14.0 m s^{-1}. Explain your answer.

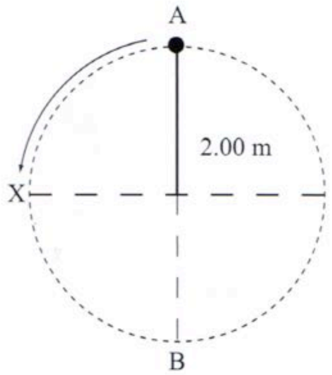
20. As a 40.0 kg gymnast swings in a vertical circle on a high bar, her centre of mass moves around 0.90 m from the bar.
    (a) At the highest point her centre of mass is moving at 1.00 m s^{-1}. Sketch a free body diagram for this situation.
    (b) How fast is she moving when her centre of mass is level with the bar? Sketch a free body diagram for this situation.
    (c) How much force must she exert on the bar in order to hang on as she passes through the lowest point of her swing? Sketch a free body diagram for this situation.

21. Passengers on a fairground ride revolve at a constant speed in a vertical circle of radius 3.60 m. The ride operator has a choice of two speeds, LOW and HIGH. At the HIGH setting, passengers feel weightless at the top of the circle; at the LOW setting, the passengers revolve at half the HIGH speed.

(a) Draw free body diagrams showing the forces acting on a passenger at the top and at the bottom, at each speed setting. (That's four diagrams altogether.)
(b) Calculate the speed at which the ride moves, at the HIGH setting.
(c) Calculate the reaction forces acting on a passenger of mass 60.0 kg at the top and bottom of the circle, when travelling at the HIGH setting.
(d) Calculate the reaction forces acting on a passenger of mass 60.0 kg at the top and bottom of the circle, when travelling at the LOW setting.

Notes

22. A stone of mass 2.50 kg is whirled in a vertical circle at the end of a 2.00 m length of string.



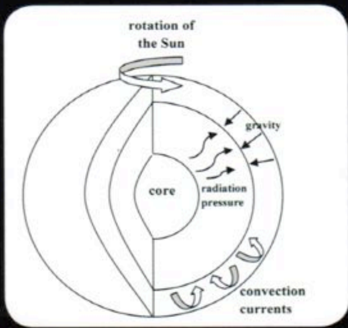
(a) The stone passes through point X at a speed of 10.4 m s^{-1}. Calculate its speed at points A and B.
(b) Calculate the tension in the string at points A and B.
(c) At which point, A, B or X, is the string most likely to break? Explain your answer.

Life cycle of a star

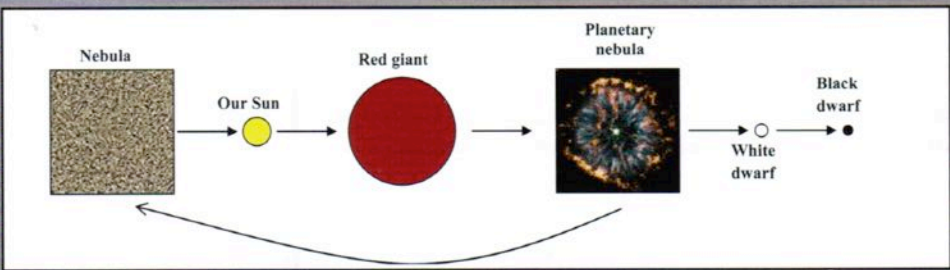
The earliest scientists considered the Earth as not only the centre of our Solar System but the centre of the Universe. Many also believed the Earth to be flat. Comprehensive study of the stars and a more open minded approach quickly replaced these misconceptions with the idea of a heliocentric system.

Mass of sun	1.99×10^{30} kg
Radius	6.96×10^{8} m
Distance from its nearest planet	5.79×10^{10} m (average)
Distance from the Earth	1.50×10^{11} m
Typical temperatures	core ~ millions °C, surface ~ thousands °C
Age	~ 5×10^{9} years

Its place amongst the stars
The Sun is actually a very ordinary and average star, currently about one half way through its life. Fortunately for us it is in a stable stage in which the radiation pressure created from within its core balances the gravitational forces as shown here:



The story of the Sun so far, and its expected future.



Who put the lights out?
Since the Sun is only mid way through its life, it will be some time before it dies and the lights go out! The Earth will probably have been engulfed by the red giant stage before this occurs, suffering the fate of all the inner planets. However, since the gravitational pull of the Sun will have decreased by this time due to its loss in mass, it is more likely that the Earth will acquire a wider orbit.

What about the other stars?
Huge stars (between 1.5 to 3 times the mass of our Sun) will follow a similar cycle, forming a red supergiant, then a supernova (the sudden explosive death of a star accompanied by a luminosity equivalent to that of an entire galaxy) and finally a neutron star. The latter stage occurs because the gravitational forces are so immense that the electrons are pushed into the nuclei of the atoms, so that only neutrons remain. Even bigger giant stars (over 3 times the mass of our Sun) follow a similar path but the ultimate stage is to become a black hole.

The Sun is a ball of gas origina
formed when a mass of d
and gases (known as nebul
compressed and contracted.
The fuel that powers the Sun
hydrogen and nuclei of hydrogen a
constantly being fused to prod
helium and vast amounts of ener
much of which is converted i
heat and light. About four billi
kilograms of hydrogen is be
used up each second and in do
so the central core of the S
will eventually contract, while
outer layers expand and cool. T
result will be a large star with gr
luminosity but a relatively lo
surface temperature – this stage
known as the red giant phase.

Eventually the Sun will expand
much, overcoming the gravitatio
pull created by its decreasing ma
that it will explode and die,
throwing a shell of gaseous ma
into space, once again forming
nebula, surrounding the embers
the Sun's core.

The core of the Sun has by th
time used up its hydrogen fu
and fusion of helium has form
heavier elements such as carbo
The mass is now concentrated in
much smaller volume, hence a ve
dense 'white dwarf' results. As
cools further (since its fuel is go
and nuclear fusion reactions can
longer occur), gravitational for
become so huge that the mass of t
white dwarf contracts even furthe
forming a black dwarf in which a
the particles of the star are so tigh
packed that there is no space betwe
them. The Universe is consider
too young at present for any bla
dwarfs to actually exist.

Life cycle of a star: comprehension questions

Comprehension questions

1. a) What does the word heliocentric mean?
   b) Which is the nearest planet to the Sun?
   c) Why is an average distance provided for this planet in Table 1?
   d) Which, if any, of the values quoted in Table 1 will remain constant in the next:
      (i) billion years?
      (ii) five billion years?

   Explain your answers.

2. a) How long would it take light to travel from the Sun's surface to the Earth's surface?
   b) In view of your answer to part a), is it possible to look back in time?
   c) Calculate the gravitational field strength, g, at the surface of the Sun.
   d) Calculate the speed of rotation of a hydrogen nucleus on the Sun's surface.

3. a) Describe briefly how the Sun produces its energy.
   b) What do you think causes the huge radiation pressure/forces generated from within the Sun's core?
   c) What creates the balancing gravitational forces?

4. a) What is the difference between the nebula that formed our solar system and the planetary nebula that occurs following the death of a star?
   b) Why is the planetary nebula that forms when the Sun dies unlikely to repeat the cycle, as indicated in the diagram opposite?

5. Explain the key difference between the red giant stage of a star and its white dwarf phase.

6. a) Why does the gravitational force increase so intensely following the white dwarf stage of a star?
   b) Estimate the original mass of the Sun at its formation.
   c) Estimate the mass of the Sun when it will become a red giant.

7. a) Why does a neutron star contain only neutrons?
   b) Explain why black holes were given this name.
   c) Draw a life cycle diagram, similar to that shown for the Sun in the diagram opposite, for a giant star.

Gravitation and satellites explained

Notes

Remember the following important principles

A force of attraction exists between any two particles that have mass. The force is directly proportional to the mass of each particle and inversely proportional to the square of the distance between them. Spherical bodies such as the Earth are regarded as point masses, in which the centre of the sphere coincides with the centre of mass of the object.

We call this relationship the Law of Universal Gravitation, and express it mathematically as:

$$F_g = G\frac{M_1 M_2}{d^2}$$

where:

- $\mathbf{F_g}$ is the force of attraction in newtons (N)
- $\mathbf{M_1}$ and $\mathbf{M_2}$ are the masses of the two objects in kilograms (kg)
- **d** is the distance between their centres of mass in metres (m)
- **G** is the Universal Gravitational constant, which has a value of 6.67×10^{-11} N m^2 kg^{-2}

A large object (such as the Earth) creates a gravitational field around itself. You can calculate the gravitational field strength at a point in a gravitational field as follows:

$$g = G\frac{M_1}{d^2}$$

where:

- $\mathbf{M_1}$ is the mass of the large object.

This value 'g' is also the gravitational acceleration experienced by an object at this point.

An object on the Earth's surface experiences weight because the Earth's surface provides a reaction force. This reaction force is normally the same size as the gravitational force pulling down on the object. You can calculate the weight of an object of mass M_x at the Earth's surface using the relationships:

$$F_W = G\frac{M_E M_X}{d^2}$$

where:

- $\mathbf{M_E}$ is the mass in kilograms (kg) of the Earth (object producing the gravitational field)
- **d** is the distance between the centre of mass of the object $\mathbf{M_x}$, and the centre of the Earth .

and

$$F_W = gM_X$$

where:

- **g** is the gravitational field strength, in newtons per kilogram (N kg^{-1}) or acceleration due to gravity, in metres per second squared (m s^{-2})
- $\mathbf{M_x}$ is the mass of the object in the gravitational field

Objects falling freely experience the gravitational force but not the reaction force, so they are said to be weightless.

For a satellite in a stable circular orbit around a star planet, or Moon the centripetal force that causes circular path is the gravitational force of attraction between the star, planet, or Moon, and the satellite. The following relationship states the condition for circular orbit:

$$F = G\frac{M_1 M_s}{r^2} = \frac{M_s v^2}{r}$$

where:

- $\mathbf{M_s}$ is the mass of the satellite, and $\mathbf{M_1}$ is the mass of the astronomical body, both in kg
- **r** is the radius of the orbit in metres
- **v** is the tangential velocity of the satellite, in metres per second (m s^{-1})
- **G** is the universal gravitational constant, of magnitude 6.67×10^{-11} N m^2 kg^{-2}.

Experiment 5.1: Measuring the mass of the Earth

Background

The centripetal force that causes the conical pendulum's bob to go around in a circle is equal to the horizontal component of the tension in the string, and the bob's weight is equal to the vertical component of the tension (see diagram)

From this you can work out that $g = \dfrac{v^2}{r \tan\theta}$

Using the value of g in the relationship $g = G\dfrac{M_E}{r_E^2}$ and knowing the Earth's radius you can calculate the mass of the Earth.

Equipment

- a small mass of between 200 g and 300 g. The mass of pendulum bob must be large compared to mass of string
- string (strong cotton thread or fishing line)
- sheet of A3 paper
- metre rule
- stop watch

Pre-lab

- Draw a circle on the sheet of paper. Make the radius of the circle about 120–150 mm and mark its centre. Measure accurately and record the radius.
- Tie the mass onto the string and mark the string so that the length of the pendulum is between 250 mm and 350 mm. Measure the length accurately and record it.
- Prepare a data table similar to this (right)

Trial	Time for 20 revolutions (s)	Period (s)	Velocity ($m\ s^{-1}$)

Lab notes

- Hold the string at the mark and with your hand over the centre of the circle marked on the paper swing the pendulum so that the mass follows the circumference as closely as possible. Measure the time for 20 complete revolutions.
- Repeat the experiment a total of five or six times.

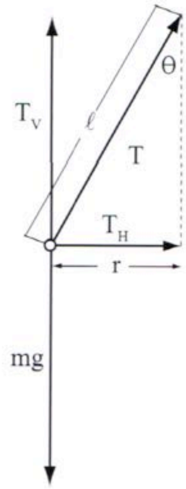
Processing of results

- Complete the data table (use $v = \dfrac{2\pi r}{T}$) and hence find the average speed.
- Using the length of the pendulum and the radius, calculate the angle that the pendulum makes with the vertical.
- Use the relationship in the background above, the average speed, the radius and the angle θ to calculate the acceleration due to gravity, g.
- Use the radius of the Earth (6.38×10^6 m) to calculate the Earth's mass.

Post-lab discussion

1. Find out the generally accepted value for the Earth's mass.
2. Calculate the percentage difference between your value and the accepted value.
3. Comment on the accuracy of your result.
4. Which part of the experiment was the greatest source of errors? Explain.
5. The most accurate values for the Earth's mass have been obtained from measurements made of artificial satellites orbiting the Earth. What measurements would you need to make? Show how the mass of the Earth can be calculated from these measurements.
6. Suggest reasons why the method discussed in question 5 gives such accurate values.

Notes

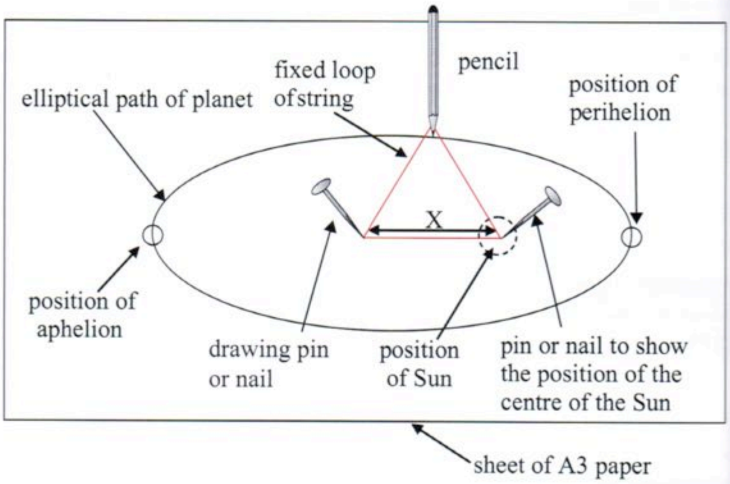


Experiment 5.2: The elliptical path of planets (short time scale)

Notes

Background

This experiment is a method for investigating the elliptical, rather than the circular path of the planets in our Solar System.



Aim

To investigate the elliptical path of planets about the Sun by constructing a two-dimensional scaled drawing.

Equipment

- the equipment illustrated above right
- a metre rule
- thick cardboard or wooden base
- drawing pins or nails, depending on the base to be used
- a hammer
- ball of string (or thread), ideally string that has very little or no elasticity
- a pencil, scissors, a drawing compass or a template for drawing circles
- sheets of A3 paper

Pre-lab

Make sure that the paper is firmly attached to the base.

Decide on the planet whose elliptical path you will depict, and research its perihelion and aphelion. As an example, precise instructions have been provided for you to accurately represent Mercury's orbit. Knowing the radii of the Sun and Mercury will be useful.

Perihelion of Mercury is 4.60×10^{10} m	Aphelion of Mercury is 6.98×10^{10} m
Radius of Mercury is 2.44×10^{6} m	Radius of the Sun is 6.96×10^{8} m

Set up a table suitable for recording the data from your investigation. An example is shown.

Scale for drawing	

Planet	Perihelion, P ($\times 10^{10}$ m)	Aphelion, A ($\times 10^{10}$ m)	P – A ($\times 10^{10}$ m)	separation of pins, X (cm)	2 x A ($\times 10^{10}$ m)	circumference of string loop (cm)

Lab notes

Draw a 2D scaled drawing of the elliptical path for Mercury

- Calculate the distance between the perihelion and aphelion of Mercury.
- Decide on a suitable scale (eg. 2 cm will represent 1.00×10^{10} m) and calculate the actual separation, **X** that the pins or nails will need to be positioned.
- Place the pins or nails into the base.
- Now double the aphelion distance.
- Use the chosen scale to calculate the circumference the loop of string has to be.
- Place the loop of string around the pins and use a pencil to draw in the path of Mercury, keeping the string tight at all times.
- Remove the pins and draw in the Sun and the position of Mercury at both its perihelion and its aphelion, if possible using the same scale as above.
- Repeat the procedure for other planets, beginning with the Earth.

Scale for drawing	**2 cm : 1 × 10^{10} m**

Planet	Perihelion, P (×10^{10} m)	Aphelion, A (×10^{10} m)	P – A (×10^{10} m)	separation of pins, X (cm)	2 × A (×10^{10} m)	circumference of string loop (cm)
Mercury	4.60	6.98	2.38	4.76	13.96	27.92

Post-lab discussion

1. Does your drawing truly represent the path of Mercury about the Sun? What are some possible sources of error that may have occurred during your procedure? How might you address these sources of error in future investigations?
2. Were you able to accurately represent the Sun and the two positions for the planet Mercury on the diagram, keeping to the scale you had chosen?
3. Find out the *average* radius of Mercury's orbit about the Sun. Explain how this average value could have been determined.

Further investigations

Draw the paths of the planets on to transparencies, using the same scale for all the planets (this will need careful consideration and quite large transparent sheets). Then, overlay the transparencies to get an idea of how the planets relate within the Solar System.

What are the limitations of such a two-dimensional model?

A three-dimensional model of the Solar System is called an *orrery* – find out more about such models.

Notes

Investigation 5.3: The elliptical path of planets (long time scale)

Notes

Background

This experiment is a method for investigating the elliptical, rather than the circular path of the Earth about the Sun. However, it will require the whole year to generate meaningful results, during which it will be possible to trace the path of the Sun across the sky.

Aim

To investigate the path of the Earth about the Sun by constructing a two-dimensional drawing.

Equipment

- a large, flat (outside) surface, that is free of shadows and relatively student free throughout the year
- a pole or large stake
- a set of tent pegs
- a spirit level

Pre-lab

Locate a suitable area in or around your school where the experiment can be set up and left so that it will not be interfered with over the course of the year.

Lab notes

- Begin by hammering the pole or stake into the ground, leaving approximately 0.50 m protruding above the ground.
- Use the spirit level to check that it is absolutely vertical – it will have to be left in this exac position for at least a year.
- Every three days (if possible), mark the position of the tip of the shadow (created by the Su of the pole), using one of the tent pegs. It is important to do this at the same time on each o your monitoring days, ignoring daylight saving. Noon is ideal.
- When a year is complete, join the pegs with a length of string.

Post-lab discussion

- What figure or shape did the path of the Earth about the Sun take?
- Why is noon an ideal time to make your observations?
- What are some possible sources of error that may have occurred during your procedure or what problems did you encounter?
- How might you address these sources of error in future investigations?

Further investigations

Investigate the reasons why you obtained the shape you did, explaining why the path of the Eart obtained from this experiment was *not* a simple ellipse.

Problem Set 5: Gravitation and satellites

1. If all objects are attracted to one another by gravity, why are you not attracted towards large buildings?

2. (a) When mountaineers climb Mount Everest to a height of about 8 km, does their weight change? Explain your answer.
   (b) How does the weight of an underground miner change as he descends into a very deep mine? Explain your answer.
   (c) A geophysicist's assistant measures the acceleration due to gravity with a very sensitive accelerometer at various places on the Earth's surface and finds that it is slightly different at each place. What are two possible reasons for this variation?

3. What is the weight of a free falling object? Explain your answer.

4. If air resistance is negligible, all free falling objects near the Earth's surface accelerate at the same rate even though they have different masses. Explain.

5. Black holes form when massive stars at least four times the mass of the Sun collapse into a tiny fraction of their original volume. Why is the gravitational force near a black hole so large that not even light can escape from it, even though its mass is the same as that of the original star?

6. A student measures the acceleration due to gravity at the Earth's surface and finds that it is 10 m s^{-2}. Calculate the mass of the Earth according to the student's result.

7. In an experiment to measure the force of gravity, a physicist suspends two 100 kg lead spheres so that their centres are 622 mm apart. Calculate the force of attraction between the spheres.

8. The gravitational force acting on the space shuttle at sea level is F.
   (a) At what height above the Earth's surface would the gravitational force acting on the shuttle be ½F?
   (b) The shuttle is in orbit around the Earth at a height of 610 km above the Earth's surface. What is the gravitational acceleration the shuttle experiences?
   (c) The Space Shuttle Discovery carried the Hubble Space Telescope to an altitude of 610 km. What orbital speed did the shuttle have to give the telescope to keep it in this orbit?

9. The Earth attracts the Moon with a force of 2.03×10^{20} N. Use this information to calculate how far the Moon is from the Earth.

10. Neptune has a mass 16.6 times that of the Earth and its radius is 3.89 times the Earth's radius. Compare the gravitational field strength at Neptune's surface with that at the Earth's surface.

11. (a) The Moon is in an almost circular orbit around the Earth. Why doesn't the gravitational force of the Earth acting on the Moon change the Moon's speed?
    (b) Calculate the net force on the Moon due to the Earth and the Sun during a solar eclipse. The radius of the Moon's orbit is 3.80×10^{8} m and the radius of the Earth's orbit is 1.49×10^{11} m.

Notes

Useful Data
Mass of Earth:
5.98×10^{24} kg
Mass of Moon:
7.34×10^{22} kg
Mass of Sun:
1.99×10^{30} kg

Radius of Earth:
6.37×10^{6} m
g at sea level:
9.80 m s^{-2}

Problem Set 5: Gravitation and satellites

Notes

12. Which is greater, the period of revolution of a communications satellite at a height in excess of 30 000 km, or that of a satellite that orbits at a height of a few hundred kilometres? Show your reasoning.

13. (a) A research satellite in low Earth orbit move across the Earth's surface at several kilometres per second. If engineers fired retro-rockets on board this satellite and slowed it down very quickly, what would happen to the satellite's orbit?
    (b) Communications satellites are always located above the same spot on the Earth's surface, that is, their speed across the Earth's surface is zero. Why do they remain in orbit?

14. (a) Why do engineers launch rockets carrying satellites in an easterly direction?
    (b) Why do engineers try to locate launch facilities as close to the equator as they can?

15. Scientists aboard an orbiting space station want to return some equipment to Earth in a capsule. What must they do with the capsule to achieve this?

16. Technicians want to move a satellite in a stable circular orbit to a lower orbit. Engineers achieve this by reducing the satellite's speed and therefore reducing its kinetic energy. As it moves to a lower orbit why does its speed increase?

17. Astronauts in orbit in a space station float around unless they are strapped into their seats. Why?

18. Estimate the period of a satellite in low Earth orbit.

19. The moon Europa orbits Jupiter at a radius of 6.71×10^8 m and an orbital period of 3.07×10^5 s.
    (a) Calculate the Europa's orbital speed.
    (b) Calculate Jupiter's mass.

20. Scientists have used data from the motions of satellites to determine accurately Earth's mass. A navigation satellite in a circular orbit 2.02×10^4 km above the surface has a period of 12.0 h. From this information, calculate the Earth's mass.

21. What is the height above the Earth's surface of a communications satellite if it always orbits above a particular spot on the equator?

22. Titan is one of Saturn's moons. It completes one orbit every 14.0 Earth days. Our Moon circles the Earth in 27.3 Earth days. The mass of Saturn is equal to 108 Earth masses. Find the ratio of Titan's orbital radius to that of our Moon.

23. The orbit of Mercury is elliptical. Its perihelion (closest approach to the Sun) is 4.60×10^{10} m and its aphelion, or furthest distance from the Sun, is 6.90×10^{10} m.
    (a) Calculate the force of attraction between the Sun and Mercury at each position.
    (b) What other parameter of Mercury's orbit changes? Calculate this quantity for the maximum and minimum distances from the Sun.
    (c) Explain how this can happen without Mercury losing energy and crashing into the Sun.

Electromagnetism

Develop an understanding of electromagnetism through investigations of electromagnetic phenomena.

Field theories have enabled physicists to explain a vast array of natural phenomena and have contributed to the development of technologies that have changed the world. Explore technologies, such as large-scale power generation and distribution, motors and generators, electric cars, synchrotron science and medical imaging.

Investigate the production of electromagnetic waves and electromagnetic interactions to understand the operation of:

- direct current motors,
- direct current (DC) and alternating current (AC) generators,
- transformers, and
- AC power distribution systems.

Continue to build skills in planning, conducting and interpreting the results of investigations and in evaluating the validity of data.

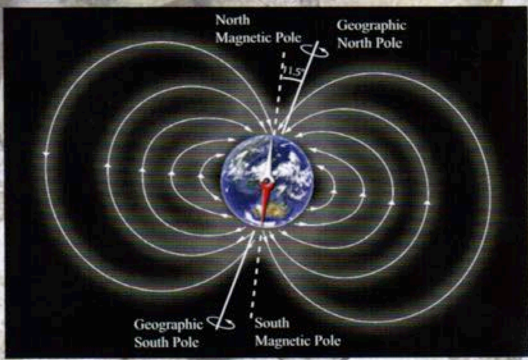
$$\Delta x = \frac{1}{2}(v_0 + v_f)(t)$$

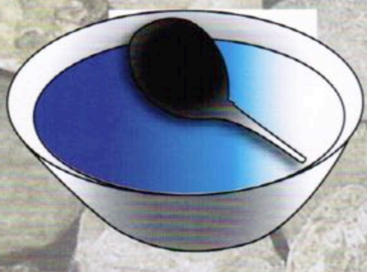
$$\hat{H} = \sum_{n=1}^{N} \frac{\hat{p}_n^2}{2m_n} + V(x_1, x_2, \ldots x_N)$$

$$v_f^2 = v_0^2 + 2a\Delta x$$

From lodestones to superconducting magnets

The Earth is surrounded by a magnetic field whose north and south poles are close to, but not in the same places as, the geographical south and north poles respectively. That is, the Earth's field has its south pole close to the geographic north pole. It has not always been thus. There is a lot of evidence that the Earth's magnetic field reverses at irregular intervals. Scientists believe that the Earth's magnetic field depends on currents within its liquid iron core. What actual mechanism creates the field, why the field is almost (but not quite) aligned with the Earth's axis of spin, and why it should reverse itself every few hundred thousand years, remain topics of active research.

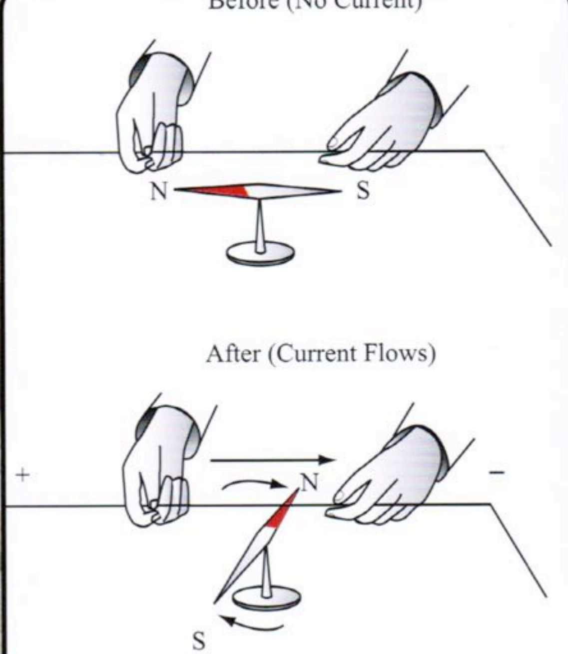




Lodestone used as a compass needle by Chinese navigators hundreds of years ago

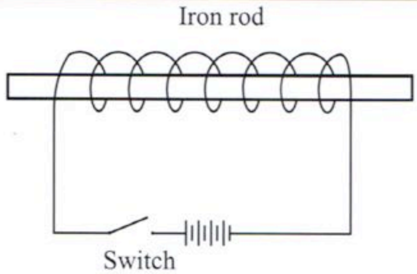
Surprisingly few metal elements (including iron, nickel, cobalt and the rare metals gadolinium and dysprosium) can be strongly magnetised. Naturally-occurring magnetic rocks are mostly pieces of a particular iron oxide called magnetite.

These 'lodestones' are permanently magnetised with magnetic fields comparable to those produced by commercial magnets. Throughout history, people have worked out that a lodestone always points in a particular direction (that is, a suspended lodestone aligns itself on a north-south axis). This property has been very useful for navigation. Until quite recently, the process by which lodestones came to be magnetised was a mystery.



Oersted's demonstration

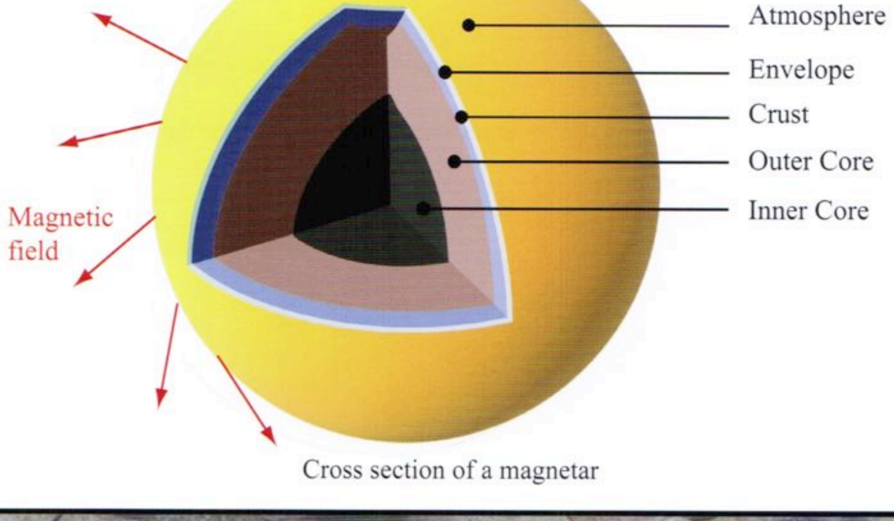
Until the early 1800s, scientists generally accepted that electricity (exemplified by a current in a conducting wire) and magnetism (exemplified by a compass needle) were unrelated. In 1819, Hans Oersted managed to demonstrate that there is a connection after all. Oersted's demonstration was that a compass needle placed above or below a current-carrying wire swung to align itself at right angles to the direction of the current. After this breakthrough, new ideas came quickly. We now know that magnetic fields are created by moving electric charges. In lodestones and magnetic metals, the moving charges are spinning electrons. In electromagnets, the moving charges are the electrons moving through the conducting coils of the device – that is, the electric current.



Electromagnet schematic

We measure the strength of a magnetic field in units called tesla (T). A field measuring one tesla is a very strong magnetic field. For comparison, the Earth's magnetic field strength is roughly 5×10^{-5} T or tesla. A permanent magnet such as a lodestone or a bar magnet is limited to a field strength of about 0.01 T because it has a limited number of spinning electrons. Electromagnets can create magnetic fields of over 1 T, but are themselves limited by the currents they can carry, and especially the heat produced by those currents. To achieve magnetic fields in the region of 10 T requires an electromagnet cooled by liquid helium at the super-low temperature of 2 K (-271 °C). This low temperature allows some materials to become superconductors, with zero resistance to an electric current. At the time of writing, the strongest electromagnets are able to produce fields around 30 T.

Much stronger fields are known to exist in extreme environments, such as the surfaces of some very massive neutron stars. These strange stars are the remains of giant stars that have gone through the supernova stage of their lives. Such 'magnetars' can have magnetic fields with field strengths around 10^{11} T, billions of times stronger than any magnet constructed by humans.



Cross section of a magnetar

From lodestones to superconducting magnets: comprehension questions

Comprehension questions

1. The 'north' end of a compass needle is sometimes called a 'north-seeking pole'. Explain.

2. A magnet, free to swing in the Earth's magnetic field, quickly aligns itself with the field lines. Explain why this alignment happens.

3. Bar magnets have north and south poles but the field around a current-carrying wire has no poles. Explain.

4. Show that the strongest permanent magnets create fields about 200 times as strong as the Earth's magnetic field.

5. How much stronger then the Earth's field is the field produced by the strongest electromagnets?

6. Estimate the force exerted on an electric current of 1 ampere by the magnetic field of:
   a) the Earth
   b) a strong permanent magnet
   c) a strong electromagnet
   d) a magnetar

7. Estimate how much magnetic flux (measured in webers) can be enclosed by a square of side length 10 cm if the magnetic field in question is produced by:
   a) the Earth
   b) a strong permanent magnet
   c) a strong electromagnet
   d) a magnetar

8. Estimate the average voltage that could be induced in a 10 cm square coil of 100 turns that is rotated at 50 times per second in the magnetic field produced by:
   a) the Earth
   b) a strong permanent magnet
   c) a strong electromagnet
   d) a magnetar

9. Why are the voltages estimated in question 8 average rather than peak voltages?

10. Sketch graphs showing the variation of voltage with time for the rotating coils in question 8.

Chapter 6: Magnetic fields

Magnetic fields explained

Remember the following important principles

A straight, current carrying wire will deflect a nearby compass needle. This shows that an electric current produces a magnetic field around the wire.

If you put the straight, current carrying wire between the poles of a horseshoe magnet the wire experiences a force. The direction of the force is at right angles to the magnetic field. The force is due to the interaction between the magnetic field that the current flowing in the wire produces, and the magnet's magnetic field.

The magnitude of the force on a straight current carrying wire placed perpendicular to a magnetic field is directly proportional to:

1. the current I in the wire,
2. the length ℓ of wire in the magnetic field, and
3. the strength of the magnetic field, B

You can determine the force on a current carrying wire in, and perpendicular to, a magnetic field by:

$$F = I\ell B$$

where:

F is the force in newtons
I is the current in amperes
ℓ is the length in metres of the current-carrying wire in the magnetic field
B is the magnetic flux density, in tesla (T)

Magnetic Flux

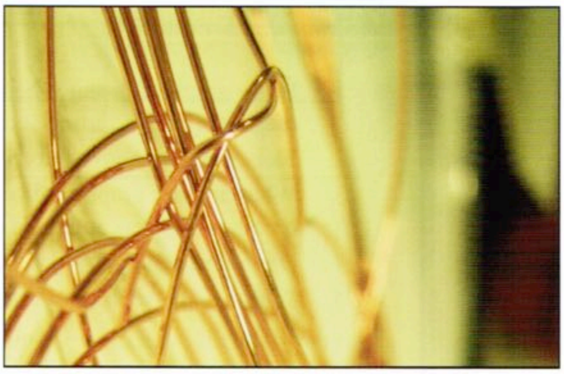
Magnetic flux is the product of the flux density, B, and the area, A, when the flux is at right angles to the area:

$$\phi = BA$$

where:

ϕ is the magnetic flux, in weber (Wb)
B is the magnetic flux in tesla (T) or webers per square metre (Wb m^{-2})
A is the area in m^2

Notes



Experiment 6.1: The force-distance relationship for a bar magnet

Notes

Context

Some books state that the relationship between force and distance for poles of magnets are like electrostatic forces. This would mean that there is an inverse square relationship between the force of attraction or repulsion and the distance. In this exercise you will measure the forces and the distances and explore the relationship between the two variables.

Background

An easy way of measuring force is to place one of the magnets on an electronic balance. After zeroing the balance, any additional force (other than the weight of the magnet) will be recorded by the balance. Multiplying the reading on the balance (in kg) by 9.8 gives the force in newtons. Alternatively, you could use some other force-measuring device. For example, if you have access to data logging equipment, you could use the force meters from that equipment rather than an electronic balance.

Equipment

- magnets
- rulers
- electronic balance or other electronic force meter

Pre-lab

Use tables like the one shown below to record your results:

Distance between the magnets	Reading on the balance	Force due to the second magnet

- Place one magnet upright on the electronic balance or force meter and zero the reading.

Lab notes

- Place another magnet approximately 1m away from the upper pole of the magnet on the balance and take a reading of force (or "weight")
- Repeat this for a number of readings as you bring the second magnet closer to the magnet on the balance.

Post-lab discussion

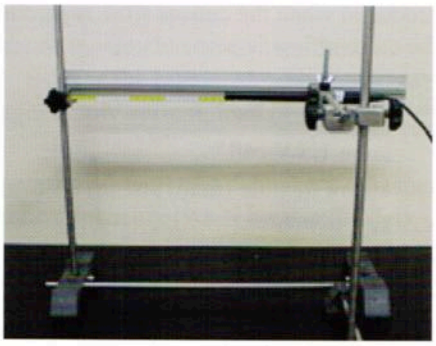
1. Plot a graph of distance between the magnets (on the horizontal axis) and force between the magnets (on the vertical axis).
2. Plot graphs as above but try the inverse square of distance on the horizontal axis.
3. What do your graphs indicate about the relationship between the forces applied by magnets on other magnets and the distances between them?
4. Do your data support or refute the information mentioned in Question 3 from the textbooks?
5. What are the sources of error and uncertainty in this experiment?

Experiment 6.2: Understanding magnetic field and the Inverse Square Law

Aim

To collect magnetic field strength vs distance data. Develop an inverse square relationship and determine gradient linear analysis of B vs r^{-2} graph.

Equipment



- Data Logging Software
- Magnetic Field Probe
- 30 cm Ruler
- 2 Rare Earth Magnet
- Digital Camera if required
- Retort stand

Lab notes

1. Set up the rare earth magnet and 30 cm ruler as shown above.
2. Load the data logging software and ensure that you set up either a manual distance entry with magnetic field or a video capture with magnetic field.
3. Clamp the magnetic field probe in a retort stand. Be careful with the Earth's magnetic field. You may need to re-zero the probe or place the apparatus in a plane where the B from the planet has a minimal effect. This can be done by placing the plane of the ruler and probe in an East/West orientation.
4. Move the magnetic field probe towards the rare earth magnet. Record the magnetic field strength for every 2.00 cm starting from 20.0 cm. Most data logging software will allow you to manually enter the distance as you move the probe.
5. Stop recording when the probe reaches the maximum reading. Most probes will do this when they are 1-2 cm away from the rare earth magnet depending on the strength of the magnet.
6. Draw or view the magnetic field vs distance graph. Do a curve analysis to the graph and ensure you select the inverse square function.
7. Draw a second graph using inverse square distance instead of distance. You may need to insert a calculated column and do a function insert if needed. This can also be manually entered.
8. Determine the gradient from this B vs r^{-2} graph.
9. Repeat the process but add an additional magnet.

Results

Distance from magnet (cm)	20.0	18.0	16.0	14.0	12.0	10.0	8.00	6.00	4.00	2.00
Inverse square distance (cm^{-2})										
System 1 Magnetic field (B)										
System 2 Magnetic field (B)										

Post lab discussion

1. What does the gradient from the magnetic field strength vs r^{-2} graph represent?
2. How did the additional magnet change the shape of the graph?
3. How close is the B vs distance graph to an inverse relationship? (From Curve Fit analysis)
4. What errors are present in the system?
5. How could you improve this process?

Notes

Experiment 6.3: Force on a conductor in a magnetic field

Notes

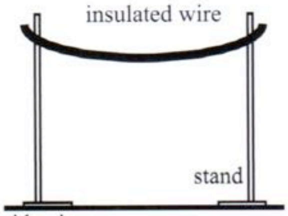


Figure 6.3.1

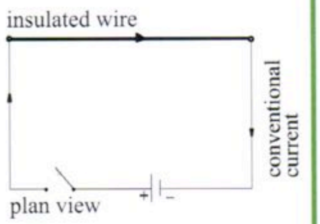


Figure 6.3.2

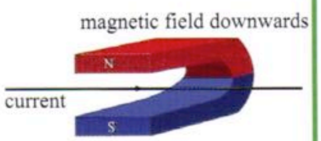


Figure 6.3.3

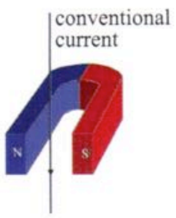


Figure 6.3.4

Background

The passage of a current through a conductor creates a magnetic field. When a current-carrying conductor is placed in a magnetic field, the field may exert a force on the conductor. No force is produced when the current flow is parallel to the magnetic field. Maximum force is produced when the current flow is perpendicular to the magnetic field.

Equipment

- large 1.5 V cell
- 80 cm flexible (multi strand) PVC insulated copper wire
- key switch
- connecting leads
- horse shoe magnet
- retort stands and clamps

Pre-lab

- Support the insulated copper wire between two retort stands as shown in Figure 6.3.1.
- Assemble the circuit shown in Figure 6.3.2.
- Create a table like the one shown below.

Direction of current flow	Direction of magnetic field	Direction of force
left to right	downwards	
left to right	upwards	
right to left	downwards	
right to left	upwards	

- Press the key switch only for short periods.

Lab notes

- Hold the horseshoe magnet so that the PVC wire passes between the poles of the magnet as shown in Figure 6.3.3
- Press the key switch. Remember that conventional current flows from the positive to the negative terminal.
- Complete the table from your observations.

Post-lab discussion

1. Explain why you were instructed to hold the switch down only for a short time period.
2. State the direction of current flow in a circuit, with reference to the terminals of the cell.
3. State the direction of the magnetic field between the arms of the horseshoe magnet.
4. Develop a rule that predicts the direction of the force on the wire in terms of the current and magnetic field directions. Explain the physical principles that make the rule work.
5. Predict and explain which way the wire will move in Figure 6.3.4.

Experiment 6.4: Efficiency of an electric motor

Background

Electric motors are used to do work. They are commonly used to lift weights, for example on cranes or in lifts. The input to the motor is electrical energy and the output is work. In this activity you will investigate the input power and the output power of a motor.
You will use these measurements to calculate the efficiency of the motor and explore the relationship between efficiency and operating conditions. Explore the relationship between efficiency and one other variable such as the supply voltage, supply current, load lifted, etc.

The work done in lifting a mass is its change in potential energy, $\triangle E_P = m\,g\,\triangle h$ where m is the mass (kg) of the weight being lifted, g is the gravitational field intensity (9.8 N kg^{-1}) and $\triangle h$ is the height (m) through which the mass is lifted. The useful power developed by a motor is the rate at which it can alter the potential energy of the mass it is lifting.

Hence $P = \dfrac{mg\triangle h}{\triangle t}$ where $\triangle t$ is the time (s) taken to lift mass m through a height of $\triangle h$.

The input power to the motor is V I where V is the potential difference across the motor (V) and I is the current (A).
The efficiency of the motor is the ratio of output power divided by the input power.
Hence efficiency is given by:

$$\text{efficiency} = \frac{\text{output power}}{\text{input power}} = \frac{\left(\dfrac{mg\triangle h}{\triangle t}\right)}{V\,I}$$

Aim

To determine the efficiency of a small electric motor.

Equipment

You will need at least the following list. Negotiate with your teacher or technician for other items.

- small electric motor with attached pulley
- DC voltmeter (0–5 V) or voltage sensor
- cotton or nylon thread
- masses such as 50g brass slotted masses on a holder
- DC ammeter (0–1 A) or current sensor
- power supply
- timer\

Pre-lab

- Use a set-up similar to the one shown in Figure 6.4.1.
- Keep accurate records of your procedure and measurements. Photographs of your set-up may be useful for your report. Be sure to ***investigate*** rather than simply ***measure***.
- Measure m, $\triangle h$, $\triangle t$, V, and I for the motor running under various conditions. Use these to plot the efficiency of the motor against another variable that you chose to explore.

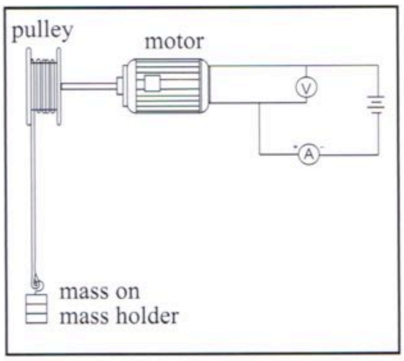


Figure 6.4.1

Post-lab discussion

1. Summarise your findings.
2. Reflect on your experimental technique. What might you have improved? How?
3. Describe any errors that may have affected the validity of your results.
4. Estimate the uncertainty in your measurement of efficiency.
5. Which of the sources of error and uncertainty had the greatest effect on your results? Explain.

Notes

Experiment 6.5: Magnetic field intensity between the poles of a horseshoe magnet

Notes

Background

Horseshoe magnets have a nearly uniform magnetic field in the region between their poles. If you sprinkle iron filings around a horseshoe magnet it will reveal the relative uniformity in that region and that the field is much weaker further from the poles. Horseshoe magnets are used when a relatively uniform permanent field is needed in a small region within a device such as a dynamo.

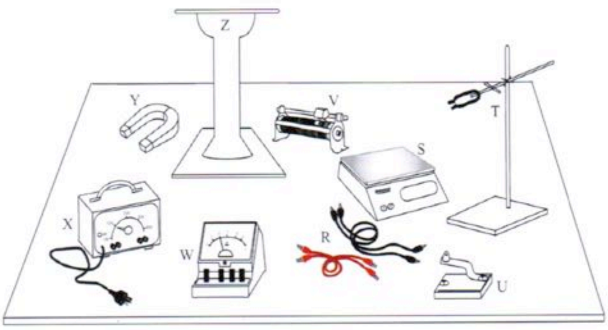
In this exercise you will measure the force on a current in a magnetic field between the poles of a horseshoe magnet in order to determine the intensity of the magnetic field.
The relationship between the relevant variables is the well known: $F = I \ell B$.

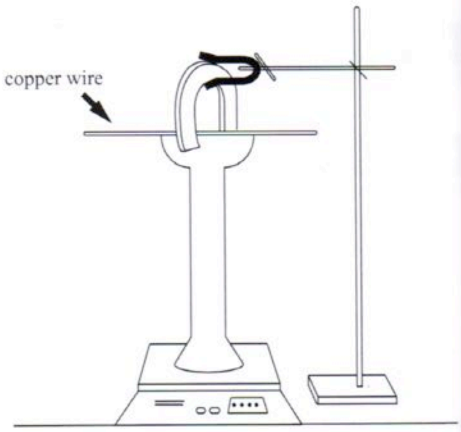
Aim

You will measure the force on a current carrying wire with an electronic balance and vary the current with a rheostat. A graph of force against current will allow you to determine the magnetic field intensity, B, from the gradient of the line of best fit of the graph.

Equipment

R	leads
T	retort stand and clamp
V	rheostat (variable resistor)
X	power supply
Z	light plastic stand with a piece of copper wire glued to the top edge
S	top-loading electronic balance
U	switch
W	ammeter
Y	horseshoe magnet





Pre-lab

- Place the wire and stand on an electronic balance and place the magnet over the wire as shown.
- Place the power supply, ammeter, and rheostat in series with the wire so that a range of known currents can be passed through the wire.
- You will need a table in which to record at least the following:

Current (A)	Balance reading (g)	Force (N)

Lab notes

- Obtain a range of force and current data.

Post-lab discussion

1. Create an appropriate graph and draw a line of best fit to the data points.
2. Explain how you used your measurements to produce a straight-line graph.
3. Determine the slope (gradient) of the graph.
4. Estimate the magnetic field intensity of the field between the poles of the magnet.
5. What are the major sources of uncertainty in this experiment?
6. Estimate the percentage uncertainty in your measurement of field intensity.

Pre-lab

- Place the power supply, ammeter, and rheostat in series with the wire so that a range of known currents can be passed through the wire.
- You will need a table in which to record at least the following:

Current (A)	Balance reading (g)	Force (N)

Lab notes

- Obtain a range of force and current data

Post-lab discussion

1. Create an appropriate graph and draw a line of best fit to the data points.
2. Explain how you used your measurements to produce a straight-line graph.
3. Determine the slope (gradient) of the graph.
4. Estimate the magnetic field intensity of the field between the poles of the magnet.
5. What are the major sources of uncertainty in this experiment?
6. Estimate the percentage uncertainty in your measurement of field intensity.

Notes

Investigation 6.6: Field intensities around magnets

Notes

Background

A magnetic plotting compass consists of a small magnetised needle pivoted in its centre on a sharp point. It can respond to magnetic fields that are too weak to affect iron filings. Compass needles can usually only rotate in the horizontal plane. Thus a compass needle will align itself only with the horizontal component of the magnetic field in its vicinity.

The end of a plotting compass needle that points due north is commonly called a north pole, but its full name is a north seeking pole.

Magnetic field lines have a direction, given by the direction of the force that the field exerts on the north pole of another magnet placed in that field. Magnetic field lines also indicate field strength: the lines are closer together in regions where the field is stronger. A null point is a spot where two or more magnetic fields cancel each other out.

Aim

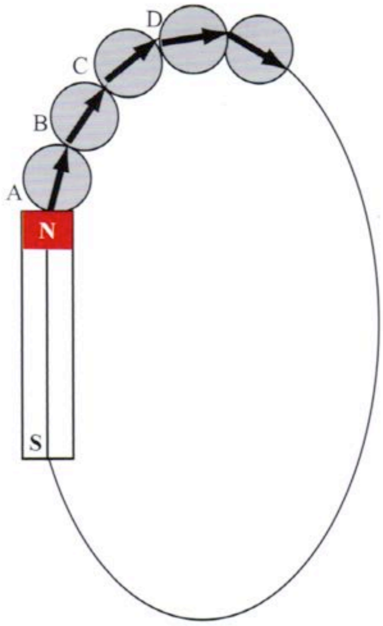
To investigate the magnetic field of a bar magnet and its interaction with the Earth's magnetic field.

Equipment

- sheet of white paper (A3)
- sheet of white paper (fish and chips size wrapping paper)
- bar magnet
- plotting compass

Pre-lab

- Place the plain A3 paper on the bench or desk so that it is clear of any iron or steel objects, including the frame of the bench.
- Place the bar magnet in the middle of the paper and trace around it.
- Place the plotting compass at the corner of the north pole of the magnet. Mark the position of the north and south ends of the compass needle by pencil dots B and A respectively.
- Move the compass until the south end of the needle is over the dot B. Mark the position of the north end with a new dot C. Repeat this process.
- Join the series of dots to give the magnetic field line. Label the line with an arrow to indicate the direction of the field line (it is from north to south)
- Plot several other field lines in the same way.



Lab notes

Use the plotting compass to align the edge of the fish and chips wrapping paper north-south. To prevent the paper moving during the experiment, hold the corners in place with small pieces of tape.

Place the bar magnet in the centre of the paper so that its south pole is pointing north. Trace around it to record its position.

Using the procedure described in the Pre-Lab, plot the magnetic field around the bar magnet. You should plot at least 12 lines. If you have access to more plotting compasses, you can work with a partner plotting lines on opposite sides of the magnet.

Post-lab discussion

1. Is the magnetic field symmetrical about the north south axis? Is it symmetrical about the east west axis?
2. Locate the points where the magnetic field of the magnet and the Earth's magnetic field cancel each other out (the null points).
3. Would you expect the same field pattern if the magnet was reversed with its north pole pointing north? Would there be any null points in this case? Test your hypotheses.
4. Describe the evidence that the magnetic field created by the bar magnet varies in strength. Is there any evidence of a relationship between distance from a pole, and the strength of the magnet?

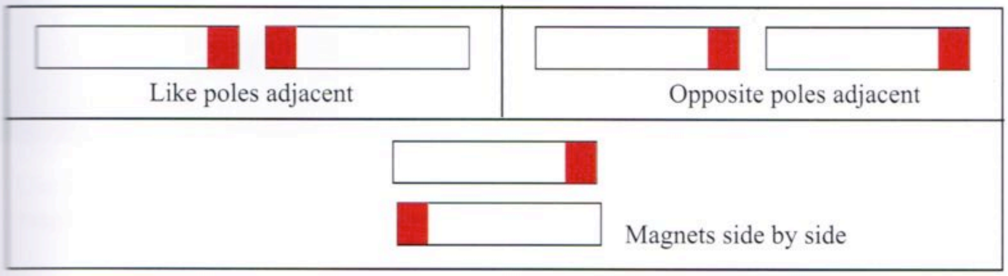
Assessment

Investigating magnetic fields with iron filings

Iron filings can also be used to study the shape of magnetic fields around magnets. Each tiny iron filing becomes a temporarily induced magnet and behaves like a very small compass needle. The filings align themselves and join together in 'chains of filings' in the direction of the field.

The direction of the magnetic field can be determined using a small compass. The direction of the magnetic field is the direction in which the north seeking end of the compass points.

- When you use iron filings to investigate the patterns around some different arrangements of magnets, make sure that you keep the iron filings off the magnets.
- Place the magnet or magnets being investigated underneath the glass or Perspex sheet, and lay the sheet of paper on top of the glass or Perspex.
- Gently shake the iron filings all over the sheet of paper and gently tap the sheet to make the filings link together.
- Sketch the field pattern for each of the following situations.



Notes

Investigation 6.7: Design and make an electric motor

Notes

Design brief

Design and operate an electric motor. You must understand and describe the science principles behind its operation. It must be able to drive a light load such as a pulley system or a fan. You might make it drive a small cart.

Details

You will work individually but are expected to collaborate wherever this will aid your learning. You should research various types of electric motor. Make yourself aware of how they produce torque. Find out what is meant by torque.

You may use any materials at all. You must do the construction yourself. There should not be an excessive use of prefabricated parts.
The motor might be just a simple single coil motor or could be a more complicated design using several coils.

Give consideration to using electromagnets rather than permanent magnets. You can borrow permanent magnets from your science teacher.

Assessment

You will be required to be able to ***demonstrate*** and ***explain*** the operation of your motor. The ***explanation*** of the motor and the science principles behind it may be the focus of an oral assessment.

Your motor will be better and you will have learnt more if:

- your motor produces plenty of torque
- your motor can drive a significant load
- your motor always starts by itself without help from you
- your design shows some creativity
- you have chosen a challenge rather than a very simple design
- your motor is robust and shows good workmanship
- you can ***verbally*** demonstrate a good understanding of your motor

Your motor will be inferior and you will have learnt less if:

- you have used too many prefabricated parts
- your motor is just a simple copy of a design that you found in a publication
- your motor does not work
- your motor falls to bits when your teacher picks it up and shakes it gently

Investigation 6.8: Fridge magnets

Background

Fridge magnets are ubiquitous, but how do they work? Are fridge magnets all the same? Why is there no magnetic attraction on the outward facing side of the fridge magnet? And what is the "Halbach array"?

The task

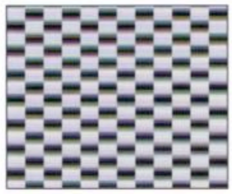
What are the unique properties of fridge magnets and how are these unique properties produced?

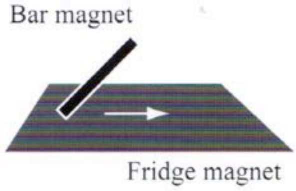
1. What is the arrangement of the magnetic poles on a fridge magnet?
   - *Try dragging the pole of a bar magnet along a fridge magnet.*
2. Are the poles of a fridge magnet arranged in strips or in a checker board pattern?
   - *Try dragging the edge of a bar magnet along a fridge magnet in different directions.*
3. Do all fridge magnets have the same pole structure?
   - *Place various fridge magnets face down under a sheet of paper and gently sprinkle the surface with fine iron filings. Record the patterns produced.*
4. How do fridge magnets affect each other?
   - *Cut a small strip from adjacent edges of a fridge magnet drag these strips over the surface of a fridge magnet and observe any effects.*
   - *Drag two identical fridge magnets over each other and feel the magnetic effects.*
   - *Drag two dissimilar fridge magnets over each other. Explain the effects felt.*
5. Can the magnetism of a fridge magnet be detected by a compass needle?
   - *Test the surface of a fridge magnet with a mounted compass needle (not a compass enclosed in a case).*
6. Using all the above tests and procedures map the surface of a fridge magnet and label the
   - poles as indicated by the mounted needle.
   You can use a HB or B pencil to map the poles by drawing On the fridge magnet.
7. What is the magnetic field on the reverse side of a fridge magnet?
   - *Use some of the above tests to study the magnetic field on the reverse side of a fridge magnet.*

Discussion

1. What is the source of the zone structure of the magnetic fields of a fridge magnet? How are the magnetic poles arranged?
2. Explain why there are differences in the magnetic effect on the reverse side of a fridge magnet.
3. What is the magnetic material used to make a fridge magnet?
4. Use this information to explain how the magnetic zones are arranged.
5. Use this information to explain why there are strong magnetic fields on one side but no magnetic fields on the other side of the sheet.

Notes





Problem Set 6: Magnetic fields and forces

Notes

1. Draw the magnetic field distribution for each of the following arrangements:
   (a) bar magnet.
   (b) two parallel (side by side) but separated bar magnets with opposite poles facing each other.
   (c) two parallel but separated bar magnets with like poles facing each other.
   (d) two bar magnets in line (end to end), separated by 50 mm, with opposite poles facing and with a small iron washer placed midway between them.

2. When plotting the magnetic field around a wire carrying a current, a student first ensured that there were no objects made of iron close to the wire. Explain why she did this.

3. A freely suspended current-carrying wire hangs perpendicularly, and parallel to a fixed similar conductor carrying an identical current.
   (a) If both currents flow in the same direction, describe movement, if any, of the suspended wire. Support answer with a diagram.
   (b) What will happen if the currents flow in the opposite direction?

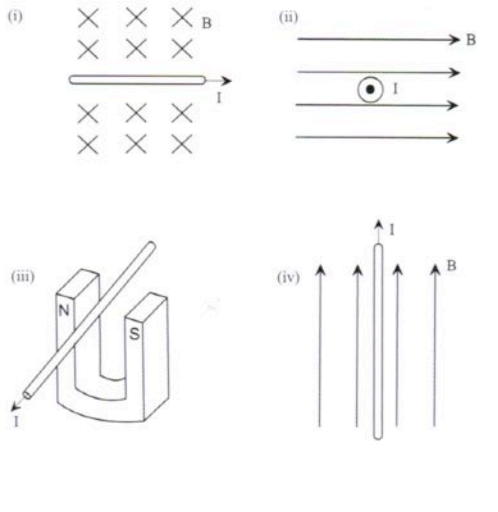
4. The starter motor in a car contains a solenoid (coil) connected to the car's starter switch. Draw a diagram of a solenoid and show the external magnetic field it produces when driver turns the starter switch on. Show the direction of both the current and magnetic field.

5. In a small household electric motor the rectangular coil of wire has 200 turns. The coil is 100 mm long and 30.0 mm wide. The coil, when it has a current of 0.200 A flowing through it, is perpendicular to a magnetic field of flux density 0.350 T. Find the torque experienced by the coil.

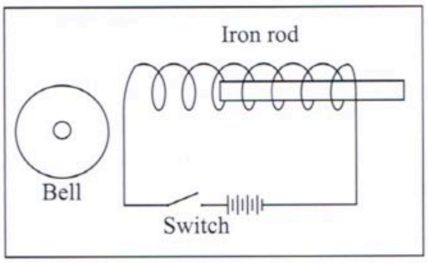
6. Draw the magnetic field pattern and show the relative strengths for:
   (a) current carrying single wire, and
   (b) a current carrying circular coil.

7. The instructions on magnetically-recorded media such as videotapes and computer hard drives state that you should not put them next to electrical power cords. What is the reason behind these instructions?

8. For each of the following, indicate the direction of the force, if any, acting on the current carrying wire.



9. The question 9 image represents a circuit for a simple electric door bell. Explain why the bell sounds when you close the switch. Suggest how you can change the arrangement shown in the diagram to make the bell ring louder.



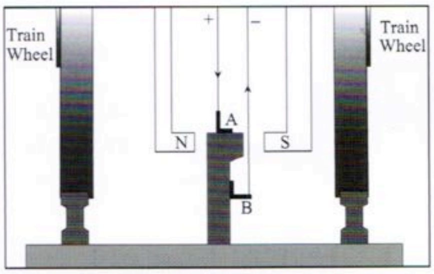
Question 9

10. An electric motor in a hair dryer draws a current of 10.0 A when operating at maximum heat and speed. If the side of the armature between the poles of the magnet in the fan motor is 120 mm long, calculate the force acting on the armature when it is perpendicular to the magnetic field of strength 2.00 T.

11. Commercial electric motors may have up to 12 coils or `windings' with each located in a different position around the armature. Such motors produce a much more even torque than motors with fewer coils. Explain, with the aid of a diagram why this is so.

12. A 75 m long DC transmission cable stretches between two light towers in an east-west direction. Estimate the magnitude and direction of the force that the wire experiences, because of the Earth's magnetic field, when a 40 A current passes through it.

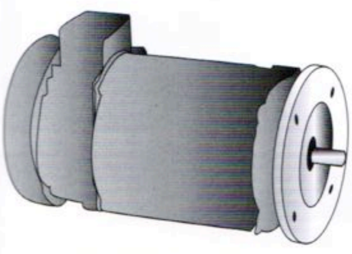
13. The question 13 image shows the design of an experimental electric train. It has the two poles of a magnet arranged on each side of a steel third rail in the middle of the track. The train has controls that can vary the direction and strength of current that passes between sliding contacts A and B.
(a) What is the direction of the magnetic force that the magnet exerts on the third rail when current flows from A to B?
(b) What is the direction of the magnetic force that the rail exerts on the magnet?
(c) In what direction would the train move?
You may find Newton's Third Law of Motion useful in your explanation.
Besides braking, the train could use some of its electric motors as generators to stop the train.
(d) What are three essential components of an electric motor?
(e) How does an electric motor differ from an electric generator?
(f) How would the train use its motor to brake?



Question 13

Notes

14. A simple electric motor contains several coils of wire. Draw a diagram of a simple coil and sketch the magnetic field around it that is produced when a current flows through the coil. Show the directions of both the current in the coil and magnetic field produced.


Question 14: Electric motor

Induction cooktops and electric toothbrushes

Induction cooktops

Induction cooktops are not a source of direct heat. They generate heat in the base of the cookware being used by electromagnetic induction. This process will only work with cookware having a base made of a ferro-magnetic material such as iron or stainless steel and will not work if the base is made from glass, copper or aluminium.

Underneath the glass top on the stove is a coil of copper wire through which a controllable alternating current flows when the switch is turned on. This alternating current will have associated with it a fluctuating magnetic field that varies at the same frequency as the current. This varying field will cause the production of a varying emf in the base of the cookware, which will become a varying current (eddy current - see page 92) due to the resistance encountered. The resistance this current encounters in the metal base results in the electrical energy being converted to heat energy which is then transferred to the food contents of the cookware.

The reasons why metals such as stainless steel and iron are most suited to being used in this process is related to an area of Quantum Mechanics. All electrons in an atom have a quantum property called spin, some in one direction referred to as "up" and others with an opposite spin called "down". Unlike other metals, ferromagnetic materials have an imbalance in the numbers of these different spin electrons. These electrons behave like tiny magnets and their numeric imbalance means the atoms themselves behave like tiny magnets and are therefore capable of being influenced by external magnetic fields. Because any change in the external magnetic field will have an immediate effect on the eddy currents, the heating effect of these cooktops can be easily and quickly controlled.

Other advantages of induction cooktops are:

1. They use less energy than conventional cooktops to cook the same food because the heat is produced in the base of the cookware and not in the cooktop.
2. The cooktop is safer because once the pot is removed from the cooktop no heat is produced.

Electric toothbrushes

The recharging of electric toothbrushes is done using induction. No moisture can be allowed to get into the electrical parts of the toothbrush so the outer case must be completely sealed and waterproof. A socket to connect an external adaptor cannot therefore be used to recharge the batteries. When the toothbrush is placed on the recharger unit there is no electrical contact between the two. The recharging occurs using electromagnetic induction where a coil of wire in the recharger unit produces a varying magnetic field that induces a current in another coil which is part of a circuit in the base of the toothbrush and is used to recharge the batteries inside the sealed unit. The physics of this process is the same as that described for the induction cooktop.

Induction cooktops and electric toothbrushes - comprehension questions

1. List two advantages and two disadvantages of an induction cooktop.
2. Describe the source of heat in an induction cooktop.
3. Explain why glass, copper and aluminium pots do not work on an induction cooktop.
4. Why is an electric toothbrush charged by induction?

Magnetic induction (emf) explained

An electric current produces a magnetic field, and in certain circumstances a magnetic field can induce an electric current. This happens whenever the magnetic field changes. We call such a current an induced current.

Electromagnetic induction is the production of an induced electric current in a conductor when there is relative motion between the conductor and the magnetic flux. Two ways of achieving this are:

- moving a magnet through a coil of wire, and
- moving a conductor through a magnetic flux.

This generates a voltage, often called an electromagnetic force (emf), in the conductor. Note that an emf is the greatest potential difference that can be generated by a particular source of electric current, and is not a force at all.

Notes

Faraday's Law of Electromagnetic Induction states that the induced emf across a conductor in the form of a coil or solenoid is equal to the rate at which the conductor cuts the magnetic flux. That is,

$$\text{emf} = -N\frac{(\phi_2 - \phi_1)}{t} = -\frac{NBA}{t}$$

where:

N = number of turns in the coil
$\phi_2 - \phi_1$ = BA = change in the magnetic flux, in weber
t = time over which the flux changes, in seconds
emf = induced potential difference, in volts

EMF of AC Generator

The coil is a straight conductor cutting a magnetic field at 90° to the field so the emf at any point in the cycle for each side of an individual winding on the coil can be calculated from:

$\text{emf} = -\ell vB\sin\theta$ where
θ = angle between v and B
ℓ = the length of the winding cutting the field
v = tangential velocity of the coil
B = strength of the magnetic field

The negative sign is because its effect is in opposition to the force producing the motion.
For N windings (turns) on the coil this becomes

	$\text{emf} = -N\ell vB\sin\theta$	for each side of the coil
Therefore	$\text{emf} = -2N\ell vB\sin\theta$	when both sides of the coil are considered

Maximum emf is when $\theta = 90°$ as $\sin\theta = 1$

Therefore $\text{emf}_{max} = -2N\ell vB$

The emf produced will vary between zero and this maximum in a sinusoidal fashion. We do not use the maximum value when dealing with alternating voltage but a value referred to as the rms value. This is found from:

$$\text{emf}_{rms} = \text{emf}_{max}/\sqrt{2}$$

The rms (effective) value of an alternating (time varying) sinusoidal waveform is the numerical value equivalent to the volts or amperes of DC that has the ability to produce the same power as that value in DC. The rms value is mathematically determined from the square root of the mean (average) value of the squared function of the instantaneous values and is found using calculus.

Lenz's Law: An induced emf gives rise to a current whose magnetic field opposes the original change in flux.

Magnetic induction (emf) explained

Eddy currents

When a conductor is moved in a magnetic field an emf is generated (Faraday's Law). The result of this emf (work/charge) and the resistance of the conductor will be the production of swirling currents in the conductor. These currents are in closed loops and their direction will be such as to produce a net magnetic field in opposition to the one that caused them (Lenz's Law). Such a field will oppose the original motion of the conductor. Currents such as these that are set up in time varying magnetic fields are named ***eddy currents***.

The work these eddy currents do (power/time = I^2R/t) is dissipated as heat in the conductor resulting in it heating up. This process will continue for the duration that the time varying magnetic field exists. The same effect will result if the conductor is held in place and the magnetic field is varied, such as would occur if a stationary coil of wire was connected to an AC supply as in a transformer.

The heating effects of eddy currents can be a serious problem in the iron cores of electric motors and transformers. In both of these cases laminations of metal are used to reduce the problem. In other examples, such as induction cookers, braking systems on electric trains and hybrid cars and brazing of metals, their existence is put to good use.

In order to reduce eddy currents, and hence their heating effects, in transformer cores and the metal stators and armatures of motors their coils are wound around a structure made from a number of thin iron (steel) sheets called laminations. Such laminations greatly disrupt the induction of eddy currents into the cores thereby reducing heating effects and greatly increasing the efficiency of the device.

Eddy current braking

The basic concept used in eddy current braking is the use of forces created by electromagnetic induction instead of friction to slow objects down. Conventional brakes rely on the frictional forces between two surfaces in contact to slow down a moving object and the greater the initial energy of the moving object the more the work needed to bring the object to rest.

Eddy current brakes rely on the interaction between the magnetic field of an electromagnet and the opposing magnetic field produced in a moving conductor as a result of the eddy currents created in that conductor due to this relative motion. This system is efficient because the magnetic field associated with the eddy currents always opposes the magnetic field that produces it.

Eddy current braking can use a linear or circular model, depending on the motion of the device or its component parts. The linear model is used to slow down roller-coaster cars, where the car is moving in a straight line and the metal track is stationary. Very high strength magnets are mounted on the straight section at the end of the track and metal plates are attached to the sides of the car so that they pass in very close proximity to these magnets. Large eddy currents are produced in the metal plates resulting in the rapid slowing down of the car.

The circular model requires one part of the braking system to be stationary and one to be rotating, which is not all that structurally different to the standard system used on a motor vehicle. In the case of an eddy current system a strong electromagnet replaces the brake pads and callipers, with the rotating disc being similar but solid. Due to the large amount of heat produced in the metal disc due to the eddy currents some sort of cooling system might be needed. Circular systems are used in some fitness training equipment such as exercise bikes, striders and rowing machines to produce a higher resistance.

Regenerative braking

This is different to eddy current braking in that it recovers the kinetic energy lost in slowing down by converting it to a form that can be stored in a form that can be re-used later. Converting kinetic energy to electrical energy is the most common form of regenerative braking. An electric motor can become a generator and the electricity produced stored in a rechargeable battery or, in the case of trains, fed back into the commercial network.

Vehicles fitted with this system still need a conventional friction braking system to bring them to a complete stop as regenerative braking is not effective at slow speeds. They also need friction brakes fitted to the non-drive wheels otherwise they have no braking system on them.

Problem Set 7: Magnetic induction

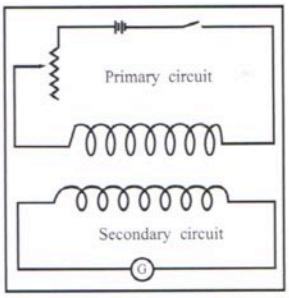
Notes

1. An aircraft flies at 980 km h^{-1} from west to east at an altitude of 10 km. If the vertical component of the Earth's magnetic field is 3.50×10^{-5} T and the aircraft has a wingspan of 60.0 m, calculate the potential difference it develops between its wing tips.

2. A portable 50.0 W television set is designed to operate on a 12.0 V battery, or by using a mains supply of 240 V connected through a transformer.
   a) If the transformer in the set is 90% efficient, what current does the television set draw if it is operating on mains power?
   b) Explain why this television set has vents in the walls of its casing.

3. A physics student inserted the north pole of a bar magnet into a coil that was connected to a galvanometer, and noticed that the galvanometer needle moved to one side. When she withdrew the magnet from the coil she notice the needle moved to the opposite side of the galvanometer. Explain these observations with the help of a diagram.

4. Referring to the diagram at right:
   a) explain why, when you close the switch in the primary circuit, you detect a transitory electric current in the secondary circuit;
   b) suggest at least two ways in which you can increase induced voltage in the secondary circuit; and
   c) explain in which direction the current flows in the secondary circuit relative to the primary circuit.



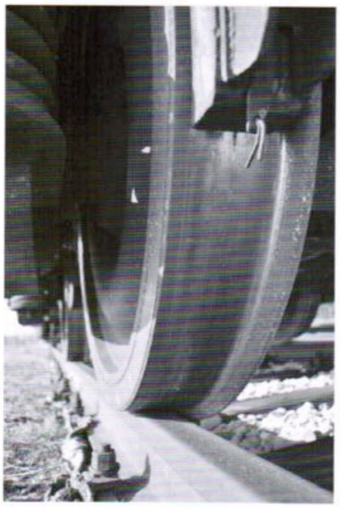
5. A 500 mm long radio aerial is attached to, and insulated from, the roof of a taxi. If the taxi is moving in an easterly direction at 60.0 km h^{-1} and the horizontal component of Earth's magnetic field is 2.50×10^{-5} T, calculate:
   a) the emf induced in the aerial;
   b) the rate at which the aerial cuts the magnetic flux.
   c) If the taxi turns a corner maintaining the same speed but now travels in a southerly direction, does the induced emf remain the same? Explain.

6. An electrical engineer working on the design of a new electric train said: 'If the opposite of Lenz's law was true, the motors in this train would soon burn out.'
   Explain why this would happen.

7. A generator coil is 30 mm in diameter. It experiences a uniform flux density change of 0.5 T in 10 s. Estimate the average emf induced in the coil.

8. A student connected the ends of a circular loop of wire with a radius of 0.100 m to a 5.00 Ω resistor. He put the coil near a transformer that, at a particular instant directed a magnetic field of 0.250 T at right angles to the plane of the coil.
   a) Calculate the emf induced in the coil if the magnetic field dropped to zero in 0.200 s.
   b) Draw a diagram of the coil and the resistor and show the direction of the magnetic field passing through the coil as it dropped to zero.
   c) Indicate the direction of the induced current through the resistor.
   d) Calculate the value of the induced current through the resistor.

Problem Set 7: Magnetic induction



Notes

9. A train is travelling with a constant velocity of 80.0 km h^{-1} in an area where the vertical component of the Earth's magnetic field is 36.0 μT. .
   a) What is the maximum size of the emf induced across each 1.00 m long axle?
   b) If the train is travelling in a south–westerly direction, describe the force acting on an electron in this axle.

10. A student timed the oscillation of a pendulum made of an aluminium plate. She noticed the period of oscillation was much less when she made the pendulum plate swing between the poles of a strong horseshoe magnet. Explain this observation. (Note that if you look at the electric power meter in your home you should see an aluminium disc rotating through the poles of a strong magnet.)

11. A commercial AC generator operates at a frequency of 50.0 Hz and produces a maximum voltage of 180 V. If the area of the coil is 2.00×10^{-2} m^2 and the armature rotates in a magnetic field of strength 0.200 T, how many turns of wire must the coil have to produce the maximum voltage? Assume the maximum flux through the coil reduces uniformly to zero over one quarter of a rotation.

12. In a laboratory investigation a student moved 20.0 mm of a length of copper wire perpendicularly across a 0.500 T magnetic field. The ammeter connected to the ends of the wire indicated a current of 10.0 mA.
   If the total resistance of the circuit was 2.50 Ω, calculate:
   a) the constant velocity with which she moved the wire through the field,
   b) the force she exerted to maintain this constant velocity.

13. A simple generator contains a square armature coil of side lengths 200 mm by 200 mm. The coil contains 300 turns of copper wire. It rotates at 60.0 revolutions per second in a uniform magnetic field
   a) What is the strength of this field if the generator produces an average voltage of 240 V?
   b) At what point in its rotation is the peak voltage produced? At what point is the voltage zero.

14. A moving coil meter has a coil that is wound on either a plastic or a metal former. These two types of meters behave completely differently when connected in a circuit. Explain how and why they would behave differently.

15. The Boeing 747-8 with a wingspan of 64.0 m is flying at 920 $kmhr^{-1}$ (Mach 0.85) through the Earth's magnetic field at a place where its vertical flux density is 1.02×10^{-5} T. Calculate the EMF induced between the wing tips given the aircraft has a metal frame and cladding.

16. A circular coil of 45.0 turns of copper wire with a resistance of 12.8 Ω and a radius 8.00 cm is placed in a uniform magnetic field of 0.850 T that is at an angle of 300 to the plane of the coil. The magnetic field-strength is increased at a constant rate from 0.850 T to 3.95 T in a time interval of 450 ms.
   (a) What is the emf generated between the ends of the loop?
   (b) What maximum current would flow around the loop during the period the magnetic field is changing if the ends of the coil are joined?

17. A 6.80 cm diameter circular coil made from 60.0 turns of copper wire is placed in a uniform magnetic field of flux density 250 mT that is perpendicular to the coil. Calculate the emf induced in the coil when the flux density is reduced steadily to zero in 3.50 s.

Notes

Each of the 300 turn coils in an AC generator is rectangular with a length of 5.00 cm and a radius of 1.80 cm. The rotor the coils are wound on rotates between the curved poles of a stator where the uniform magnetic field strength is 0.180 T. The rotor turns with a frequency of 60.0 Hz.

(a) Calculate the maximum emf produced in the coil.
(b) What is the rms value of this emf?
(c) What is the advantage of the poles of the stator being curved?

An AC generator has a coil of 85.0 turns and an area of 3.10×10^{-2} m^2 which rotates at 3600 rpm in a magnetic field of 0.250 T. Calculate the peak and rms value of the emf generated by this coil.

A generator has a coil of 240 turns, a diameter of 12.0 cm and rotates at 2400 rpm in a 0.860 T magnetic field. Calculate the maximum emf this generator produces.

A single coil of diameter 0.240 m and containing 1500 turns of copper wire is initially set up parallel to the magnetic field lines of the Earth. It is then rotated through 1800 in a time of 2.50 ms. Calculate the maximum emf generated between the ends of the coil if this experiment was performed at a place where the strength of the Earth's field was 51.0 μT.

A 2.00 kVA portable generator has several rotor coils, each with a diameter of 7.60 cm and length of 10.0 cm. Each of these coils can produce an output voltage of 240 V rms at 50.0 Hz when rotating in a 300 mT armature field. How many turns are on each coil of the rotor?

Each of the rectangular coils of a vehicle alternator has 400 turns. Each turn is 6.00 cm long by 8.00 cm in diameter. The coils rotate in an adjustable magnetic field so that each can produce a sufficient voltage to maintain, even at low revolutions, charge in the vehicle's battery. What is the field strength needed to produce a peak output of 20.0 V per coil at when it is idling at a speed of 400 rpm?

Electrical energy and power explained

Notes

Remember the following important principles

Electrical energy can be transformed into mechanical work (useful in electric motors) or thermal energy (useful in an electric stove or toaster). The following expressions give the rate at which a device transforms electrical energy:

$$\text{Power} = \frac{\text{energy}}{\text{time}} = V.I = \frac{V^2}{R} = I^2R$$

A power transformer functions on AC and changes potential difference from one value to another with a minimal loss of energy. It consists of two coils of wire, known as the primary coil and the secondary coil, wound on the same soft iron core.

An ideal (100% efficient) transformer does not lose any power so that:
electric power (primary) = electric power (secondary) i.e. $V_pI_p = V_sI_s$

Note that even the most efficient real transformers may lose up to 1 % of the input power as heat.

The turns ratio of a transformer is $\frac{N_p}{N_s}$ In an ideal transformer, $\frac{N_p}{N_s} = \frac{V_p}{V_s}$

Experiment 8.1: Transformers

Background

Transformers are extremely useful electrical devices that are able to change AC voltages. In its simplest form a transformer consists of two coils of wire wound on a soft-iron core. An AC voltage applied to one coil induces an AC voltage in the second coil.

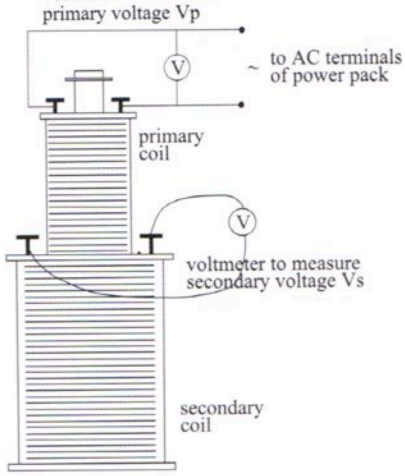
A: Non digital option

Aim

To examine the operation of a simple transformer.

Equipment

- induction coil (dissectible type with iron core)
- AC voltmeter
- 0-15 V for primary voltages
- AC voltmeter for secondary winding
- AC power pack 0-12 V
- connecting leads



coils and core shown 'exploded'

Pre-lab

- Draw up a table designed to record your results.
- With the power supply OFF connect the smaller coil to the voltmeter and AC terminals of the power pack.
- Connect the second voltmeter to the larger coil (see diagram)
- Insert the smaller coil into the larger coil and the soft-iron core into the smaller coil.
- If your voltmeter has more than one scale always start by using the least sensitive scale, i.e. the scale that can measure the highest voltages.
- Set the power pack to its highest voltage output. Do not touch any exposed terminals.

Lab notes

- Turn on the power. Record the primary voltage V_p and the secondary voltage V_s. Use a more sensitive scale on the voltmeter if it helps.
- Repeat this process for lower voltage outputs. You need at least 6 sets of results.
- Remove the soft-iron core from the primary coil and repeat your measurements.
- For the results *with* the soft-iron core, plot a suitable graph of secondary voltage output vs primary voltage input.
- On the same axes plot the results *without* the soft-iron core.

Post-lab discussion

1. Comment briefly on the shapes of the graphs.
2. What, if any, simple relationship exists between the secondary voltage and the primary voltage?
3. Secondary voltages are usually higher if a soft-iron core is used. Explain why.

Notes

Experiment 8.1: Transformers

Notes

B: Digital option

Aim

To do a live signal analysis for a transformer under a range of conditions

Equipment

- data logging software
- open core transformer with dual coils and iron core
- 2×30 V voltage probes
- 1×10 A current probes
- 8 connecting leads
- AC power pack with variable output

Lab notes

1. Setup a simple series circuit with the smaller primary coil attached directly to the AC power pack.
2. Connect the 30 V voltage probes in parallel across the terminals of the two coils.
3. Load the data logging software and change the sample rate to 1000 samples per second. Set the record time to 0.04 s. You can use a CRO if needed.
4. With the power pack off ensure the voltage readings on both probes are zero. Re-zero or calibrate if needed. Be careful with background emf in the environment from the mains power within the laboratory. It is likely that there will be a background signal visible.
5. Ensure the larger secondary coil is not connected to the power pack and is easily removable from the system.
6. Turn the power pack on at 2.00 V and view the voltage vs time data with the two coils separated.
7. Insert the secondary coil into the system. Ensure that you do not exceed the maximum voltage of the probes. Record the signal.
8. Insert the iron core. Record the signal.
9. In System 2 change the primary coil to the larger coil. This will need to be attached directly to the AC power pack. Set the voltage output on the power pack to 8.00 V.
10. Turn the power pack on at 8.00 V and view the voltage vs time data with the two coils separated.
11. Insert the secondary coil into the system. Ensure that you do not exceed the maximum voltage of the probes. Record the signal.
12. Insert the iron core. Record the signal.

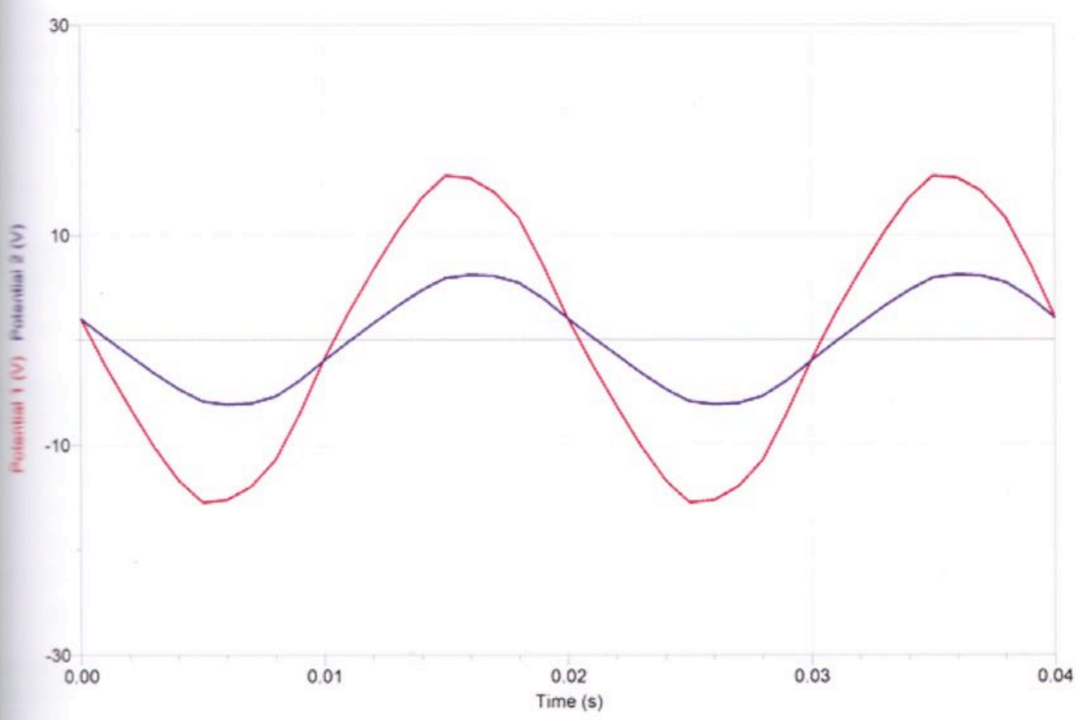
Results

Small coil cross sectional area: ______ m^2

Large coil cross sectional area: ______ m^2

System	Primary coil voltage(V)	Secondary coil voltage(V)	Period of signal (s)	Frequency (Hz)
1 Step up				
2 Step down				

A sample of the expected type of graphs are shown below. If you do not have this data you may wish to use the sample graphs to assist you in answering the questions.



A voltage vs time graph for System 1

Post-lab discussion

1. Why does the iron core heat up? When you are placing the core into the transformer what do you observe?
2. What is the effect of inserting the iron core into the transformer on the secondary voltage signal?
3. Why is there not a change in the frequency between the primary and secondary coil?
4. How could you improve the quality of the AC signal in the secondary coil?
5. Why is it advisable to record the cross–sectional area of the coils?
6. What errors are present in the system?

Extension: Efficiency of the transformer

1. Why not integrate two 10 A current probes into the transformer with a high current resistor across the secondary coil? A resistor from 20–100 Ω would be appropriate.
2. Use your understanding of Power (P = VI) to determine the percent efficiency of the transformer.

Notes

Experiment 8.2: Voltage and turns ratio for a transformer

Notes

N_p = number of turns in primary coil;
V_p = voltage across primary coil
Ns = number of turns in secondary coil;
V_s = voltage across secondary coil

or

Background

In a transformer, two coils are wound on a single iron core so that the magnetic flux created by one passes through the other. One coil is connected to the AC supply and is referred to as the primary. The other coil is called the secondary. Whenever a changing magnetic flux passes through a coil, there will be an induced EMF. In a transformer, the changing flux originates from the alternating current in the primary coil. Because this flux also goes through the secondary coil, there will be an induced EMF in both coils.

Equipment

- U-shaped iron core from a transformer kit (or a soft iron rod)
- PVC-coated or varnished wire
- electrical leads with alligator clips or banana plugs
- AC power supply
- two voltmeters or datalogger voltage sensors

Pre-lab

- Draw up a table for your results as follows:

V_p	V_s	N_p	N_s	$\frac{V_p}{V_s}$	$\frac{N_p}{N_s}$

- Wind two coils of coated wire onto an iron rod as shown. The rod can be straight or U-shaped. Make sure that the number of turns is different for each coil. The primary coil should have at least 10 turns. Record the number of turns for each coil.

Lab notes

- Connect the primary coil to a 1 V AC power supply. Connect voltmeters or voltage sensors in parallel with both primary and secondary coils. Measure and record the voltage across both primary and secondary coils.
- Increase the voltage to 2 V AC. Measure and record the new voltage across both primary and secondary coils.
- Repeat the process using coils with different numbers of turns, until you have several sets of readings.

Post-lab discussion

1. Taking possible experimental errors into account, what is the relationship between the volts ratio ($\frac{V_p}{V_s}$) and the turns ratio ($\frac{N_p}{N_s}$)?
2. Explain the theoretical basis for the ratio of volts to turns that you found.
3. What should the turns ratio be in a 'step-up' transformer (one that increases output voltage compared with input voltage)?
4. Explain why a transformer will not work on a constant DC supply such as a dry cell.
5. The soft iron core in most transformers is laminated. What does this mean, and why is it done?

Experiment 8.3: Measuring electric energy

Background

Electrical energy can be converted into other forms of energy. A common conversion is the heat produced when an electric current flows through a resistor. Electric kettles, electric hot water systems and bar heaters all depend on this energy conversion.

The energy required to change the temperature of an object is given by:

Energy = (mass of substance)(specific heat of substance)(change in temperature)

Aim

To investigate the relationship between current, potential difference and electrical energy.

Equipment

- Joule's calorimeter
- access to a balance
- thermometer [0 °C–100 °C]
- 0–12 V power supply
- ammeter and voltmeter, or multimeter
- switch
- rheostat
- clock or stopwatch
- electrical leads
- water

Pre-lab

- Prepare tables to record the data you will gather (e.g. initial and final temperatures, the masses of water and of the calorimeter, currents, potential differences and times)

Lab notes

- Determine and record the masses of the calorimeter and its accessories, and of the water.
- Set up the equipment.
- Briefly switch on the power supply and use the rheostat to get a steady potential difference across the calorimeter (eg 5 V) and a steady current in the circuit (eg 2 A). Switch off immediately after setting this up.
- Gently stir the water and record the initial temperature to the nearest 0.5 °C.
- Turn the power and the timing device on simultaneously.
- Stir occasionally, and use the rheostat to maintain steady values of current and potential difference. Maintain the current for about 10 minutes, or until the temperature has risen by about 30 °C.
- Just before switching the current off, stir gently again and record the final temperature.

Post-lab discussion

1. Calculate the electrical energy supplied.
2. Calculate the energy absorbed by the calorimeter and the water which resulted in the measured temperature increase.
3. Compare the two energy amounts. Account for any discrepancies.
4. Estimate the uncertainties in the values of energy, and comment on your result.

Notes

Experiment 8.4: Back-emf in a DC motor.

Notes

Background

In a DC electric motor a direct current is supplied to a coil situated in a magnetic field. This current produces a magnetic field in the windings of the coil and it is the interaction between these two fields that causes the coil to rotate about a central axis. The magnetic field of the field coils of the motor interacts with the magnetic fields associated with the electric current in both arms of the coil producing a force, hence a torque, in opposite directions in each side of the coil causing the coil to turn.

Once the coil of the motor starts rotating it cuts through the permanent magnetic field of the motor. As a consequence it experiences a change in magnetic flux linked with it. This rate of change of flux increases as the motor speeds up. From Faradays Law this causes an emf to be induced in the coil when the magnetic flux through the coil changes, the numerical value of which, in volts, is proportional to the rate of change of the flux linked with the rotating coil. From Lenz's Law the direction of this induced emf will oppose the emf applied to the coils. This is why this induced emf is called the "back–emf".

Net emf at the motor = Applied emf - back emf

As the speed of rotation of the coil increases so does the back emf and the difference between the emf applied to the motor and the back emf produced by the motor will decrease the faster the rotation of the coil. The difference between these two emfs is the value measured across the coil of the operating motor and hence would determine the current that flows in the coil. The emf measured when a motor starts up will always be greater than the emf measured when running, hence the startup current through the coil will always be larger than the operating current. This can be a problem, particularly in large motors, as a large current could burn out the coil of the motor. To overcome this potential problem starting resistors, which can be switched out of the circuit once the motor reaches its operating speed, are placed in series with the coil of the motor to reduce the voltage across, and hence current through, the coil.

DC motors can also be speed controlled by varying the supply voltage as it is the back emf that determines the motor speed for any given voltage.

A: Digital option

Aim

To collect a voltage vs time graph for a back EMF signal from a DC motor.

Equipment

- data logging software
- 0-6 V voltage probe
- constant emf source
  (6 V DC AA Pack or 4 × 1.5 V AA batteries)
- 2 leads and a switch
- DC motor (student made preferred)

Lab notes

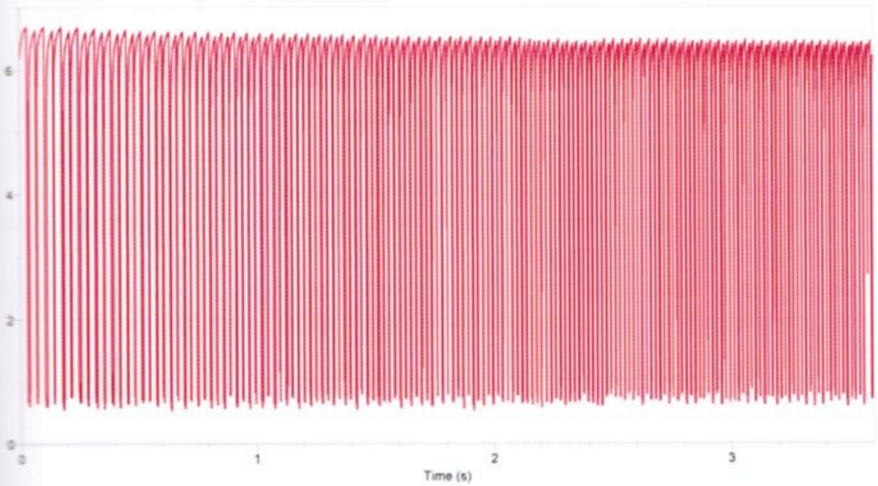
1. Set up a simple DC motor circuit running off a constant 3V-6V DC source. It is advisable that you do not use the AC power packs as the rectified DC is a 100 Hz fluctuating signal.
2. Connect the 6 V voltage probe across the terminals of either the motor or the battery.
3. Load the data logging software and change the sample rate to 1000 samples per second. Set the record time to 5.00 s. You can use a CRO if needed.

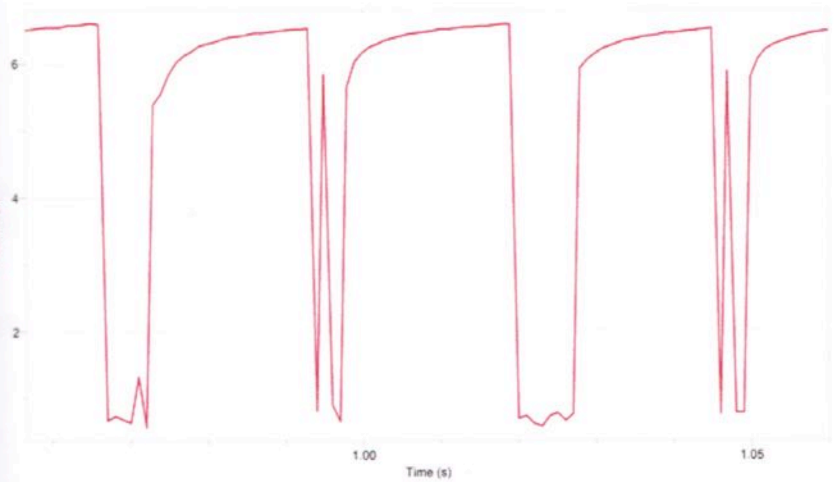
4. Start recording then switch on the DC motor. Check that your data has the first second or so of the motor turning on and then around 2 seconds of the motor increasing in rpm.
5. Zoom in on the signal and record the period of rotation and maximum voltage at the first, second, third and fourth second of data.
6. You may wish to change the number of coils within the motor, or change the motor, and then repeat the process.
7. Draw the shape of the voltage signal.
8. Determine the frequency of rotation of the motor from this signal.

Results

A sample of the expected type of graphs follow. If you do not have this data you may wish to use the sample graphs to assist you in answering the questions on page 105.

Voltage vs time





Zoomed in voltage vs time graph: determine the frequency (in Hz or rpm) of the motor.

Notes

Experiment 8.4: Back-emf in a DC motor.

Notes

B: Non-digital option

Aim

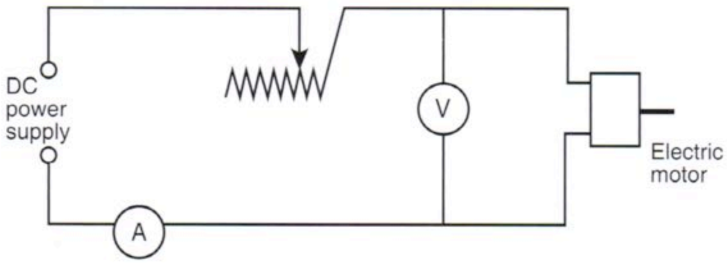
To collect a voltage vs time graph for a back emf signal from a DC motor.

Equipment

- small electric motor.
- voltmeter or voltage probes
- ammeter or current probes
- data logger if using probes (Labquest or similar)
- leads with banana plugs and/or alligator clips
- switched power supply and rheostat or variable power supply to 6 V DC

Lab notes

1. Clamp the small electric motor so that its shaft is horizontal.
2. Connect the voltmeter or voltage probe to the terminals of the motor.
3. Rotate the shaft of the motor slowly by using your thumb and forefinger and observe what happens to the reading on the voltmeter whilst this is happening.
4. Connect the circuit according to the diagram below and as shown in the photograph making sure the power supply is switched off.
5. If you are using a switched power supply make sure it is set at 2 V DC and the rheostat is at its highest resistance. If you are using a variable supply make sure it is set to zero.



6. Switch the power supply on and check that the shaft of the motor is not spinning.
7. By slowly decreasing the resistance varying the rheostat, take readings of voltage and current for up to six voltage readings between 0 and 1.5 V. Record your sets of readings in a table.
8. Switch off the power supply.
9. Set the rheostat to zero resistance and change the voltage setting on the power supply to 4 V DC.

Processing of results

1. Draw two graphs of voltage vs current, one for each set of results, on the same set of axes.
2. From the first set of results calculate the resistance of the armature.
3. Calculate a value for the resistance of the armature from the second set of results. Comment on the shape of this second graph.
4. Give a detailed explanation for the different behaviour of the armature in each of these sets of results

Post-lab discussion

1. What is the general trend on the voltage vs time graph over the time that the motor is running and increasing its frequency of rotation? Why is it decreasing?
2. When zoomed in on one rotation, what does the signal look like? Why is not a simple sine wave?
3. In what position do you think the motor is providing the greatest back emf? Use a diagram to explain your answer.
4. How do you think temperature of the motor will be effecting the system?
5. What errors are present in the system?
6. How could you improve this process?

Notes

Investigation 8.5: Energy sources and efficiency

Notes

Background reasearch

Prepare brief notes explaining the following:

- What do we mean by the term 'electricity'?
- Through what materials will electricity flow?
- Distinguish between 'conventional current' and 'electron flow'.
- What is an emf, and how is it measured?
- What are the units used to measure current flow?
- What are the units used to measure the resistance to electricity flow through a conductor?
- What is the unit of electrical power and how is it measured?
- Distinguish between between AC and DC.

The task

- First, make yourself familiar with the various sources of electricity (or sources of electrical energy) by answering the following background questions:
- Identify the various energy transformations by which electrical energy can be produced from other forms of energy, e.g. sound energy to electrical energy.
- Name some of the technological devices that employ each method, e.g. the microphone.
- Name or describe the physical process that each device used e.g. piezo-electric microphone.

Finally, report on your investigation, taking note of the power output available from each source.

Investigation 8.6: Electrical power for transport

1. The most common type of AC motor used in industry is the 'induction' motor.
   a) Explain how an AC induction motor works.
   b) Three-phase AC induction motors have several advantages over single-phase AC induction motors. What are these advantages?
   c) Explain how a linear induction motor works.
   d) Outline some uses of linear induction motors.

2. Perth's urban trains are powered by DC motors. These same motors can also be used as brakes.
   a) Explain the principles of regenerative braking as used on Perth's trains.
   b) Suggest a reason or reasons why the electrical power generated is dissipated as heat in resistors rather than fed back into the electrical supply.

3. Many electric cars are driven by DC motors that are powered from rechargeable batteries. These batteries must be recharged with 15 V DC, but the domestic power supply is 240 V AC. Outline the main features of an AC/DC converter capable of changing 240 V AC to 15 V DC.

Eddy current brakes can be found on semi-trailers.
   a) What are eddy currents?
   b) How do eddy current brakes work?
   c) Do eddy current brakes have any advantages over other types of braking systems?

Notes

Investigation 8.7: Safety and efficiency of electricity in your home

Notes

This investigation requires you to do a survey of the safety and efficiency aspects of the electricity supply in your home.

For safety aspects you will need to investigate the following. In each case you will need to research how they work, and then investigate if they are present in your home. How is electrical energy distributed to homes?

- What types of fuses are used in houses? (melting wire, trip switches, etc.)
- What is an earth wire? What is its purpose? How is it integrated into household wiring?
- What are RCDs and how do they work?
- What are surge protectors and how do they work?
- What are reset buttons for, and how do they work?
- What are the latest regulations/standards for 3 pin plugs and connecting leads?

For efficiency aspects you will need to investigate the following.

- How do you read the electricity meter in the meter box?
- What are the units of electrical energy?
- What is the unit cost of electrical energy?
- How efficient is your home?
- How much electrical energy per hour is used in the daytime when the house is unoccupied?
- Many devices are left in stand-by mode. How much energy is used per hour by these appliances in stand-by mode in your house? (Note: Turn the fridge off during this period of measurement.)
- How much CO_2 is put into the atmosphere by power stations for each unit of electrical energy produced? Note that each kilogram of coal burned produces 3.7 kilograms of CO_2.
- How much CO_2 is put into the atmosphere by power stations during one year of normal operation of your home? Note that each kilogram of coal burned produces 3.7 kilograms of CO_2.

Problem Set 8: Electrical energy and power

1. A defibrillator is a device medical personnel use to return an irregular heart beat to its normal rhythm. A defibrillator passes a 20 A current at 3000 V through a patient's heart in about 5 ms. Estimate the following:
   a) How much electrical power does a defibrillator provide?
   b) How much electrical energy passes through a patient?
   c) What is the resistance of the patient's body in this circuit?

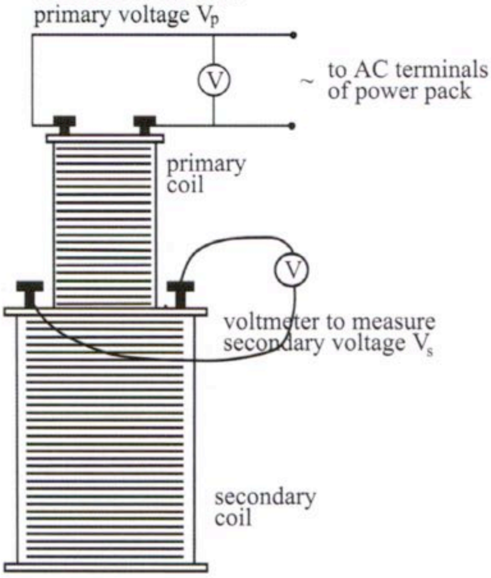
2. A particular communications satellite consumes electrical energy at a rate of 2000 J s^{-1}. The satellite is powered by a solar panel that receives 1373 J of per second from the Sun on each square metre of panel.
   a) If the panel converts solar energy into electrical energy at 10.0% efficiency, what is the area of the panel required to meet the satellites energy needs?
   b) If the panel provides an output voltage of 50. 0 V under optimum load, calculate the load's resistance.

Notes

3. An electric train has a motor rated at 1.50 kV, 125 kW.
   a) Calculate the current the motor draws.
   b) Calculate the circuit resistance.

4. While performing a laboratory investigation on the structure of a step-down transformer, a student noticed that the wire in one of the coils was thicker than the wire in the other coil. Does the thicker coil belong to the primary coil or the secondary coil? Explain why this is so.

5. The diagram at right shows a simplified view of a transformer without its metal core plates. It consists of two coils of wire, one inside the other. If the current in the outer coil is flowing in an anticlockwise direction and is increasing, explain how you would determine the direction of the current induced in the inner coil. Lenz's Law may be useful in explaining your answer.



coils and core shown 'exploded'

6. A transformer in a neon sign changes 240 V to 12.0 kV.
   a) Assuming that the transformer is ideal, compare the magnitude of the current in the secondary coil to the magnitude of the current in the primary coil.
   b) If the primary coil had 200 turns of wire, how many turns should there be in the secondary coil?
   c) If the transformer is actually 98.0% efficient, how large is the current in the secondary coil compared with the current in the primary coil?

7. An electric jug has a rating of 240 V, 2.50 kW.
   a) Calculate the jug's resistance.
   b) If the jug is used to heat water over a 2.00 minute period, how much electrical charge will have passed through the jug in that time?

Notes

8. A car engine needs about 1 kW to start it. The starter motor supplies this power. The starter motor is 80% efficient and it runs off a 12 V battery.
   a) Estimate the current the starter motor draws from the battery to start the engine.
   b) In what way is the diameter of the copper wire that joins the battery to the starter motor quite different to the other electrical wires in the car? Why is this so?

A substation

9. a) For a typical electricity grid system, what is the role of a 'sub-station'?
   b) Suggest some reasons why an electricity company would not use the same sub-station to supply electricity to both an electric train system and to nearby houses.
   c) A power station generator produces a voltage of 18.0 kV, but the voltage in the transmission line that carries the electrical energy to the suburban sub-stations is 330 kV. Why does the electrical utility 'step up' the voltage before it is transmitted?

10. An electricity generation plant in a small town produces an average of 500 kW of electric power. The 10.0 km length transmission line from the power plant to the town's sub-station has a total resistance of 0.500 Ω. The voltage is stepped up at the plant from 2.00 kV to 20.0 kV and then down to 240 V in the town.
    a) If the plant had transmitted electricity at 2.00 kV, what power loss would have occurred in the transmission line when working at the average power output?
    b) Under normal circumstances the plant transmits at 20.0 kV. What power loss would occur in the transmission line at this voltage?
    c) Compare your answers to a and b. Give a reason why power is usually transmitted at very high voltages.

11. Electric utilities usually transmit energy at very high voltages. However, engineers have worked out that voltages over 1000 kV are uneconomical, and have an impact on the environment. Why should this be so?

12. An electric motor in a goods lift needs a minimum voltage of 405 V to operate. The cable supplying power to the motor comes from a transformer that has an output of 415 V. When the lift is operating, the cable carries a current of 200 A and has a resistance of 4.0×10^{-1} Ω per metre of cable.
    a) Determine the power loss in the cable when the voltage at the electric motor drops to 405 V.
    b) Determine the maximum length of cable that can supply the minimum of 405 V to the motor.
    c) How would you change the this arrangement to allow the motor to work at a larger distance from the transformer?

13. A portable generator can provide 5.00 kW of electrical power. A petrol engine drives the generator. The generator is 80.0% efficient.
    a) How much mechanical power must the engine provide?
    b) Explain where you think the power losses occur in the generator.

Notes

14. Electric motors, fluorescent lighting systems and arc welding equipment all use some of the electrical energy they consume to create magnetic fields. If you have several such devices operating at your house, what effect would this have:
   a) on the voltage available to other devices on your property?
   b) on the temperature of the supply lines to your property?
   c) on the brightness of electric lights on your property?

15. A 3.00 MW substation provides current at 25.0 kV to electric trains through overhead wires. The wires are designed to operate in the voltage range 20.0 to 25.0 kV. If the resistance of the overhead wires is 1.20 Ω km^{-1}, how far from the substation can the train travel before the supply voltage drops below its operating needs?

16. A transformer is manufactured with a primary coil of 300 turns and a secondary of 4800 turns. The transformer is known to have a design efficiency of 92.0%. When the primary is connected to a 240 V rms supply the current in the secondary, under normal operating conditions, is measured at 40.0 mA rms.
   (a) Name two possible sources of inefficiency in the transformer.
   (b) Calculate the peak secondary voltage when there is no load on the output.
   (c) What will be the peak primary current when the current in the secondary circuit is measured at 40 mA rms?

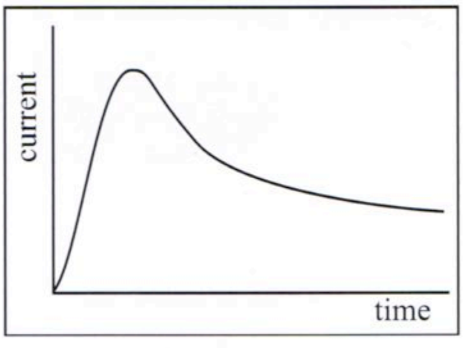
17. A transformer designed to work on a primary input of 240 V rms has two independent sets of secondary windings. One of these is step down and delivers 6.30 V rms at 8.00 A to the heating element of the electron gun of a cathode ray tube and the other is a step up that delivers 35 000 V rms at 15.0 mA to the velocity filter of that same electron gun. The secondary coil of the 6.30 V secondary coil has 84.0 windings. Assume the transformer has an efficiency of 100% in your calculations.
   (a) How many turns (to the nearest whole number) are on the primary coil?
   (b) How many turns (to the nearest whole number) are on the 35 000 V secondary coil?
   (c) Calculate the total current in the primary coil when both secondary coils are drawing there operating currents.
   (d) How would the wires in the two secondary coils differ from each other? Explain.

18. A DC motor with a resistance of 20.0 Ω is connected to a 414 V supply. It draws an operating current of 9.00 A.
   (a) Calculate the back emf and the operating voltage across the terminals of the coil.
   (b) What value series resistor would be needed to ensure the coil never draws more than 12.0 A on start-up?

19. A DC motor with a coil resistance of 6.30 Ω is connected to a 240 V supply. The motor generates a back emf of 212 V at maximum revolutions. Calculate:
   (a) The current drawn by the motor at switch on.
   (b) The current drawn by the motor at maximum speed.

20. The 12 V DC motor in an electric train set draws a current of 5.00 A when the train starts moving and this drops to 1.20 A when the train reaches full speed. Calculate the back emf this motor generates at full speed.

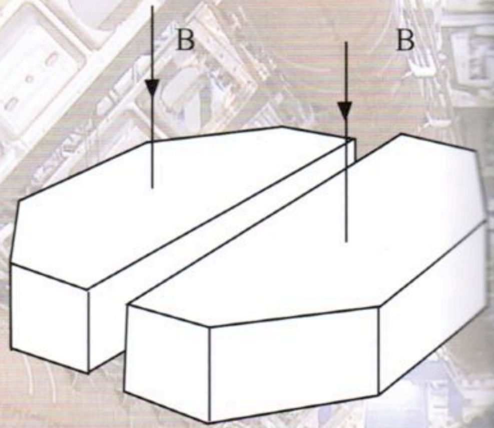
21. A simple DC motor is connected to a battery pack and the current through it measured using an digital ammeter. The results obtained were plotted against time for the first few seconds and the graph (right) was obtained. Explain the shape of this graph.



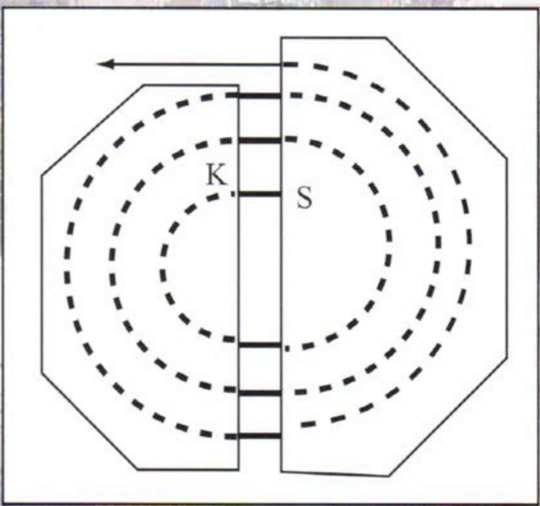
The Large Hadron Collider

Particle accelerators are machines that feed energy into charged particles. The particles have to be charged because electric and magnetic fields will not accelerate neutral particles. There are many types of particle accelerator, two of which are described here.

A cyclotron is a machine for accelerating ions to very high kinetic energies. It consists of two hollow electrodes (called 'dees') situated in a strong magnetic field B perpendicular to the dees, as shown in the diagram at right.



A source S, situated near the centre and at the edge of one dee, emits ions of mass m and charge q with negligible velocity. These ions are accelerated across the narrow gap between the dees by a potential difference V applied between the dees. The path of the ions is shown in the diagram at left in which you are looking down on the dees along the magnetic field. In fact, the ions make many more circuits than are shown in the diagram.



The maximum particle energy in a cyclotron is limited because the particles increase in mass as they increase in energy (so-called 'relativistic effects') and this makes the accelerating fields get out of step with the orbiting particles.

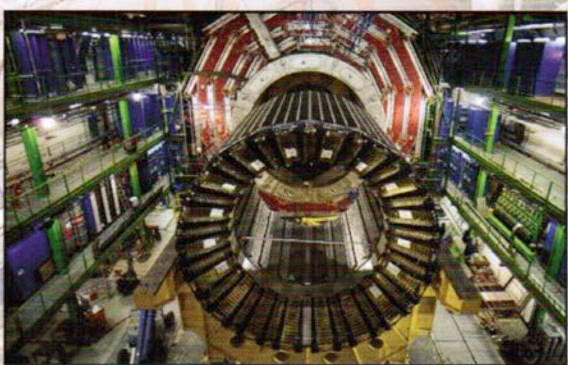


Photo: NASA

The machine that gives ions the greatest energy increase at the present time is the Large Hadron Collider, LHC, in Switzerland. That's 'large collider', not 'large hadrons'.

In the LHC the ions are sent in a circular path with regular energy boosts along the way. The particles may circulate at about 10 000 revolutions per second for ten hours or more, gaining energy all the way. Then, two particle beams, each of very high energy, are directed by magnetic fields into collision courses, doubling the collision energy. In the LHC, protons can be accelerated to 7 TeV (7×10^{12} eV) so they collide with a combined energy of 14 TeV. At 7 TeV, a proton's velocity is 99.9999991% of c, the speed of light. The result of such collisions can then be compared to predictions from theory. This feedback between theory and experiment leads to improvements in both the theory and the experiments.

The scale of the LHC is staggering compared to most other accelerators. The first synchrotron ever built had dees about 10 cm in diameter. The LHC is an evacuated tube with a diameter of 8.6 kilometres, with about 1600 immensely powerful superconducting electromagnets that have to be cooled to 1.9 K (-271°C) in order to operate.

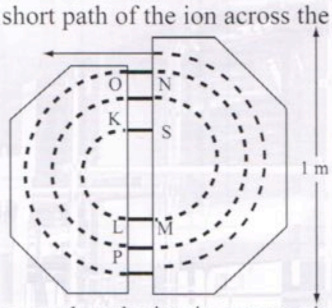
The Large Hadron Collider: comprehension questions

Comprehension questions

In the questions that follow, give your answers where appropriate in terms of V, B, m and q.
Questions 1 to 9 are about the behaviour of particles in a synchrotron.

1. Determine the speed v of an ion, emitted by the source, after this ion has moved across the gap and is just entering the left hand dee at point K. Assume that the effect of the magnetic field can be neglected for the short path of the ion across the gap.

2. After it enters the left hand dee, the ion is in a region of constant potential (no electric field) and is subject only to the influence of the magnetic field. Determine the radius of curvature of the ion's path as it makes its first passage through the dee (K to L in the diagram at right).



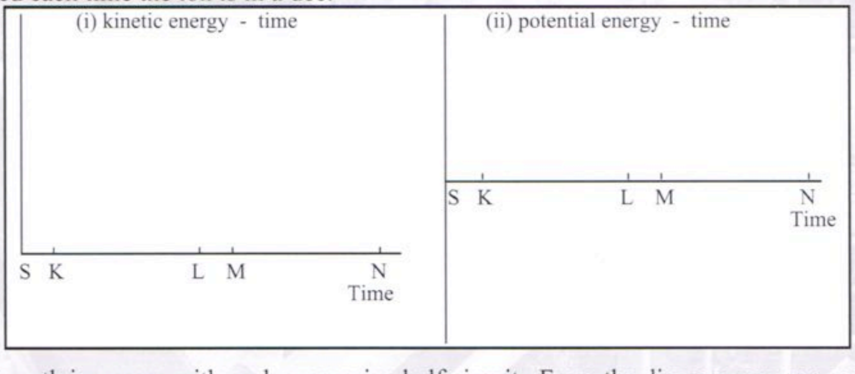
3. While the ion is in the left hand dee, the potential difference V between the dees is reversed so the ion is once again accelerated as it crosses the gap a second time (from L to M). Determine the speed of the ion as it re-enters the right-hand dee at M.

4. By what factor will the radius of curvature of the ion's path M to N in the right hand dee differ from the pervious radius on the path K to L?

5. This sequence of events is repeated many times and the ion follows a path of increasing radius, as shown in the diagram above. What time does the ion spend in the dees while travelling any of the semi-circular paths such as OP?

6. The reversal of the potential difference between the dees is accomplished by a high speed electronic reversing switch. The gap is very narrow so the ion spends negligible time in the gap compared to the time spent in the dees. How frequently must the switch reverse the potential difference?

7. Sketch graphs (see axes below) showing how (i) the kinetic energy and (ii) the potential energy of the ion vary with time. The times at which the ion is at the points S, K, L, M and N are indicated on the axes supplied below. Remember that the potential difference V is reversed each time the ion is in a dee.



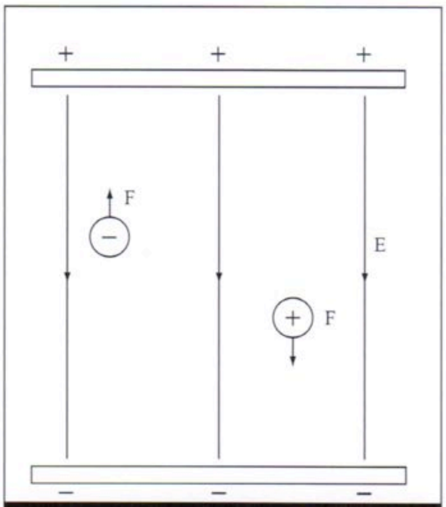
8. The radius of the ion's path increases with each successive half circuit. From the diagram you can see that the ion finally emerges from the dees when its path diameter is about equal to the width of the dees. In a particular cyclotron the width of the dees, as shown in the diagram, is 1.0 m, B is 1.0 T, V is 500 volt and the ion being accelerated has charge $q = 1.6 \times 10^{-19}$ C and mass $m = 3.5 \times 10^{-27}$ kg. Estimate how many orbits (complete circuits) this ion will make before it emerges from the dee.

9. For the data supplied, calculate the approximate kinetic energy of the ion (in electron-volts) as it emerges from the cyclotron.

10. Show that the mass of a 7 TeV proton is about 2×10^{-23} kg.

11. Why is this mass greater than the rest mass of a proton?

Charged particles in an electric field explained



Parallel plates

Remember the following important principles

The region around a charge or group of charges that can influence another charge placed in that region is known as an electric field. When a charge is in an electric field it experiences a force. The force is a result of the interaction between the electric field and the charge.

The magnitude of an electric field is the size of the force it causes on a charge placed at a point in the electric field.

The relationship between the electric field strength (E) and the force it causes to act on a charge is:

$$E = \frac{F}{q}$$

Where:

F is the force acting on a small charge, q

Notes

Electric field strength is a vector with the unit newton per coulomb ($N\ C^{-1}$) or volt per metre ($V\ m^{-1}$).

Two oppositely charged parallel plates that are close together have an electric field between them that is uniform, except near the edges. A charged particle in the uniform electric field between the plates experiences a force and therefore moves.

You can determine the work done by the electric field in moving the charge a distance d parallel to the field by the relationship:

$$W = Fs = Eqd \qquad \text{i. e. } W = Eqd$$

where:

W is the work done (joules, J)
E is the electric field strength ($N\ C^{-1}$)
q is the charge on the particle (coulombs, C)
d is the distance the charged particle moves (metres, m)

also,

$$W = V\,q$$
$$Eqd = V\,q$$

where:

V is the potential difference through which the charged particle is moved.

Experiment 9.1: Mapping an electric field

Background

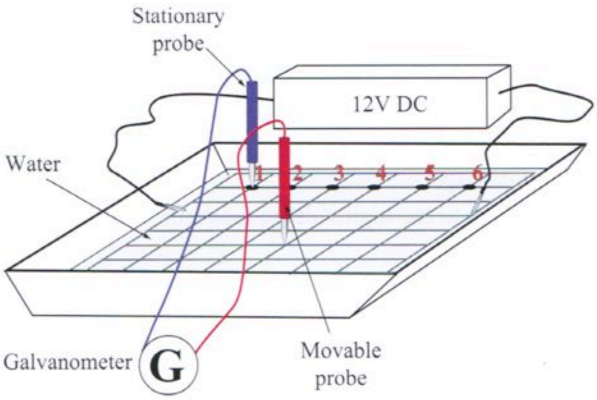
Equipotential lines join points having the same electric potential. Points along an equipotential line are all at the same voltage, so no current flows between them. Electric field lines are always at right angles to equipotential lines.

Pre-lab

- Set up an electric field in a bath of salt water by placing positive and negative electrodes in it.
- Map the equipotential lines by finding curves along which no current flows.
- Map the electric field by drawing lines connecting the electrodes that intersect the equipotential lines at right angles.

Lab notes

- Make sure that your pan contains a plotting sheet. Cover the sheet with a thin layer of water.
- Place the positive and negative electrodes at the ends of your plotting sheet as shown. Your instructor will check the circuit before turning up the voltage.
- Place the stationary probe at the first of six locations as shown. An electric circuit connects this probe through a galvanometer (current meter) to a moveable probe. When current flows through this circuit, the galvanometer will register it; as the current goes to zero, the galvanometer reading will go to zero also. By searching with the moveable probe for points of zero current, and marking them on the plotting sheet, you can map out an equipotential line.
- As you locate each point of zero current in your pan, mark this location on your individual sheet of graph paper.
- Repeat the Pre-lab for each of the stationary probe locations (see diagram below). Note that you should gather enough data to draw at least six equipotential lines.



Post-lab discussion

1. Points along the same equipotential are mapped by finding locations in an electric field between which no current flows. Explain.
2. Why was the experiment carried out in salty, rather than pure, water?

Notes

Experiment 9.2: The Van de Graaff generator

Notes

Background

A van de Graaff generator is a high voltage, electrostatic generator. The electric charge is carried by a belt and transferred to a large-diameter, hollow metal dome. The sphere stores the charge; every extra electron on the dome increases its electric potential (voltage).

Under ideal conditions, charge may accumulate on the dome until the potential reaches several hundred thousand volts. Such high voltages are possible because the belt that transfers charge to the dome is an insulator, and the air around the dome is also an insulator, trapping the charge.

Dust or humidity increases the air's conductivity. Under these less-than-ideal conditions, the dome cannot reach very high potential because it continually leaks charge into the air.

Aim

To charge a van de Graaff generator and explore some of the effects of very high voltages.

Equipment

- van de Graaff generator and its accessories
- balloons or a Leyden jar
- spoon with an insulated handle
- Hamilton's mill
- fluorescent tube
- candle
- aluminium foil
- paper strips
- ebonite or plastic rod
- two metal plates
- access to a water tap, scissors and glue

Warning: Although the van de Graaff generator normally produces a very small current when it is discharged, the high voltage spark can still cause harm. In particular:

- Avoid bringing your face anywhere near the dome, as a spark into the eye can cause permanent damage.
- Avoid exposure to the high voltage discharge if you have any type of heart condition or a history of epilepsy.

Pre-lab

- Make sure that the belt and metal dome are clean and dry.
- If necessary, dry the van de Graaff belt and the air around it with an electric heater.

Lab notes

Notes

Once the van de Graaff dome is charged, you can remove charges from it by 'spooning'. A copper blade set in an insulated handle is suitable. Touching the charged spoon to an inflated balloon should transfer charge to the balloon. Find out what happens if you bring your finger close to a charged balloon; bring two charged balloons close to one another; or bring a charged balloon close to a volunteer with long, loose hair.

Your school may have one or more Leyden jars. These can be used to store and carry charge more efficiently than a balloon.

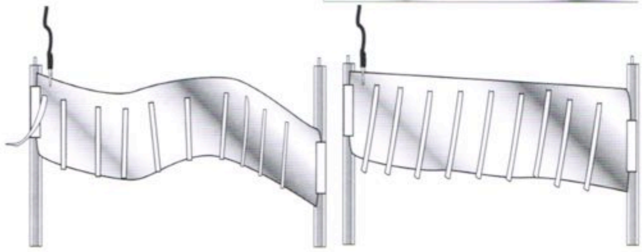
Connect a small metal sphere attached to an insulated handle to the earth terminal of the generator. Bringing the small sphere close to the charged dome of the generator should cause a spark. Find out how the distance between the dome and the sphere affects the way that the generator discharges.

A Hamilton's mill (basically a wire windmill on an insulating stand) can be fitted to the top of the dome and connected to the dome with a wire before charging. Observe what happens when the dome charges up.

Connect a needle or pin to the generator dome before charging, and support it on an insulated stand about 20 mm from a lit candle. Observe what happens when the dome charges up.

Hold the metal contacts at one end of a fluorescent tube onto the generator dome. Observe what happens when the dome charges up.

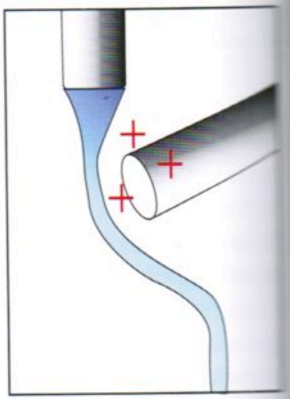
Cut narrow strips of paper and glue them near one edge of a band of aluminium foil. Support the aluminium foil band on two insulated stands as shown, and attach a wire from the dome of the generator to the foil, before charging. Observe what happens to the paper strips when the generator charges up.



Experiment 9.2: The Van de Graaff generator

Notes

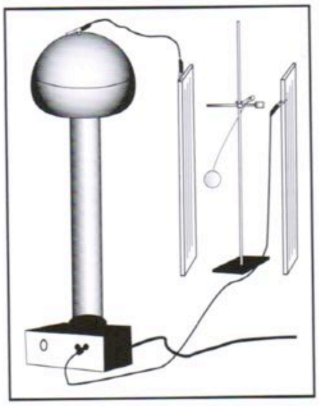
Charge an insulating rod (ebonite or plastic) and hold it near the column of water from a slow running water tap. Observe what happens to the water stream as the generator charges up.



Suspend two pith balls on individual cotton threads from an insulated stand. Connect the ends of the threads to a lead from the dome of the generator, before charging. Observe what happens when the generator charges up.

Suspend a pith ball on a cotton thread from an insulated stand. Place a flat metal plate on one side of the pith ball. Connect the plate to a lead from the generator dome, before charging.
Set up another plate on the other side of the pith ball and connect it to the dome as well.

Make sure the plates are insulated from each other. After the apparatus is set up, start the charging process. Use an insulating (non-conducting) rod to adjust the gap between the plates until the pith ball swings from plate to plate.



Post-lab discussion

1. Explain how you can charge a balloon by contact with a 'spoon' as described above.
2. What causes the light you see when the dome discharges in a 'spark'? What causes the sound?
3. What does the Hamilton's mill apparatus do as the dome charges up? Explain.
4. Explain the effect of the charged needle on the candle flame.
5. Why does the fluorescent tube light up when the generator dome charges up?
6. Consider the paper strips glued to aluminium foil and connected to the generator. Explain the behaviour of the paper strips when the foil is curved, and when it is held straight.
7. Why does a charged rod affect a stream of water?
8. Consider the two suspended pith balls charged by the generator. Explain why they behave as they do.
9. Consider the 'electrostatic pendulum' in which a suspended pith ball is placed between parallel charged plates. Explain what you observe.

Investigation 9.3: Lightning

Notes

1. What is lightning, and what causes it?
2. What causes thunder?
3. Why is there a time lag between the flash and the sound?
4. Are clouds necessary in producing lightning?
5. Can lightning occur in any type of cloud?
6. What is 'ball lightning'?
7. Does lightning occur only in Earth's atmosphere or is there evidence of lightning on other worlds?

Research these questions, and write a report that highlights the physics underlying each. Your report should include relevant mathematical treatments of the information where these are appropriate. Remember that this is a Physics report and ensure that the physics ideas are given appropriate importance. You may wish to review your notes about Experiment 9.2 if you have done it.

Make sure that you give credit to any sources that you use, for example by indicating direct quotations and by listing the title, author and related details in your reference list.

Problem Set 9: Charged particles in an electric field

Notes

3b

1. At a point in an electric field, an electron experiences force of 7.20×10^{-13} N. Determine the electric field strength at this point.

2. Two scientists measure the electric field strength in a region. One reports it as 200 N C^{-1} while the other reports it as 200 V m^{-1}. Show that these two units are equivalent.

3. A cathode ray tube (CRT) contains parallel plates that are 30.0 mm long and have an electric field strength between them of 2.50×10^4 N C^{-1}. An electron travelling at 2.90×10^7 m s^{-1} enters the field at right angles.
   a) Draw a diagram to represent the electric field between the charged plates.
   b) Compare the velocity (including direction of movement) of the electron as it leaves the electric field with its velocity on entering the electric field.
   c) Explain why the electron experiences a change in its velocity.
   d) Explain how a CRT uses the deflection of electrons by such parallel plates.

   The CRT accelerates an electron from rest through a potential of 1.80 kV. Find:
   e) the electron's gain in kinetic energy; and
   f) the electric field strength if the electron travelled 30.0 mm.

4. The radio frequency component of a radio or television set is totally enclosed in a hollow aluminium box. Explain why the manufacturers do this.

5. Two parallel conducting plates are separated by 3.00 mm and have an electric field between them of 2.20×10^4 N C^{-1}. A charge of +5.00 nC moves against this field from one conducting plate to the other. Find
   a) the work done on the charge, and
   b) the potential difference between the plates.

6. What is the electric field strength between two parallel plates 120 mm apart that have a potential difference of 12.0 V?

7. An electron is accelerated by a potential difference of 5.00 kV. Determine the electron's gain in kinetic energy
   a) in electron-volts
   b) in joules

8. An alpha particle (helium nucleus) is accelerated by a potential difference of 5.00 kV. Determine the alpha particle's gain in kinetic energy
   a) in electron-volts
   b) in joules

9. The gap between electrodes in a particular spark plug is 2.70×10^{-4} m and they have a potential difference of 1.50×10^4 V between them. Calculate
   a) the electric field strength between the electrodes; and
   b) the energy gained or lost by an electron that moves between the electrodes.

10. When the driver got out of a car after stopping it at the side of a dry gravel road, the driver's polyester shirt attracted dust particles.

   a) Explain why the shirt attracted the dust
   b) If the electric field strength is 9 N C^{-1} and the shirt has a charge of 4 μC, estimate the magnitude of the electric force acting on a dust particle
   c) If a dust particle acquired 3.6×10^{-7} J of kinetic energy, estimate how far it moved towards the shirt, and through what potential difference it moved?

10. a)

11. Many coal fired electric power stations have electrostatic precipitators inside their chimney stacks. Explain:

   a) how an electrostatic precipitator works
   b) why a power company would install one.

11.

12. To demonstrate the magnitude of the electric field produced by a Van de Graaff generator, an investigator used a fluorescent tube. When she held the tube so it pointed towards the generator, it produced light and flickered. When she held the tube at right angles to the generator, it produced no light. Explain why the tube produced light in the one orientation but not in the other.

12

13. An initially stationary proton is accelerated by a potential difference of 800 V. Determine the proton's final speed.

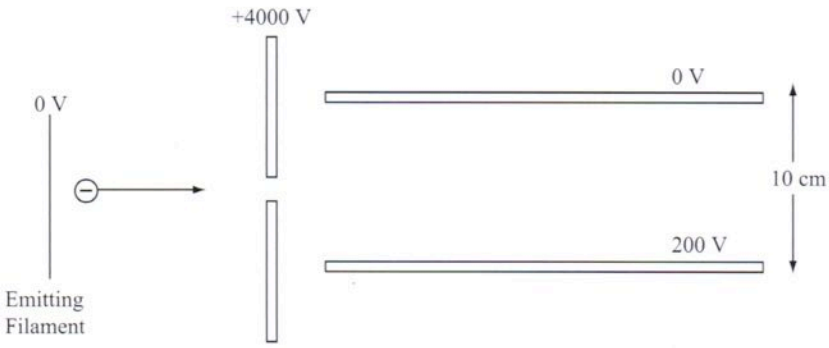
14. An initially stationary electron is accelerated over a distance of 10.0 cm by an electric field of strength 2.50×10^{4} V m^{-1}.

   a) Draw a labelled diagram showing the direction of the field and the direction of the electron's final velocity;
   b) Determine the electron's change in kinetic energy;
   c) Calculate the magnitude of the electron's final velocity.

   If the same field had accelerated a proton instead of an electron,

   d) Draw a labelled diagram showing the direction of the field and the direction of the proton's final velocity.
   e) Would the proton have gained more than, the same as, or less than the kinetic energy gained by the electron?
   f) Would the magnitude of the proton's final velocity be greater than, the same as, or less than the final velocity of the electron?

15. An electron in a cathode ray tube was accelerated from the emitting filament to a plate, through a potential difference of 4000 V.



a) Assuming the electron started at the filament with negligible velocity, calculate the energy and velocity it attained by the time it reached the plate

b) The electron then passed through a hole in the plate and moved between two long, parallel deflecting plates 10.0 cm apart. If these plates were at a potential difference of 200 V, calculate the electric field strength between them, and hence the deflecting force acting on the electron.

c) Draw a diagram showing the plates, the electric field between them, and the path of the electron assuming that it did not contact either plate during its passage.

Notes

16 c), d)

16. A plane heated filament emits electrons having negligible kinetic energy. There is a plate parallel to the filament, situated 5.00 cm away in vacuum, that is maintained at +2000 V with respect to the filament.
    a) Explain why this would be done in a vacuum.
    b) Calculate the acceleration of the electrons.
    c) If there is a small hole in the plate and there is no electric field in the region of space on the side of the plate away from the filament, sketch suitably labelled graphs to indicate how the following quantities vary as a function of distance from the filament to a point 2.00 cm beyond the plate:
       (i) acceleration of emitted electrons;
       (ii) velocity of emitted electrons;
       (iii) kinetic energy of emitted electrons.
    d) On the same graphs that you drew for (c) above, plot the way that the same three quantities would vary with distance if the hot filament is replaced by a source that emits heavy, singly-charged negative ions. Make sure that your graphs show clearly which lines apply to electrons and which to ions.

17. Calculate the electrostatic force between the proton and electron in the hydrogen atom, assuming the average atomic radius is 5.30×10^{-11} N.
(permittivity of a vacuum = 8.84×10^{-12} C^2 N^{-1} m^{-2})

18. Two small positively charged spheres, carrying charges of 7.00 nC and 9.00 nC, are situated 25.0 cm apart in paraffin oil. Calculate the force on each sphere given the permittivity of paraffin oil is 4.18×10^{-11} C^2 N^{-1} m^{-2}.

19. Two identical charges of 1.20 μC are immersed in a liquid. When they are separated by a distance of 68.4 cm a force of 1.86 N is measured between them. What is the permittivity of the oil?

Charged particles in magnetic fields explained

Notes

A small charged particle such as an electron or a proton is not affected by a magnetic field unless the particle is moving across the field lines. A moving charged particle creates around itself a small magnetic field. The particle's field interacts with the magnetic field through which the particle is moving, as long as the particle's path crosses field lines. The result is that a force acts on the particle, at right angles to its velocity. As long as the force is at right angles to the velocity, the particle moves in a curved path, for example tracing out a half circle if the field is big enough.

Note that if the particle travels parallel to the field lines, there is no interaction with the field and hence no magnetic force. Such a particle travels through the magnetic field undeflected.

The magnitude of the deflecting force is given by:

$$F = qvB$$

where:

q = particle charge in coulombs (C)
v = particle velocity (m s^{-1})
B = magnetic field strength (T)

You can determine the direction of the force by applying the 'right-hand rule'.

For a charged particle moving in a circular path:

$$F_{magnetic} = F_{circular}$$

$$q\,v\,B = \frac{m\,v^2}{r}$$

$$\therefore r = \frac{m\,v}{q\,B}$$

This formula is useful in calculating the radius of the circular arc travelled by a charged particle in a magnetic field.

Many instruments make use of magnetic fields to control the path and width of a beam of electrons. Examples include cathode ray oscilloscopes or CROs, cathode-ray televisions, and electron microscopes. (Note that LCD and plasma television sets work on a very different principle.)

Two instruments that use the charged particles will move in a circular path in a magnetic field are the mass spectrometer and the cyclotron or synchrotron.

The problems in Set 10 do not take into account relativistic effects.

Experiment 10.1: Electromagnetic stirrer

Notes

Background

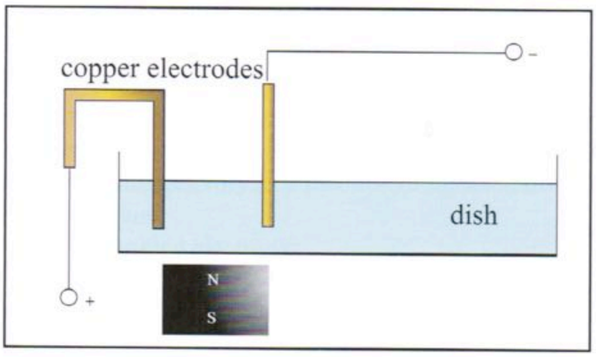
A current passing through a solution involves charges moving between two electrodes. If these charges also move through a magnetic field, they experience a force that stirs the liquid.

Equipment

- Very strong rare-earth disc magnet
- glass petri dish
- saturated solution of $CuSO_4$
- copper electrodes
- 12 V DC power supply

Pre-lab

- Connect the apparatus as shown in the diagram. It helps if you glue the electrodes into place.



Lab notes

- Turn on the current and observe and record the result. Some chalk dust on the surface makes this more obvious.
- Try reversing the field or current directions. Observe and record the result.

Post-lab discussion

1. Using a labelled diagram, explain how the magnetic stirrer actually stirs the liquid.
2. Using a labelled diagram, explain the effect of reversing the current direction.
3. Using a labelled diagram, explain the effect of reversing the magnetic field.

Investigation 10.2: The Earth's magnetic field

Notes

The Earth's magnetic field is usually shown as roughly the same shape as the field around a bar magnet, with the poles of the bar magnet near the Earth's north and south poles. What is the shape of the Earth's magnetic field on a smaller scale – for example, inside your Physics laboratory?

Discuss and plan how you will determine the direction of the Earth's magnetic field at various locations in the laboratory. If you have access to instruments that can measure the strength of a weak magnetic field such as that of the Earth, you should determine both the direction and the strength of the field at a range of locations. You should also plan how you will record and map this information.

Be sure to explain both regularities and anomalies in your mapped field, and relate your findings to the 'bar magnet inside the Earth' model described above.

Problem Set 10: Charged particles in a magnetic field

Notes

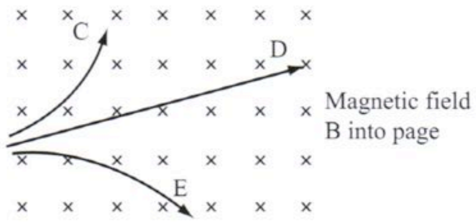
1. a) Explain what we mean by the term *magnetic field*.
   b) Sketch the shape of the magnetic field surrounding the Earth.
   Indicate clearly the geographic and magnetic poles, and show the direction of the field.
   c) A short straight length of steel wire that has been stroked from end to end with a magnet, and a short straight length of copper wire carrying a current, each produce a magnetic field. Describe how these fields *differ*.
   d) How could the copper wire be made to produce a field more like the field produced by the steel wire?

2. Sketch the magnetic field distribution for each of the following arrangements, indicating any null points:
   a) bar magnet,
   b) two bar magnets in line, with opposite poles facing each other and separated by 50 mm,
   c) two bar magnets in line, with similar poles facing each other and separated by 50 mm,
   d) two bar magnets placed parallel to each other, about 50 mm apart, and with opposite poles adjacent,
   e) two bar magnets in line, separated by 80 mm, with opposite poles facing and with a small iron washer placed midway between them.

3. Draw the magnetic field pattern for each of the following:
   a) a single straight current-carrying copper wire, and
   b) a current-carrying circular coil of wire.

4. An electron, travelling at a constant speed, enters a region of uniform magnetic field. Describe the subsequent motion of the electron if the field direction is:
   a) parallel to the electron's direction of motion;
   b) perpendicular to the electron's direction of motion.

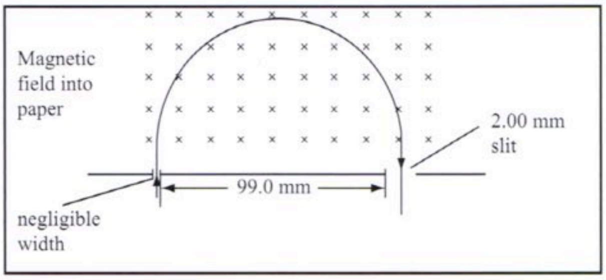
5. Particles C, D and E follow the paths shown in the diagram as they pass through a magnetic field. What conclusions can you draw about the charges on particles C, D and E?



6. A proton of mass m is emitted from the Sun and enters the Earth's magnetic field with a velocity v. Assume that this magnetic field has a magnitude of B, is uniform and at right angles to the direction of travel of the proton.
   a) Using the variables listed above, write an expression for the force F experienced by the proton.
   b) Hence deduce the subsequent path of the proton. Use a labelled diagram and explain clearly why the path has its particular shape.
   c) This path is a repeated one. Derive an expression for the rate at which it is repeated (that is, derive an expression for the frequency).
   d) If you could measure this frequency, what information (if any) would it give you about the speed of the proton and the strength of the Earth's magnetic field?

7. A beam of particles, each with a charge of $+1.60 \times 10^{-19}$ C and a velocity of 5.00×10^{6} m s^{-1}, is directed through a narrow aperture into a uniform magnetic field of strength 10.0 T as shown at right. The particles move in a semi-circular path and leave the magnetic field through a slit of width 2.00 mm as shown.

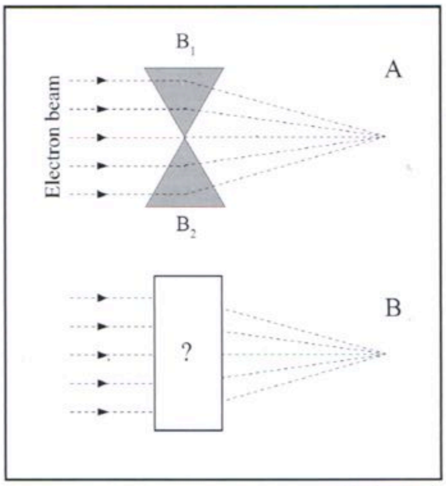
Find the range of masses of particles in the beam that could pass through this slit.



Question 7

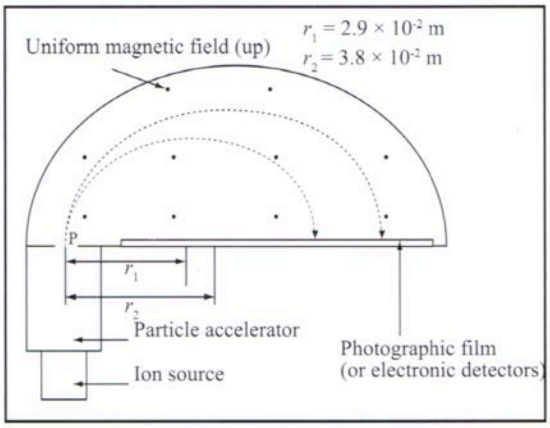
8. A proton moving at 1.00×10^{4} m s^{-1} in a uniform magnetic field of 2.50 μT travels at right angles to the field, and remains in the field.
   a) Determine the radius of the proton's path in this field.
   b) In this field, how long does the proton take to complete one revolution?
   c) Explain how the time for one revolution might change if the magnetic field strengthis increased.
   d) Explain how the time for one revolution might change if the proton's initial velocity is greater.

9. An electron microscope uses a "magnetic lens" to focus a wide beam of electrons to a point, as shown in diagram A. In this case, all the electrons have the same speed.
   a) What would be the directions of magnetic fields B_1 and B_2?
   b) The electron velocity is 1.50×10^{6} m s^{-1} and the magnetic lens has field strength 0.100 T. Calculate the deflecting force.
   c) The triangular shape of the magnetic field deviates the outer electrons more than the inner electrons. Explain.
   d) If the magnetic field was not triangular but had the shape shown in diagram B, how could you achieve different amounts of deviation?



Question 9

10. A mass spectrometer allows researchers to determine the charge to mass ratio $\frac{q}{m}$ of the various components of a mixture of isotopes or fragments of a molecule.
   a) Derive an expression relating $\frac{q}{m}$ to the radius, velocity and magnetic field strength.
   b) A mixture of helium isotopes produces lines as shown at right. If their velocity on entering at P is 2.20×10^{5} m s^{-1} and the field strength is 0.120 T, find the charge to mass ratio of these isotopes.
   c) Two helium isotopes are $^{4}_{2}He^{2+}$ and $^{3}_{2}He^{2+}$. Could these isotopes produce the lines shown? Explain.
   d) In a similar experiment a sample of oxygen forms +1 ions that enter the mass spectrometer at 4.50×10^{4} m s^{-1}. The magnetic field strength is unchanged. The technician identifies three particles at radii 62.0 mm, 66.4 mm, and 70.1 mm. Identify the three isotopes of oxygen in her sample.



Question 10

11. A positively–charged ion travelling at 0.5e enters a uniform magnetic field at right angles and follows a path of radius 4 cm. Estimate the field strength involved.

The Australian Synchrotron

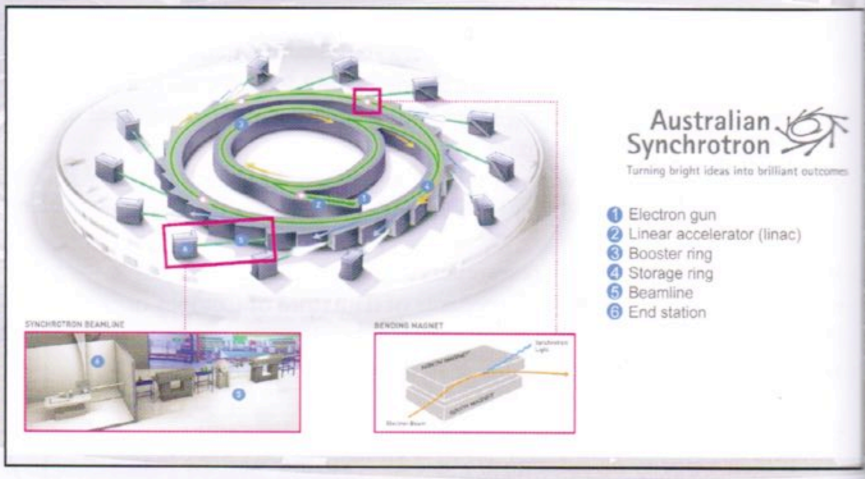
Researchers use the Australian Synchrotron's light source, which is a million times brighter than the Sun, to advance innovation across sectors as diverse as medicine and mining. The only facility of its kind in Australia, it has helped researchers develop improvements to the design of the bionic eye, find ways to boost nutrients such as iron within rice grains and discover how polymer transistors can be used to produce flexible, see-through electronics for mass markets.

Australian and New Zealand scientists use synchrotron light radiation to understand the structure of materials and the workings of whole systems in unprecedented detail. Providing researchers this otherwise impossible level of detail can lead to scientific breakthroughs in areas such as the development of drugs to fight diseases including cancer, diabetes, Alzheimer's or coeliac.

Synchrotron light has also been used in archeology and cultural studies, to determine the source of ochre found in rock paintings in the Northern Territory and to digitally reproduce hidden layers of paintings by artists such as Arthur Streeton, Picasso and Degas. It has even been used to discover what a Victorian dinosaur had for its last meal without breaking bedrock.

So how does the synchrotron produce this bright light and allow researchers to see such brilliant detail?

When electrons are forced to travel in a circular orbit at almost the speed of light, they emit radiation in the form of photons of various wavelengths, ranging from infrared to X-rays. This radiation is called synchrotron radiation and is characterised by its high intensity, making it very useful for studying the absorption, reflection and diffraction properties of matter.



The diagram shows a model of the Australian Synchrotron. Electrons are generated by the electron gun and accelerated to close to the speed of light by the linear accelerator (linac) and the booster ring. They are then transferred to the storage ring. The electrons are forced into circular orbit by a series of powerful bending magnets.

As the electrons are deflected through the magnetic field created by the bending magnets, they give off electromagnetic radiation, with a beam of synchrotron radiation produced at each bending magnet. These intense beams are then directed down a beamline to the end station where a specific wavelength appropriate for a particular technique or specific experiment can be selected. In 2015, the Australian Synchrotron has 10 experimental end stations, but could house more than 30.

For more information, visit the Australian Synchrotron's website, at synchrotron.org.au/education

Comprehension questions

1. What has the Australian synchrotron been used for?
2. Using a flow diagram describe how the synchrotron produces such bright light.

Chapter 11: Charged particles in combined electric and magnetic fields

Charged particles in combined electric and magnetic fields explained

Remember the following important principles

A charged particle experiences a force when it is affected by:

- an electric field. The field acts on the particle's charge, whether the particle is moving through the field, or is stationary. The force equation is $F = Eq$.
- a magnetic field that is at an angle to the direction in which the particle is moving. When the field is at right angle to the direction of the particle's velocity, the force equation is $F = vqB$.
- Its mass is affected by a gravitational field. This happens whether the particle is moving through the field, or is stationary. The force equation is $F = mg$.

We can ignore the gravitational force in most problems, because its effect is weak in comparison to the electric and magnetic forces.

An electric and a magnetic field can exist in the same space. Each can deflect a particle passing through. If the electric and magnetic fields are correctly oriented, a charged particle may pass through them undeflected. This only happens at a particular velocity, and an arrangement of "crossed fields" is sometimes called a *velocity filter*.

Notes

Experiment 11.1: The cathode ray oscilloscope (CRO)

Notes

Background

The cathode ray oscilloscope (CRO) is a laboratory measuring device used to measure and display voltage waveforms. A heart monitor is a form of CRO used to monitor the electrical activity of the heart.

The purpose of this activity is to familiarise you with the controls of a CRO so that you can use it to measure voltages and display wave forms.

Equipment

- Cathode ray oscilloscope
- AC/DC power supply 0 –12 V
- Appropriate leads and coaxial cables
- Lemon
- Copper
- Aluminium and zinc electrodes
- 1.5 V dry cell

Pre-lab

- Not all CROs are the same. Locate the following switches and dials on the CRO you are using.
- *volts/cm switch*: used to obtain trace of convenient height and also for voltage measurement
- input earth
- *Intensity and ON-OFF switch*: turns the instrument on and varies the brightness of the trace on the screen.
- *Focus:* used to control the sharpness of the trace.
- *Time base switch or Time/cm*: The various switch positions give the fastest sweep speed on each range. The control situated in the centre of this switch can be used to vary the sweep speed. Leave this control in the CAL or calibrated position-this is usually fully clockwise.
- *Horizontal position or X-shift*: moves the trace on the screen to the left or to the right.
- *Vertical position or Y-shift*: moves the trace up and down.
- *Sensitivity or volt/cm switch*: adjusts the sensitivity of the instrument.
- *AC-DC switch*
- *Input terminal or socket*
- *Internal-external or Int-Ext switch*: use in the internal position.
- *Triggering or stability control*: use in the auto position.

Lab notes

Before turning on:

- Set horizontal position or X-shift, vertical position or Y-shift and focus to a central position
- Set internal-external to internal
- Set triggering or stability to auto
- Set time base to 10 ms with centre control to cal or calibrated
- Set voltage sensitivity or V/cm to 0.5

Notes

Turning on

- Turn on the power and allow to warm up for a minute or two
- Turn intensity control to maximum (clockwise) till trace appears. If trace does not appear adjust Y-control
- Centre the trace on the screen using the horizontal (X-shift) and vertical (Y-shift) position controls
- Set focus control for a sharp trace

Measuring the battery voltage

- Turn AC-DC switch to DC. Check that the trace is still centred and adjust if necessary
- Connect the 1.5 V dry cell to the input terminals. Record the effect and calculate the cell voltage, using:
  cell voltage = (volts cm^{-1} setting on dial) × (number of cm the trace moved)
- Reverse the battery leads and record the effect.

Measuring the lemon cell voltages

- Insert the aluminium, zinc and copper electrodes into the lemon.
- Measure and record the voltage between the various combinations of electrode pairs: $A\ell$/Zn, $A\ell$/Cu and Zn/Cu.
- Which combination gives the highest voltage?

Displaying waveforms

- With the power pack off, connect the AC terminals of the power pack to the CRO input terminals.
- Set the AC-DC switch on the CRO to AC. Ensure the trace is centred.
- Set the power pack voltage to 2 V and turn on.
- Record the shape of the trace and determine the maximum and minimum voltages of the waveform.
- Measure the period T of the wave using T = time/cm setting × number of cm between adjacent peaks
- Calculate the frequency f of the waveform

Post-lab discussion

1. Why does the CRO need a minute or two to warm up? Which part of the tube actually "warms-up"?
2. How does the horizontal position (X-shift) control move the trace to the left and right?
3. How does the vertical position (Y-shift) control move the trace up and down?
4. Incandescent lamps work equally well on AC and DC. Given a solar cell and a CRO how could you determine if a lit lamp was operating on AC or DC? The leads to the lamp are, of course, not accessible.

Investigation 11.2: Particle accelerators

Notes

Particle accelerators used in research laboratories include the van de Graaff generator, the cyclotron, the synchrotron, the linear accelerator and the colliding beam accelerator.

A related device, the mass spectrometer, is routinely used in laboratories around the world.

The cathode ray oscilloscope (CRO) is also a widely used laboratory tool in which fields are used to accelerate and direct particles.

The X-ray tube accelerates particles as a part of the X-ray production process.

Select any one of these devices, research its development and application, and write a report that highlights the purpose, use of fields in, and the limitations of the device. Your report should include relevant mathematical treatments of the information. Remember that this is a Physics report and ensure that the physics ideas are given appropriate importance.

Make sure that you give credit to any sources that you use, for example by indicating direct quotations and by listing the title, author and related details in your reference list.

Problem Set 11: Charged particles in electric and magnetic fields

Notes

1. Moving charges may be deflected by electric or by magnetic fields. Describe the subsequent motion of a proton that enters
   a) a uniform electric field parallel to the field lines
   b) a uniform magnetic field parallel to the field lines
   c) a uniform electric field at right angles to the field lines
   d) a uniform magnetic field at right angles to the field lines

2. An electron is fired vertically downwards between two vertical, parallel, charged metal plates. The West plate has a positive potential with respect to the East plate. To exactly balance the effect of the electric field, what must be the direction of a magnetic field in this region?

3. A region of space contains a magnetic field of intensity 24.5 mT. A proton travelling at 4.50×10^{6} m s^{-1} enters this field at right angles.
   a) Calculate the strength of an electric field in the same region of space that would allow the proton to pass through undeflected.
   b) Would an electron, travelling at the same speed and also entering the region at right angles to the two fields, pass through undeflected? Explain.

4. A narrow electron beam enters a region at a speed of 6.00×10^{6} m s^{-1} and is suddenly influenced by a magnetic field.
   a) Describe and explain the effect on the electrons in the beam if the field is perpendicular to the beam.
   b) Describe and explain the effect on the electrons in the beam if the field is parallel to the beam.
   c) The electron beam leaves the magnetic field and enters a region in which there exists an electric field of strength 1.00×10^{3} V m^{-1}. Calculate the path of the electrons in the beam if the field is in the same direction as the beam.

5. An electron, initially at rest, is accelerated through a potential difference of 15.0 kV. It is then allowed to circulate at right angles to a uniform magnetic field of strength 2.35 T.
   a) Calculate the electron's final speed before entering the magnetic field.
   b) Determine the electron's path radius in the magnetic field.
   c) Assuming a completely circular path, calculate the electron's time of rotation.

6. A proton moves in a circular path of radius 50.0 mm at right angles to a uniform magnetic field of strength 1.50 T.
   a) Calculate the velocity required for the proton to maintain a circular orbit while in the field.
   b) Determine the frequency and period of the proton's rotation.
   c) Calculate the potential difference through which the proton was accelerated in order to have this speed.

Problem Set 11: Charged particles in electric and magnetic fields

Notes

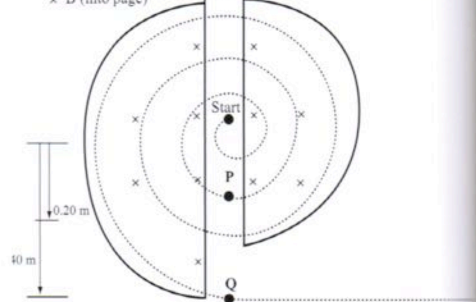
7. An electron beam in a cathode ray oscilloscope can be deflected by either an electric field or a magnetic field.
   a) Compare these two methods with regard to
      (i) the direction of the deflection produced;
      (ii) the effect of the speed of the electrons on this deflecting force;
   b) Show in a diagram how an electric field and a magnetic field can be arranged so that together they produce no resultant force on an electron passing through them.
   c) Such a cancellation of forces can occur for only one particular electron velocity. Calculate the value of this velocity if the electric field has a strength of 1.00×10^4 V m^{-1} and the magnetic field strength is 0.100 tesla.

8. A proton is accelerated from rest through a potential difference of 20.0 kV. The proton then enters, at right angles, a uniform magnetic field of 0.200 T.
   a) Determine the magnitude and direction of the acceleration of the proton in the magnetic field.
   b) Explain why the resulting path of the proton is circular.
   c) What is the strength of the electric field required to be superimposed on the magnetic field in order to allow the proton to proceed in a straight line?

9. An electron travelling at 1.60×10^4 m s^{-1} enters a region where there exists a uniform magnetic field of 3.00×10^{-2} tesla, at right angles to the electron's path.
   a) Calculate the radius of curvature of the electron's path.

   The electron now enters a region where the magnetic force exerted on it is balanced by an electric field.
   b) Calculate the magnitude of the electric field strength required.
   c) Show in a labelled diagram the vectors representing the motion of the electron, the magnetic field and the electric field.
   d) A second electron having a velocity greater than 1.60×10^4 m s^{-1} enters the same region. Using labelled diagrams, show the paths of both electrons through the region, indicating the directions of both the magnetic and the electric fields.

10. A cyclotron accelerates small charged particles in a circular path to very high speeds, then releases the particles to strike a target and make radioisotopes. The cyclotron shown accelerates protons that start at its centre. These travel in circles because of two magnetic fields called dees. An alternating electric field in the gap between the dees accelerates the protons to higher velocities. The magnetic field strength is 1.50 T.
    a) Why does the proton's path radius increase?
    b) Calculate the proton velocities at positions P and Q.



Revolutions in modern physics

The development of quantum theory and the theory of relativity fundamentally changed our understanding of how nature operates and led to the development of a wide range of new technologies, including technologies that revolutionised the storage, processing and communication of information.

Develop your understanding of these modern theories by:

- Examining observations of relative motion, light and matter that could not be explained by existing theories.
- Investigating how the shortcomings of existing theories led to the development of the special theory of relativity and the quantum theory of light and matter.
- Evaluating the contribution of the quantum theory of light to the development of the quantum theory of the atom.
- Examining the standard model of particle physics and the Big Bang theory.

Explore modern physics through such contexts as black holes, dark matter, space travel and the digital revolution and technologies, such as photo radar, fibre optics, DVDs, GPS navigation, lasers, modern electric lighting, medical imaging, nanotechnology, semiconductors, quantum computers and particle accelerators, and astronomical telescopes such as the Square Kilometre Array.

Investigate and apply an understanding of relativity, black body radiation, wave/particle duality, and the quantum theory of the atom, to make and/or explain observations of a range of phenomena, such as atomic emission and absorption spectra, the photoelectric effect, lasers, and Earth's energy balance.

Acknowledgements:
See page one for acknowledgements of the support and contributions of individuals and organisations to the Revolutions in Modern Physics section of this book.

References:
Resources used in preparing explanations and background information for the Revolutions in Modern Physics section of this book may also be useful support with additional information and detail:

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Chapter 12: Wave and photons

Waves and photons explained

Notes

The modern understanding of light

Any form of electromagnetic radiation exhibits properties that combine characteristics of discrete particles (i.e. energy is transferred in "bundles") and characteristics of waves (the best model to describe diffraction and interference).

Physicists accept the dual nature of light. They define light as a collection of one or more photons propagating through space as electromagnetic waves.

This dual nature is known as wave-particle duality. It is not an "either/or" situation. Duality means that the characteristics of both waves and particles are present at the same time. A photon will behave as a particle and/or as a wave depending on the experiment.

Photons

The light particle is known as a photon and it comes into existence when energy is released from an atom. In a simple atomic model, electrons orbit a nucleus made up of protons and neutrons. The electrons occupy separate energy levels, or orbitals. Each orbital can accept only a discrete amount of energy. If an atom absorbs some energy an electron in an orbital close to the nucleus (a lower energy level) can jump to an orbital that is farther away from the nucleus (a higher energy level). The atom is now said to be excited. This excitement generally does not last very long and the electron falls back into the lower energy level. A packet of energy, called a photon, is released. This emitted energy is equal to the difference between the high and low energy levels and, depending on its frequency, might be seen as light.

Waves

The wave form of light can be understood as energy that is created by an accelerating or oscillating charge. This produces an oscillating electric field and an oscillating magnetic field, hence the name electromagnetic radiation. Note that the two fields oscillate perpendicular to each other as shown in figure 12.1. Light is only one form of electromagnetic radiation. All forms are classified on the electromagnetic spectrum by the number of complete oscillations per second that the electric and magnetic fields undergo. This is called the frequency and has the unit cycles per second or hertz (Hz). The amount of energy depends on the frequency of the radiation. Gamma rays, the highest frequency radiation, are the most energetic photons in the electromagnetic spectrum.

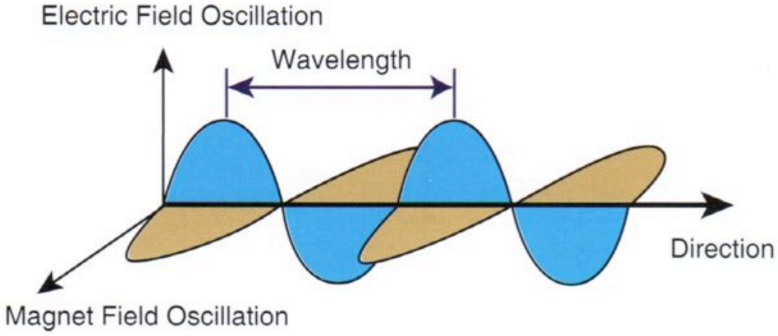
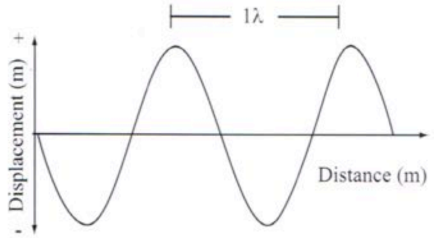
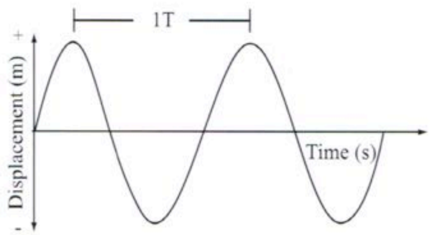


Figure 12.1: Electromagnetic radiation

Summary

- Light exhibits many wave properties; however, it cannot be modelled only as a mechanical wave because it can travel through a vacuum.
- Current understanding of the nature of electromagnetic radiation (emr), including light, states that emr has both wave and particle characteristics.
- Low energy electromagnetic radiation seems to be most noticeably wavelike and high energy electromagnetic radiation seems to be most noticeably particle-like.
- We can represent waves by a sine curve on a displacement-distance graph, or, if looking only at the motion of one point of the wave, on a displacement-time graph.





- A particle of electromagnetic radiation is called a photon. A photon has a discrete amount of energy called a quantum of energy. Each photon energy has its own characteristic frequency, found by using the formula:
  $E = hf$
- The following formulae apply to electromagnetic radiation whether we picture it as waves or particles.
  $f = \frac{1}{T}$ $c = \lambda f$

Term	Symbol	Definition	Unit
Energy	E	Photon energy	J
Wavelength	λ	The distance between two adjacent points in a wave which are in phase	m
Frequency	f	The number of crests or troughs which pass a point or per unit time, or the number of cycles per second	s^{-1}
Period	T	The time taken for one complete cycle, or the time taken for one complete wave to pass a given point	s
Speed of light	c	The speed of light is 3.00×10^8 m s^{-1}	m s^{-1}
Amplitude	a	The maximum displacement of a particle from its mean position	m
Planck's constant	h	6.63×10^{-34} J s	J s

- A wave model explains a wide range of light-related phenomena, including reflection, refraction, dispersion, diffraction and interference; a transverse wave model is required to explain polarisation.
- Electromagnetic waves are transverse waves made up of mutually perpendicular, oscillating electric and magnetic fields.
- Oscillating charges produce electromagnetic waves of the same frequency as the oscillation; electromagnetic waves cause charges to oscillate at the frequency of the wave.
- Energy and matter exhibit the characteristics of both waves and particles. Young's double slit experiment is explained with a wave model but produces interference and diffraction patterns even when one photon at a time or one electron at a time are passed through the slits.

Notes

Waves and photons explained

Notes

Reflection, refraction and diffraction

Reflection is when the wave bounces off a surface. The laws of reflection determine the wave's direction after reflection. When a sound wave is reflected, you hear an echo if the reflecting surface is sufficiently far away.

Refraction is when waves bend as they pass from one medium to another. The change in direction is caused by a change in the speed of the wave as it enters a new medium.

Diffraction occurs when a wave passes through a narrow opening (aperture). The greatest diffraction results when the width of the opening that the wave passes through is similar to the wavelength of the wave. Diffraction also occurs at the edges of an obstacle. In this case, waves of greater wavelength tend to diffract more noticeably.

The electromagnetic spectrum

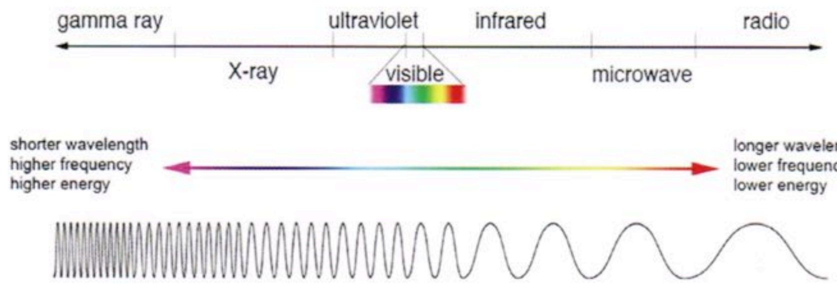


Figure 12.2: Electromagnetic spectrum (Picture credit: NASA)

Radio waves can be produced by electrons accelerating through conducting wires. They are used in radio and television communication systems.

Microwaves are also generated by electronic devices. Because of their short wavelengths, they are well suited for radar systems and for studying the atomic and molecular properties of matter. Microwaves interact with the molecular rotation energy levels in a molecule and can lead to molecules vibrating and causing an increase in temperature. Microwave ovens rely on this property.

Infrared waves are produced by molecules vibrating and are readily absorbed by most materials. Infrared (IR) energy absorbed by a substance appears as internal energy because the energy agitates the atoms of the object, increasing their vibrational or translational motion, which results in a temperature increase. Infrared radiation has practical and scientific applications in many areas, including physical therapy, IR photography, and vibrational spectroscopy.

Visible light is the most familiar form of electromagnetic radiation. It is the part of the electromagnetic spectrum that the human eye can detect. Light is produced by the rearrangement of electrons in atoms and molecules. The sensitivity of the human eye depends on wavelength, being a maximum at a wavelength of about 5.5×10^{-7} m.

Ultraviolet waves (UV) are also produced by the rearrangement of electrons in atoms and molecules. The Sun is an important source of UV light, which is the main cause of sunburn. Sunscreen lotions are transparent to visible light but absorb most UV light.

X-rays: The most common source of X-rays is the deceleration of high-energy electrons bombarding a metal target. X-rays are used as a diagnostic tool in medicine, as a treatment for certain forms of cancer and are also used to study crystal structure (because X-ray wavelengths are comparable to the atomic separation distances in solids - about 0.1 nm).

Gamma rays are electromagnetic waves emitted by radioactive nuclei (such as 60_{Co} and 137_{Cs}) and during certain nuclear reactions. High-energy gamma rays are a component of cosmic rays that enter the Earth's atmosphere from space. They are highly penetrating and produce serious damage when absorbed by living tissues.

Experiment 12.1: Making waves

Background

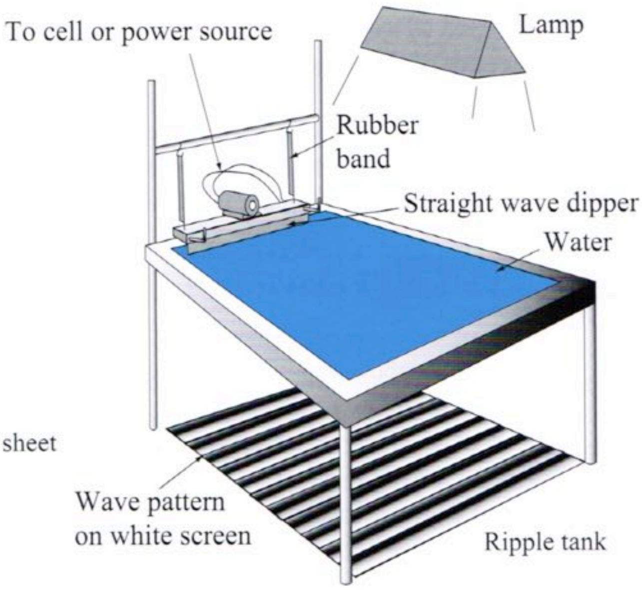
Mechanical waves are affected by various barriers, boundaries, apertures and media. When waves strike barriers they can be reflected. When they pass through apertures or pass edges their direction changes due to diffraction. When they pass from one medium to another, their velocity changes and so may change direction due to refraction. When two different waves collide they interfere. You can observe and study these wave properties using water waves.

Aim

This is a qualitative investigation designed to investigate various wave properties.

Equipment

- white paper
- stroboscope
- rheostat
- power supply
- leads
- ripple tank kit, including
    - motor
    - vibrator bar
    - dippers
    - reflectors
    - barriers and small Perspex sheet
    - overhead light



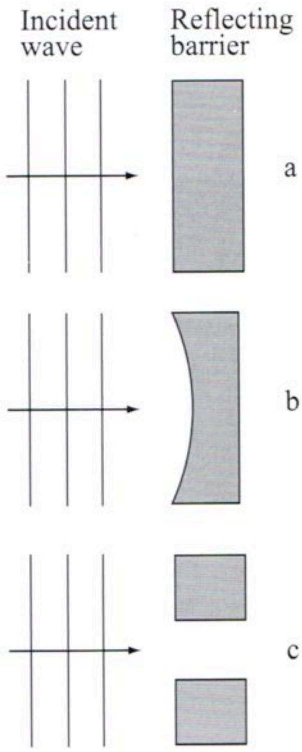
Pre-lab

- Set up the equipment as shown in the diagram.
- Place a lamp 50 cm above the tank.
- Arrange the equipment to show an image of ripple tank on a white backing.
- Add water to 5 mm depth in the tank. Adjust the tank to ensure it is level.

Lab notes

- Adjust the rheostat and observe the relationship between frequency of the vibrator and wavelength. Draw and describe what you observe.
- Place a flat barrier in the tank and observe "head on" reflection. Draw and describe what you observe.
- The diagram at right provides an outline which could be redrawn in your laboratory notebook and completed.

Notes



Experiment 12.1: Making waves

Notes

- Move the barrier so that the waves now strike it at an angle. Again describe and draw what you observe.
- Remove the barrier and replace it with a concave surface. Use the diagram as a guide to describe and draw what you observe.
- Turn the barrier around so that it is now a convex reflector. Describe and draw what you observe.
- Remove the barrier. Place the Perspex sheet into the tank to create a a shallow region. Draw a diagram to show the effect of the shallow water upon waves normal to it.
- Turn the sheet so that the waves are now incident at an acute angle. Draw what you observe.
- Place two barriers in the tank to create a small aperture. Draw what you observe.
- Use the rheostat and increase the wavelength. Again draw what you observe.
- Increase the aperture and repeat the previous two steps. Draw appropriate diagrams to show the observed effects.
- Remove one of the barriers and observe what occurs at the end of the remaining barrier. Describe and draw what you observe.
- Replace the bar with a dipper to create circular waves.
- Repeat all the previous steps using circular waves. Draw your observations.
- Remove the dipper, and replace it with two dippers. Draw what you observe.

Post-lab discussion

1. In which of the above experiments did you observe reflection?
2. In which of the above experiments did you observe refraction?
3. In which of the above experiments did you observe diffraction?
4. In which of the above experiments did you observe interference?
5. What is the general relationship between wavelength and diffraction?
6. How does this relationship explain the fact that sound travels around corners? Which wavelengths of sound would you expect to hear most easily around a corner?
7. Under what conditions would you expect sound waves to interfere?
8. Under what conditions would you expect sound waves to create a stable interference pattern similar to that created in your experiment? Describe what this pattern might sound like to a stationary observer, and to an observer who moves through the pattern.

Investigation 12.2: A short history of light

A Short history of light

500BC: Ancient Greek and Hindu philosophers viewed light as one of five fundamental elements.

400BC: Empedocles postulated that light is produced within the eye and that it interacts with the light that objects give off.

300BC: Greek philosopher Euclid published *Optica*. He described the law of reflection and questioned the origin of light within the eye.

55BC: Lucretius hypothesised that light is made up of particles from the Sun.

400: Buddhist philosophers Dignāga and Dharmakirti theorised that light is a stream of energetic particles, similar to our idea of photons today.

984: Ibn Sahl derived what will later be known as Snell`s Law in Baghdad. Not being an European, no one even considered giving him credit for it.

1011-1021: Alhazen wrote his seven-volume treatise on optics. He wrote "from each point of every colored body, illuminated by any light, issue light and color along every straight line that can be drawn from that point". He described his idea of the anatomy of the eye.

1621: Willebrord Snellius derived, but did not publish, a version of Snell`s law. He was posthumously awarded the credit.

1637: René Descartes published the first theory of refraction of light. This theory treated light as a wave phenomenon. It assumed that light travels faster in dense media (by analogy with sound). He independently derived Snell`s Law and was accused of plagiarism, despite the fact that Snell never published his work. Descartes got credit, but only in France.

1676: Ole Roemer calculated the speed of light using the timing of the eclipses of Jupiter's moons.

1680: Christiaan Huygens introduced the ether, a medium that light was thought to travel through.

1675: Newton published his *Hypothesis of Light*, which viewed light as particles that he called corpuscles. He explained refraction by allowing the particles to behave like a localised wave

1803: Thomas Young showed through experimentation that light passing through a double slit showed interference and thus wave properties. The wave explanation of Young's double slit demonstration was initially rejected until other physicists, including Fresnel and Poisson, showed that light was able to undergo diffraction, a property of waves.

1821: Augustin-Jean Fresnel showed mathematically that light can only be polarised if it is a transverse wave.

1847: Michael Faraday discovered that the plane of polarisation of light can be rotated by a magnetic field. This leads to the realisation that light is actually a high frequency electromagnetic wave.

Notes

Investigation 12.2: A short history of light

Notes

1860s: James Clerk Maxwell developed a theory of electromagnetism and showed that electromagnetic waves would travel through space at the speed of light implying that light was an electromagnetic wave.

1870: Daniel Colladon and Jacques Babinet demonstrated the first application of total internal reflection. This discovery is used in modern fibre optic cable.

1887: Albert Michelson and Edward Morley attempt unsuccessfully to detect the ether.

1900s: Max Planck resolved the 'Ultraviolet Catastrophe' mathematically by treating the light emitted by a blackbody as discrete particles, called quanta.

1900: Lord Kelvin is quoted to have said "There is nothing new to be discovered in physics now. All that remains is more and more precise measurement."

1905: Albert Einstein resolved a longstanding issue with the photoelectric effect by treating light as a particle. These particles were later called photons.

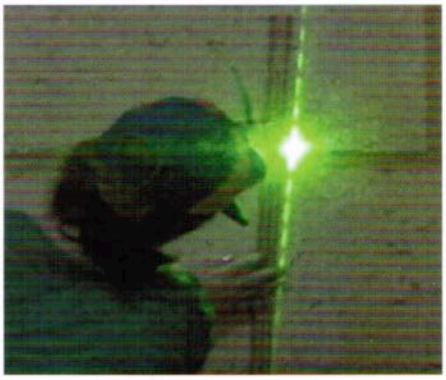
1924: Louis de Broglie showed that not only are waves capable of acting like particles, but particles can behave like waves.

The task

The following scientists and philosophers contributed to our understanding of light today. For each write a short paragraph noting their contribution. Beside each denote with a P or a W to describe how they envisaged light – as particles (P) or as a wave (W).

- Empedocles (400BC).
- Euclid (300BC).
- Lucretius (55BC).
- Dignāga and Dharmakirti (400).
- Ibn Sahl (984).
- Alhazen (1011-1021)
- Willebrord Snellius (1621).
- René Descartes (1637).
- Ole Roemer (1676).
- Christiaan Huygens (1680).
- Isaac Newton (1675)
- Thomas Young (1803).
- Augustin-Jean Fresnel (1821)
- Michael Faraday (1847).
- James Clerk Maxwell (1860s)
- Daniel Colladon and Jacques Babinet (1870)
- Albert Michelson and Edward Morley (1887).
- Max Planck (1900s).
- Albert Einstein (1905).
- Louis de Broglie (1924).

Experiment 12.3: Finding the width of cotton thread



Background

Diffraction is the bending of a wave, including light around an object or through an opening. Light is diffracted by very small diameter objects, such as cotton thread, human hair or a slit in a piece of paper. In this experiment when the light wave is diffracted by the cotton thread, it creates an interference pattern. The distance between successive dark bands in the interference pattern is related to the size of the object that caused the scatter, in this case the thread. By measuring the distance between the dark bands you can calculate the width of the cotton thread.

Equipment

- laser pointer
- cardboard (10 cm × 15 cm)
- retort stand and clamp
- adhesive tape
- 8 cm of a fine cotton thread
- ruler
- a room that can be darkened

Notes

Lab notes

1. Make a frame to hold the cotton by cutting a 1 cm by 4 cm rectangle inside the piece of cardboard.
2. Tape each end of the 8 cm of fine cotton, as tightly as you can, across the middle of the inside rectangular cutout in the cardboard.
3. In a dark room, place a desk or table about 2 metres from a blank wall.
4. Using the retort stand and clamp hold the frame containing the cotton on the desk or table. Shine a laser pointer at the wall from just behind the cotton, making sure it hits the cotton along the way. You will see the light scatter to the sides as you hit the hair with your laser pointer.
5. Measure the distance in centimetres from your cotton to the wall.
6. Check the wavelength of light produced by your laser pointer. A red laser pointer will be about 650 nanometers and a green one will be about 532 nanometers. Usually this is listed on the laser pointer itself.
7. Measure the average distance between the "dark" lines by measuring the distance across the dark lines from the centre then dividing this value by the number of lines.

Post-lab discussion

Use the following equation to determine the thickness of the thread. Make sure that all of your measurements are in the same units, in this case centimetres.

$$d = \frac{\lambda L}{x}$$

where:

d is the diameter of the thread.

λ (lambda), is the wavelength of the laser, note that 650 nanometres = 0.000065 cm.

L is the distance to the wall (cm)

x is the average distance (cm) between the "dark" lines.

Further investigation:

Repeat the experiment to determine the thickness of a human hair.

Experiment 12.4: Observing light sources

Notes

Caution: *Do not look* ***directly*** *at the Sun with your eyes or through the spectroscope.*

Caution: these salts are toxic if ingested. Wash your hands after handling them.

Background

The range of photons emitted by a source is called its spectrum. Spectra can be classified as absorption or emission spectra. These can be further classified as line, band or continuous.

Aim

To observe various spectra using a direct-vision spectroscope.

Pre-lab

- Practise using a direct-vision spectroscope until you understand where the slit has to be pointed in order for you to see a useful image.
- Look through the hand held spectroscope at a light source. Adjust the slit and eyepiece to obtain a clearly focussed spectrum.

Part 1: Observing light sources

Lab notes

- View the following light sources through the spectroscope, observe and record the spectra produced.

sodium vapour lamp	neon lamp	fluorescent lamp
incandescent lamp	bright blue sky	

Post-lab discussion

1. Draw a spectrum of each of the light sources. Label the colours seen.
2. Comment of similarities between the spectrum of the sodium lamp, neon lamp, and the fluorescent light tube.
3. Comment of similarities and differences between the solar spectrum and the incandescent lamp spectrum.

Part 2: Observation of the spectra of heated compounds

Lab notes

- Adjust the flame of a Bunsen burner until it is very pale blue.
- Using a platinum or nichrome wire, heat a loopful of sodium chloride in the flame until it fuses and vaporises. Record your observations.
- Repeat using calcium chloride, strontium nitrate and barium nitrate. Use a different loop for each salt.

Post-lab discussion

1. Draw diagrams of the spectra observed through the spectroscope, labelling the colours seen.
2. Comment on the similarities of the flame colours of calcium and strontium nitrate. Can you separate the two salts on the basis of their spectral colours?
3. What are the main differences between the spectrum of the sodium vapour lamp and the spectrum of sodium chloride?
4. What is the difference between a continuous emission spectrum and a line emission spectrum? Identify each with reference to your experiment.
5. It is possible to produce a spectrum for each element by using an electric discharge or arc between two electrodes that contain a sample of the element. Using this method how could you determine which elements are present in a mixture of substances?
6. Calculate the frequency and wavelength of a photon resulting from an electron in the hydrogen atom moving from one energy level to another with an energy difference of 10.21 eV.
7. How do scientists gain information about the composition of distant stars?

Experiment 12.5: Line spectra

Background

After gaining energy (e.g. from high-temperature atomic collisions, or by absorbing a photon) an atom quickly loses this energy by emitting one or more photons.

Equipment

- gas discharge tubes
- an induction coil and DC power pack
- direct vision spectroscopes
- darkened room

Pre-lab

- Mount the gas discharge tube vertically using a retort stand and clamp.
- Connect the high voltage terminals of the induction coil to the discharge tube terminals.
- Connect the primary terminals of the induction coil to the DC terminals of the power pack. Set the power pack to the required voltage and turn on. Be sure to follow the manufacturers' safety rules.

Lab notes

- Examine the light emitted by the tubes through a direction vision spectroscopes. Record your observations.
- Choose one tube and estimate the wavelength and frequency of each line in its visible spectrum. This may done by using the wavelength markings on the display in the spectroscope if these are provided. If not, find out the approximate frequency or wavelength range for each colour in the spectrum and estimate the characteristics of the visible lines that way.

Post-lab discussion

1. Sketch the emission spectrum for each tube you observed. Label line colours clearly.
2. Consider the element for which you estimated the wavelengths and frequencies of the lines. Work out the photon energies involved and construct a partial energy level diagram for that element. Show clearly the size and direction of each transition responsible for a spectral line.
3. Why is this a partial energy level diagram?
4. Are any of the lines that you observed the result of transitions to or from ground state? Explain.

Notes

Experiment 12.6: Band spectra

Notes

Background

Gaseous atoms create line spectra by emitting or absorbing light at particular frequencies or wavelengths. Compounds behave differently, by emitting or absorbing many frequencies or wavelengths – in effect, creating bands rather than lines.

Equipment

- coloured filters
- solutions of coloured salts (copper sulfate, nickel sulfate, cobalt chloride, very dilute potassium permanganate) or vegetable dyes, in parallel-sided glass or plastic containers
- white light source
- direct vision spectroscopes
- darkened room

Pre-lab

- Set up the white light lamp so it shines toward the viewing location.
- Check where the spectroscope has to be placed to obtain a bright, clear spectrum.

Lab notes

- While one group member observes the spectrum from the white light source, another member inserts a filter or sample of coloured liquid between the lamp and the spectroscope. Note changes in the spectrum when the coloured material is introduced, and record your observations. While still observing the spectrum, have the filter or solution sample removed.
- Repeat this for filters or solutions of a range of colours.

Post-lab discussion

1. Did you observe emission or absorption spectra? How can you tell?
2. Choose any two different coloured materials and explain how they caused the spectrum that you observed.
3. Line spectra can be used to identify individual elements by matching the locations and brightness of several lines. Could band spectra be used in a similar way? Explain.

Experiment 12.7: Detecting infrared radiation

Notes

Background

Most television remote control units work using invisible infrared radiation. Infrared radiation has longer wavelengths than visible light and is affected differently by obstacles in its path.

Aim

To investigate diffraction, absorption and transmission of beams of visible and infrared radiation.

Equipment

- television set and remote control unit
- hand mirror
- clear glass or plastic container with flat, parallel sides
- electric torch
- flour or baby powder
- water

Pre-lab

- Prepare a table to record your results.
- Find a place that allows a direct line, between 2 to 3 metres, from you to the television set.
- Darken the room.
- With the television off, check that you can see the light from the torch reflecting from the screen.
- Check that the remote control also works from your chosen position.

Lab notes

- Get your lab partner to stand directly in front of the screen, about halfway between you and the television. Operate the remote control "on" button and record the result. Shine the torch beam at the television and record the result.
- Get your lab partner to stand off to one side, about halfway between you and the television, holding the hand mirror. Point the torch at the mirror, and move the mirror around until it shines on the screen. Now point the remote control at the mirror, operate the remote control "on" button and record the result.
- Repeat this using just the lab partner's body (that is, without the mirror).
- Get your lab partner to blow a small amount of flour or baby powder into the air between you and the television. Try to turn on the television through the cloud; then repeat, using the torch. Record your results.
- More than half fill the container with water. Hold the water directly in front of the torch, then the remote control, while pointing at the television. Record your results.
- Get your lab partner to hold one hand between you and the television, at several distances from the remote control unit. Record when the hand obstructs the infrared beam and the visible light beam.

Post-lab discussion

1. Make general statements about the observed behaviours of infrared and visible beams.
2. Explain your observations in terms of the relative wavelengths of infrared and visible light.
3. Why would television manufacturers use infrared rather than visible light beams in their remote control units?
4. Infrared sensors can locate people in total darkness, but do this best when the air temperature is low. Explain.
5. Infrared sensors can locate the seat (hottest part) of a fire, but have difficulty detecting hot objects in rain, cloud or fog. Explain.

Experiment 12.8: Detecting ultraviolet radiation

Notes

Background

Human eyes are not able to see ultraviolet (UV) light as a colour. We can however see the result when UV light shines on a fluorescent material.

Aim

To use fluorescence to detect ultraviolet light.

Equipment

- two clear, plastic cups
- waterproof markers
- one litre of tap water
- one litre of tonic water
- black backdrop material (cloth, paper or felt, roughly A4 size)
- access to direct sunlight or a source of UV radiation ("black light")

Safety note: *UV is harmful if it shines directly into your eyes.*
If you use a black light source, use a shield to protect your eyes from direct UV emissions.

Pre-lab

- Label the plastic cups "tonic" and "water."
- Nearly fill each cup with tonic water or water as required.
- Place the cups in direct sunlight, or place a UV source above the cups, so that sunlight, or UV radiation, strikes the liquid surface in both cups.

Lab notes

- Hold a backdrop behind the cups to increase contrast. Looking through the sides of the cups, observe the surfaces of the liquids.
- Record your observations.

Post-lab discussion

1. Which material is fluorescent? What is your evidence?
2. How do you know that the cup is not fluorescent?
3. Tonic water contains water, sugar and quinine. Suggest how you could determine which one or more of these ingredients causes the fluorescence.
4. Many common substances are fluorescent. If you are using a black light source, test a range of objects and record the results. Do all fluorescent objects glow with the same colour? If so, what colour is it?
5. If you used sunlight, describe how you would test whether the position of the Sun in the sky makes a difference.

Extensions:

- If time permits, you can see how UV light is affected by passage through glass, Perspex, or cellulose acetate (used to make some overhead transparencies).
- How could you test the efficiency of sunscreens of different SPF values?

Investigation 12.9: Light intensity

Measuring light intensity

You can use a photographic light meter or a 35 mm camera with in-built exposure meter to compare light intensities.If you are using a light meter be sure to use the diffusing screen accessory. If you are using a camera you will obtain more reliable results if you use a diffusing screen in front of the lens. A piece of frosted glass or a piece of greaseproof paper will both work. The film's exposure is controlled by the shutter speed and the f-stop number which is a measure of the lens aperture size. For a given fixed shutter speed the f-number needed for correct film exposure is an indirect measure of the light intensity. In fact, the light intensity I is directly proportional to the square of the f-number f. For example, if light intensity increased by a factor of 4 then the f-number would have to increase by a factor of 2.

$$I = \text{constant} \times f^2$$

If you are using a photographic light meter, set the film speed to 400 ASA, hold up the meter to the light source and determine the f-number required at a shutter speed of $\frac{1}{60}$ s. By always using the same film speed and shutter speed settings the square of the f-number (f^2) will be your measure of light intensity.

If you are using a camera with an in-built exposure meter, set the film speed to 400 ASA and the shutter speed to $\frac{1}{60}$ s. Point the camera at the light source and determine the f-number needed for correct exposure. By leaving the film speed and shutter speed settings fixed, the square of the f-number (f^2) will be your measure of the light intensity.

Notes

Part 1: Comparing light sources

Background

The aim of this activity is to compare the relative intensities of several light sources. Read the section above on Measuring light intensity before you start.

Equipment

- Photographic light meter or a camera with in-built exposure meter
- light sources, e.g. various sizes of incandescent lamps, spotlights etc.
- metre rule or tape measure
- darkish room

Pre-lab

Position the light measuring device a fixed distance from the brightest lamp.
Select a shutter and film speed that gives you an exposure of f/16.

Lab notes

Keeping both the distance and the film speed fixed, determine the f-numbers needed for the other lamps. Record your results in a suitable chart.

Post-lab discussion

1. Plot a suitable graph of the square of the f-number (f^2) vs lamp type.
2. Which lamp gave the highest intensity?
3. Does the most intense lamp have to be the most efficient? Explain.

Investigation 12.10: Fluorescence

Equipment

- UV 'black light' source
  *(**CAUTION:** do not look directly at the light source when it is turned on)*
- a range of fluorescent materials such as: the minerals fluorite or calcite; soap powder
- quinine sulfate or fluorescine solution; motor oil; vaseline smeared on paper; zinc sulfide; highlighter pens of various colours

Pre-lab

- A darkened room works best.

Safety note: UV is harmful to the unprotected eye. Make sure that no-one can see the UV lamp directly when it is turned on.

Lab notes

- Compare the colours of the materials when viewed under white light and when viewed under ultraviolet light.
- Explain what happens in terms of photons and energy levels.

Post-lab discussion

1. Explain the difference between 'fluorescence' and 'phosphorescence'.
2. Were any of the materials that you observed phosphorescent? How do you know?
3. What makes a UV lamp more potentially harmful to your eyes than a normal bright lamp?
4. Some insects that feed on nectar and pollen from certain flowers have eyes that can detect UV light. Are the flowers on which they feed likely to be fluorescent, or non-fluorescent? Explain.

Notes

Problem set 12.1: Waves and photons

Notes

1. What is meant by stating that light is transmitted as an electromagnetic wave?

2. (a) Two light sources are described as coherent. What does this mean?
   (b) Would the light from two identical incandescent lamps be coherent? Explain.

3. The energy of an electron depends on its velocity. All photons in air have the same velocity. How is it that photons in the visible spectrum with different colours can have different energies?

4. A red LED emits light with a frequency of 3.85×10^{14} Hz. What energy would be associated with the photons produced?

5. The photons in a beam of electromagnetic radiation have an energy of 1.00×10^{-17} J. What will be the photon frequency and to what part of the electromagnetic spectrum does it belong?

6. A long range surveillance radar unit operates at a frequency of 1.30 MHz.
   (a) What is the energy of one quantum of electromagnetic radiation emitted from this radar?
   (b) What would be the wavelength of a photon in this beam?
   (c) What would be the velocity of an electron that has the same kinetic energy as the energy of an individual photon in this radar beam?

7. A microwave oven has a power rating of 1100 W and operates at a frequency of 2650 MHz.
   (a) Calculate the wavelength of the radiation produced.
   (b) What is the energy of each photon produced?
   (c) A cup of water is heated in this microwave oven for 2.50 minutes in preparation for making a cup of coffee How many photons are produced by the oven in this time assuming 100% efficiency?

8. An individual laser diode emits radiation of wavelength 905 nm at a peak power of 34 W and a pulse length of 150 ns.
   (a) To which part of the electromagnetic spectrum does this radiation belong?
   (b) What is the energy of a photon produced under these conditions?
   (c) How many photons are in each pulse?

9. Television antennas are mounted in the horizontal and not the vertical plane. Explain why this is done?

10. A microwave transmitter transmits a 1.52×10^{9} Hz signal at an average power of 5.00 W. The microwaves are emitted in pulses of duration 1.50 μs, the time between pulses being 4.00 ms.
    (a) Calculate the wavelength emitted.
    (b) What is the energy of each photon?
    (c) How many photons are emitted by the transmitter each second?
    (d) Calculate the power output of each pulse of radiation.

11. A green laser of wavelength 435 nm is used to burn data onto plastic DVDs and CDs. Calculate the energy transferred to the disc by such a laser beam if it produces 3.25×10^{18} photons every second and it is focused on the disc for 1.2 ms.

12. A 1.00 W ruby laser emits monochromatic light of wavelength 694 nm.
   (a) What is the energy per photon in the beam produced by this laser?
   (b) What is the intensity of the laser beam if its cross sectional area is 10.0 mm^2?
   (c) The average intensity of sunlight at the Earth's surface is about 1000 W m^{-2}. Compare the intensity of this laser beam with the average intensity of sunlight.

12. b, c
17 b

13. The human eye is adapted to seeing, most clearly, colours in the middle of the visible spectrum. The retina can detect yellow light with a wavelength of 6.00×10^{-7} m at a minimum power of only 1.70×10^{-8} W. What is the minimum number of photons per second that the human eye can detect at this wavelength?

14. One of the ABC radio stations in Perth transmits on the AM band at a frequency of 720 kHz using a 50.0 kW transmitter. This transmission is continuous over any 24 hour period.
   (a) At what wavelength does it transmit?
   (b) Estimate how much energy it sends out per 24 hour broadcast period.

15. The air traffic control tower at Perth Airport monitors the movement of all aircraft in the vicinity of that airport. It uses radar that emits microwaves with an average energy per photon of 2.00×10^{-24} J.
   (a) What is the frequency of these microwaves?
   (b) What is the wavelength of these microwaves?
   (c) How does the energy, frequency and wavelength of these microwaves compare with those of visible light? Give your answers as higher, lower or greater or smaller.

16. A method for determining water depth in oceans, up to around 70 metres, can be found by shining an intense beam of laser light pulsed at around 900 pulses per second from an aircraft vertically onto the surface of the water and measuring the difference in the time taken to receive back the pulses reflected from bottom and surface of the water. The device uses a beam splitter to split a green laser beam into a green beam and an infrared beam. The infrared beam is reflected from the surface and the green beam from the bottom. The green light has a wavelength of 532 nm in air, which decreases by 25% in water.
   (a) Why is a green and not infrared laser used to reflect from the bottom?
   (b) Why does this beam need to have a high intensity and what is meant by "high intensity"?
   (c) What is the wavelength of this green laser light in water?
   (d) What is the frequency of this light beam in water?
   (e) If the difference in time between receiving the two reflected pulses is 3.8 μs, estimate the depth of the water.
   (f) If the pulses are all 1.00 μs long, what is the power of each green photon?

17. Yellow incandescent filament lamps can be used in outside areas to help control insects at night. A globe in one such lamp is rated with a power output of 75.0 W and the frequency of the maximum intensity photons it emits is 5.28×10^{-16} Hz with. This globe gets very hot when operating.
   (a) Explain why the temperature of this globe will increase.
   (b) Draw a graph of what you think the distribution of blackbody radiation from this globe would look like. Make sure you clearly indicate colours on the relevant axis.
   (c) Calculate the wavelength of the highest intensity photons.
   (d) Calculate the energy, in eV and joules, of the photons with the greatest intensity.
   (e) How many such photons would be emitted by this globe per second?
   (f) Why would it not be possible to determine the number of photons from experimental measurement?

Photoelectric effect explained

Notes

The photoelectric effect is the process of emission of electrons from a metal surface when that surface is irradiated with light in the range from infrared to ultraviolet. It is classed as a low energy phenomenon.

Heinrich Hertz (1887) noticed, in his experiments with electrical discharge, that electrodes more readily produced an arc when they were irradiated with UV light.

Observations made and experiments conducted on these effects were in direct conflict with Maxwell's Electromagnetic Wave Theory, which assumed that the production, transmission and absorption of electromagnetic radiation could be described by using the properties of continuous waves.

Planck postulated light is radiated or absorbed in packets (called them quanta), the energy of which is proportional to their frequency: $E = hf$

Albert Einstein used this to explain the photoelectric effect and why it did not obey the wave theory. He published a paper in 1905, for which he received the Nobel Prize in 1921, in which he explained the emission of photoelectrons being caused by light having discrete quantised packets of energy (following on from the Quantum Theory of Planck) and behaving as particles, not waves. His explanation of the photoelectric effect was therefore that of a particle collision.

Experimental evidence shows:

1. For photoelectrons to be emitted from a metal surface there is a minimum frequency (energy) needed in the incident radiation below which no photoelectric emission will occur. This frequency is called the threshold frequency for that metal. It is different for all metals.
   e.g. Caesium – yellow – 5.16×10^{14} Hz
   Potassium – green – 5.53×10^{14} Hz
   Calcium – violet – 6.93×10^{14} Hz
   Magnesium – ultraviolet – 8.83×10^{14} Hz

2. The kinetic energy of the emitted photoelectrons is independent of the intensity of the incident light.

3. An increase in intensity of the incident radiation causes more photoelectrons to be emitted. The photoelectric current is directly proportional to the intensity of the incident light provided its frequency is above the threshold frequency.

4. The higher the frequency of the incident radiation above the threshold frequency the greater the number of photoelectrons emitted.

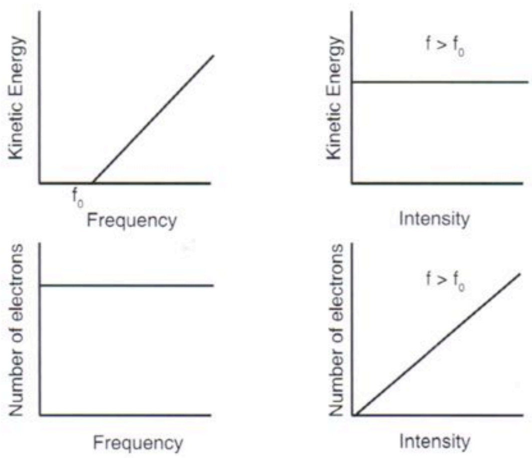


Figure 12.3:Characteristics of the photoelectric effect

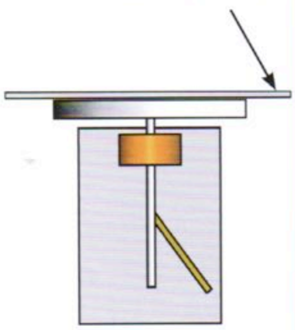
The table below gives the work function for a number of surfaces - both in joules and in electron volts. The threshold frequency for each surface is also included.

Notes

Element	W (Joules)	W (eV)(V)	f_o (frequency) (Hz)	λ_o (wavelength) (nm)
Sodium	3.8×10^{-19}	2.40	5.8×10^{14}	520
Caesium	3.0×10^{-19}	1.88	4.5×10^{14}	666
Lithium	3.7×10^{-19}	1.88	5.6×10^{14}	560
Calcium	4.3×10^{-19}	2.69	6.5×10^{14}	462
Magnesium	4.3×10^{-19}	3.69	8.9×10^{14}	337
Silver	7.6×10^{-19}	4.75	11.14×10^{14}	263
Platinum	10.0×10^{-19}	6.75	15.1×10^{14}	199

Experiment 12.11: The photoelectric effect

Notes



In 1905, during his "miracle year," Albert Einstein published five papers. These included special relativity, which dealt with space and time, as well as general relativity, which related mass and energy through the equation $E = mc^2$. However, Einstein won his only Nobel Prize for work he did that same year on the photoelectric effect.

At the time, it was known that light shining on certain materials could knock out electrons to produce a current. It stood to reason that the stronger the light, the greater the current. Researchers also found that how much of a kick the electrons got (or how much kinetic energy they had) depended on the color of the light. Many scientists expected a stronger light would also release an electron with greater energy.

It took Einstein's brilliance to understand why the color (or frequency) of the light played such a key role in determining how much energy the electrons came away with. The consequences of this insight, along with the contributions of many other scientists, lead to the development of quantum mechanics, which is the basis for the modern electronic world.

This experiment introduces you to the photoelectric effect and guides you to recreate the type of data Einstein interpreted.

Equipment

- piece of zinc metal
- short lead/wire
- source of visible light (incandescent lamp)
- sandpaper or steel wool
- plate of glass
- electroscope (gold leaf)
- source of ultraviolet light - carbon arc lamp or a strong "black light" or laser pointer/pen

Lab notes

1. Rub the piece of zinc with a piece of sandpaper or steel wool. This removes oxides to expose the metal.
2. Discharge the electroscope by touching your finger to the electrode.
3. Using a very short lead/wire, attach the zinc to the electroscope.
4. Darken the room.
5. Shine the light from an ultraviolet source onto the zinc.
6. Observe the effect on the electroscope leaves.
7. Discharge the electroscope and shine visible light onto the zinc.
8. Observe the effect of shining the ultraviolet source through a pane of glass that transmits mostly visible range light, but hardly any ultraviolet light.
9. Charge the electroscope positively using a charged glass rod and observe the effect of shining ultraviolet light on the zinc.
10. Charge the electroscope negatively using a charged polythene rod and observe the effect of shining the ultraviolet light on the zinc.

Post lab discussion

1. Compare the effect of the ultraviolet source and the visible source.
2. compare the effect of shining the ultraviolet source through a pane of glass that transmits mostly visible range light, but hardly any ultraviolet light.
3. Ultraviolet light shining on a piece of zinc results in a charge separation. This charge causes the leaves of a negatively charged electroscope to separate further and causes the leaves of a positively charged electroscope to come together. This indicates the charge is negative or, more specifically, consisting of electrons. Visible light does not result in this charge being developed in the zinc.

Problem set 12.2: The photoelectric effect

Notes

1. The photoelectric effect was explained by Einstein, using the idea of Planck, that light consisted of photons with discrete energies dependent on their frequency. Explain how the photoelectric effect is used as evidence for the particle nature of light.

2. An experiment on the photoelectric effect was conducted and the maximum energy of the emitted photoelectrons measured at two different frequencies. When a wavelength of 4.00×10^{-7} m was used the maximum energy of the emitted electrons was 1.40×10^{-19} J and with an incident wavelength of 3.00×10^{-7} m the energy was 3.06×10^{-19} J. From these data derive a value for Planck's constant.

3. Green light with a frequency of 6.7×10^{14} Hz is incident on a caesium metal surface with a work function 2.14 eV. What is the maximum kinetic energy of an electron emitted from this surface as a result of this collision?

4. The work function of aluminium is 4.08 eV.
   (a) What does the term "work function" mean in this context?
   (b) What is the maximum wavelength of photons incident on this surface that will cause photoelectrons to be emitted?

   An aluminium surface is irradiated with ultraviolet radiation of frequency 2.39×10^{15} Hz.
   (c) Calculate the maximum kinetic energy of the photoelectrons emitted from this surface under these conditions.

5. Whether electrons are, or are not, emitted from a metal surface that is illuminated by light depends on certain factors. State how, if at all, the following properties or factors affect the emission of photoelectrons from a metal surface.
   (a) The thickness of the piece of metal.
   (b) The area of surface illuminated.
   (c) The length of time for which the surface is illuminated.
   (d) The type of metal the surface is made from.
   (e) The wavelength of the incident light.
   (f) The intensity of the incident light beam.
   (g) The cleaniness of the surface.

6. A nickel surface, work function of 5.01 eV, in an evacuated chamber is irradiated with light of wavelength of 325 nm.
   (a) What stopping potential will prevent the emitted photoelectrons from travelling between the pair of plates in the chamber?
   (b) The intensity of the incident light is doubled but the frequency remains constant. What effect will this have on the stopping potential? Explain your answer.

Problem set 12.2: The photoelectric effect

Notes

7. The threshold frequency for aluminium is 1.25×10^{14} Hz.
   (a) Calculate the work function of aluminium in both joules and electron-volts.
   An aluminium surface was then irradiated with blue light with a frequency of 6.95×10^{14}Hz and the resultant emitted electrons analysed. Calculate, showing all working:
   (b) The wavelength of the incident blue light.
   (c) The energy of the incident photons in both joules and electron-volts.
   (d) The maximum kinetic energy of the emitted photo-electrons
   (e) The maximum velocity of the emitted photo-electrons.

8. The surface of a piece of cadmium is irradiated with electromagnetic radiation of wavelength 287 nm. Photoelectric emission stops when a reverse potential of 3.68 V is applied between the anode and cathode of the photoelectric cell.
   (a) From this data calculate the work function of cadmium in joules.
   (b) Calculate the maximum velocity of electrons emitted.

9. An experiment is conducted where the surfaces of both platinum and sodium are irradiated with blue light of wavelength 465 nm. Photoelectrons are found to be emitted from the sodium surface but not the platinum surface.
   (a) Explain why this different effect has occurred with the two metal surfaces.
   Explain the effect each of the following changes would have on the photoelectric current for each of the metals.
   (b) The intensity of the incident beam is increased.
   (c) The blue light was replaced with a light of much longer wavelength.
   (d) The blue light was replaced with a light of much shorter wavelength.
   (e) A small reverse potential is applied between the anode and cathode of the photoelectric tube.

10. Ultraviolet light with a wavelength of 3.55×10^{-7} m from a mercury vapour lamp strikes a clean metal surface with a work function of 2.64×10^{-19} J and causes photoelectrons to be emitted.
    (a) What is the frequency of the incident ultra-violet radiation?
    (b) What is the energy of a single photon incident on this surface?
    (c) What is the maximum kinetic energy any photoelectron emitted from this surface can have?
    (d) What is the longest wavelength of radiation that will eject photoelectrons from this surface?

11. One type of smoke detector contains a photocell, a device that reacts to the amount of light falling on it, and a small permanent light source. If smoke enters the detector, reducing the intensity of light falling on the photocell below a minimum value, the current change in the circuit will set off the alarm. How does the presence of smoke affect the emitted photoelectrons? Does it change their number or their energy or both? Explain.

12. The following data comes from an experiment using a photocell coated with magnesium. The frequency of the incident light was varied and the maximum kinetic energy of the emitted photoelectrons was determined at each frequency.

Notes

Frequency	Kinetic energy (J)
1.0×10^{15}	6.0×10^{-18}
1.2×10^{15}	1.9×10^{-19}
1.4×10^{15}	3.3×10^{-19}
1.6×10^{15}	4.6×10^{-19}
1.8×10^{15}	5.3×10^{-19}
2.0×10^{15}	7.2×10^{-19}

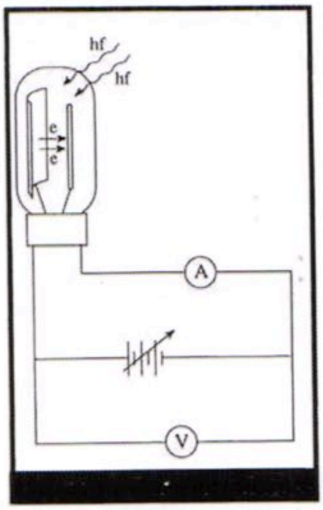
(a) Plot a graph of kinetic energy against frequency.

(b) From the graph determine each of the following.

(i) The threshold frequency of magnesium.

(ii) An experimental value for Planck's constant.

(iii) The work function of magnesium.



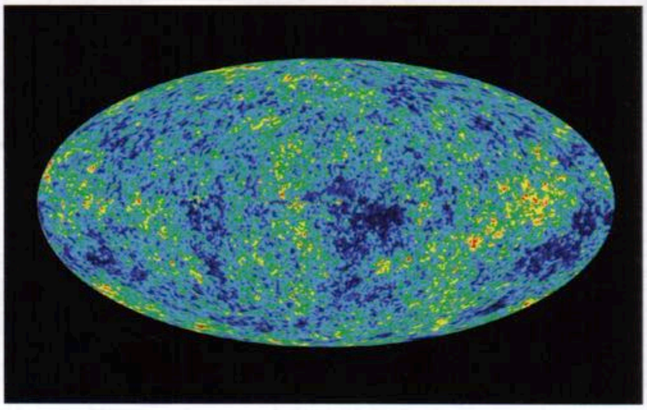
Black body radiation and radio astronomy

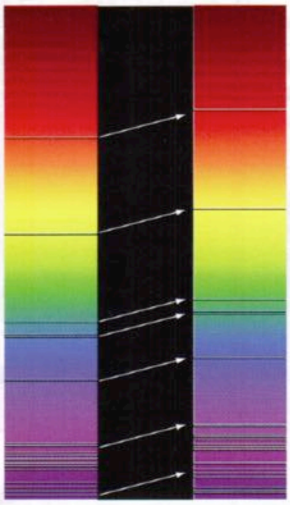
Black Body Radiation

Objects emit thermal radiation which, depending on the emitting body's temperature, can be in the infrared, visible or ultraviolet part of the electromagnetic spectrum. This radiation is produced by the vibrational motion of the atoms and molecules in that object; the hotter the object, the greater the vibration, and hence the higher the frequency of emitted radiation. However, this reasoning would suggest that if you were to create a fire hot enough you would be able to heat an object to a temperature where it could produce X-rays or even gamma rays.

But it is not possible to generate more and more powerful forms of electromagnetic radiation. This limit was a great puzzle at one time; why a sufficiently heated body does not cross over the threshold so that it produces ultra-violet radiation (the "ultraviolet catastrophe"). It was Max Planck who discovered the limits imposed by quantum mechanics. The amount of energy that a photon can receive from heating due to combustion cannot be greater than the quantised energy allowed when vibrating molecules jump to a lower energy level. This energy can be no more than is acquired when molecular bonds are broken in the combustion process. The quantised nature of thermal radiation also explains why radiation from a cool object is not able to increase the temperature of a warmer object.

Astronomers use the relationship between temperature and colour to determine the surface temperatures of stars. **Red stars are cooler than orange stars, which are in turn cooler than blue stars** (as shown in the image). If we study the spectrum emitted by the Sun and plot its intensity against wavelength we obtain a graph very similar to that from a tungsten filament light globe, with the greatest intensity from both being yellow light with a wavelength of around 5×10^{-7} m. The operating temperature of a tungsten filament is around 5800 K so we can conclude that the surface temperature of the Sun must also be around 5800 K. This idea can be applied to most other stars. Measurement of the maximum-intensity wavelength in their spectrum enables their surface temperatures to be determined. The latest research on black body radiation, with the potential to give a greater insight into the formation of the Universe, is the use of radio astronomy to study the 3 K background radiation found throughout the cosmos. This is thought to be radiation, highly red-shifted, that was produced by the Big Bang.





Doppler Effect and Redshift

You can hear the Doppler effect whenever a vehicle with a siren recedes from you: the sound of the siren falls in pitch as the sound source moves further away increasing the distance between one wavefront and the next. Redshift is the term used to describe the change in light wavelength (or frequency) from a fast-receding object. The redshifts of galaxies increase as their distances from us increase, leading to the idea of an expanding Universe. The diagram shows the redshift of the light from a distant galaxy.

Determining the Elemental Composition of Stars

Astronomers can determine the elemental composition of stars and other matter in space by studying their emission or absorption spectra. Each distinct line in such a spectrum is characteristic of the elemental atoms emitting or absorbing the light. The Sun, consist mainly of the lighter elements hydrogen and helium, while older and hotter stars can contain higher proportions of heavier elements.

Black body radiation and radio astronomy: comprehension questions

The SKA

The Square Kilometre Array (SKA) is a multi-billion dollar international project to build the world's largest radio telescope. Co-located primarily in South Africa and Western Australia, the SKA will be a collection of hundreds of thousands of radio antennas with a combined collecting area equivalent to approximately one million square metres, or one square kilometre. The project is one of the largest scientific endeavours in history and will be many times more sensitive and much faster at surveying galaxies than any current radio telescope. The incredible flow of data from the telescope will be supported by supercomputers faster than any current facility and one trillion times the computing power that helped put us on the Moon.

The SKA will collect radio waves, a form of light invisible to the human eye, to give us a unique view of the Universe we live in. It will use three different configurations of radio antennas – Australia's Murchison region will host the low-frequency antennas that look a little like Christmas trees, whilst the mid to high frequency 'dishes' will be based in South Africa's Karoo desert. Construction of the SKA will be completed in two phases, with Phase 1, 10% of the telescope, due to begin later this decade and early science expected early next decade.

Background image: *The SKA low frequency antennas that will be constructed in Western Australia. Credit: SKA Office.*

The SKA is aiming to solve five fundamental and long-standing mysteries of the Universe.

1. **How did the first stars, galaxies and black holes form?**
   With its incredible sensitivity, the SKA will look back 13 billion years in time to the Universe's Dark Ages. At this point in the Universe's infancy, the opaque plasma created by The Big Bang recombined to form the first neutral particles which coalesced into the first stars and galaxies.
2. **Is Einstein's Theory of Relativity correct?**
   Eintstein's famous Theory of Relativity predicts that moving objects cause ripples in the fabric of the Universe, spacetime. These fluctuations are called gravitational waves and, since the most powerful sources are so distant, they are extremely weak by the time they reach Earth and have eluded scientists for nearly a century. The SKA's extraordinary sensitivity will allow us to indirectly study gravitational waves from powerful cosmic processes, such as a pair of orbiting black holes.
3. **Are we alone in the Universe?**
   The extreme sensitivity of the SKA is also expected to reveal new planets outside our solar system – exoplanets – some of which may be capable of supporting life. The SKA may even detect transient signals from extraterrestrial life itself, proving that we are not alone in the Universe.
4. **What is dark matter and dark energy?**
   More than three-quarters of all matter in the Universe cannot be directly observed because it does not absorb, emit or reflect light. We call this 'dark matter' and its nature remains one of the greatest mysteries in the Universe. Mass distribution in the Universe is also affected by an enigmatic force that pulls matter apart, which we call 'dark energy'. The rapid survey speed of the SKA will produce detailed maps of the mass and motions in millions of galaxies, helping us to figure out the nature and abundance of dark matter and dark energy in the Universe and to refine our cosmological models.
5. **What drives cosmic magnetic fields?**
   Magnetic fields exist through the entire Universe and affect the way stars form and galaxies evolve. Most sources of cosmic magnetism produce very weak emissions, which makes them very hard to detect. The sensitivity and survey speed of the SKA will revolutionise the study of cosmic magnetism by detecting these weak emissions from billions of distant galaxies, creating three-dimensional maps of cosmic magnetism throughout the Universe.

Comprehension questions

1. Explain what is meant by 'redshift'. How does redshift occur in an expanding Universe?
2. The frequencies the SKA is expected to receive will be very low. Explain.
3. Consider the 'Doppler Effect' redshift diagram on page 164, which spectrum represents a receding galaxy? Explain.

Chapter 13: Quantum theory

Qantum theory explained

Notes

Main points

- Atomic phenomena and the interaction of light with matter indicate that states of matter and energy are quantised into discrete values
- At the atomic level, electromagnetic radiation is emitted or absorbed in discrete packets called photons. The energy of a photon is proportional to its frequency. The constant of proportionality, Planck's constant, can be determined experimentally using the photoelectric effect and the threshold voltage of coloured LEDs.
- A wide range of phenomena, including black body radiation and the photoelectric effect, are explained using the concept of light quanta.
- Atoms of an element emit and absorb specific wavelengths of light that are unique to that element; this is the basis of spectral analysis.
- The Bohr model of the hydrogen atom integrates light quanta and atomic energy states to explain the specific wavelengths in the hydrogen spectrum and in the spectra of other simple atoms; the Bohr model enables line spectra to be correlated with atomic energy-level diagrams.
- At the atomic level, energy and matter exhibit the characteristics of both waves and particles. Young's double slit experiment is explained with a wave model but produces the same interference and diffraction patterns when one photon at a time or one electron at a time are passed through the slits.
- Applications of quantum physics (including lasers, photovoltaic cells) have influenced society.

Mathematical formulae

The speed of an electromagnetic wave is a product of its wavelength and frequency:

$$c = f.\lambda$$

The energy of a photon is proportional to its frequency.

$$E = hf = \frac{hc}{\lambda}$$

The kinetic energy Ek of an electron ejected from a metal by an energetic photon is given by:

$$E_K = hf - W$$

Where W is the work function of the metal

Atoms of an element emit and absorb specific wavelengths of light that are unique to that element; this is the basis of spectral analysis

$$\Delta E = hf, \quad E_2 - E_1 = hf$$

The de Broglie wavelength is related to the particles momentum as follows:

$$\lambda_{dB} = \frac{h}{mv}$$

Constants

The speed of light in vacuum (defined)
$c = 299{,}792{,}458\ \text{m s}^{-1}$

Planck's constant (measured)
$h = 6.62606896 \times 10^{-34}\ \text{J s} = 4.13566733 \times 10^{-15}\ \text{eV s}$

E=hf

Notes

Introduction

Quantum physics (or quantum mechanics) and general relativity are amongst the most important 'discoveries' of the past century. General relativity presents a picture of the very big (space-time and gravity), while quantum physics presents a picture of the very small (atoms and sub-atomic particles).

The popular literature surrounding quantum physics has led to many weird and wonderful ideas. It is believed to be responsible for all sorts of strange occurrences such as quantum entanglement, particles kilometres apart able to communicate instantaneously, hypothetical cats that are dead and alive at the same time and photons that are capable of going in two directions at one time and being able to interfere with each other.

But quantum physics is also responsible for the technological advances that make modern life possible. Without quantum physics there would be no transistors, and hence no personal computers, no lasers, and hence no Blu-ray players. It is fundamental to our understanding of chemistry and biology. It is the basis for a huge range of technologies and applications used in everyday life, including lasers, CDs, DVDs, solar cells, fibre-optics, digital cameras, photocopiers, bar-code readers, fluorescent lights, LED lights, computer screens, transistors, semi-conductors, super-conductors, spectroscopes, MRI scanners, etc.

History

Quantum mechanics developed over many decades beginning at the turn of the 20th century, around the same time that Albert Einstein published his theories of relativity. Unlike relativity, however, the origins of quantum mechanics cannot be attributed to any one scientist. Rather, multiple scientists contributed to a foundation of three revolutionary principles that were gradually verified experimentally and gained wide acceptance. These three principles are:

1. **Wave/particle duality:** Experiments showed that light behaved as a wave: it bounces off walls and bends around corners, and crests and troughs of waves can add together or cancel out. Quantum theory revealed that light can sometimes behave as a particle.
2. **Quantised properties:** Properties, such as energy, position and momentum, are realised in specific, discrete quantities, much like steps on a ladder or a digital readout that "clicks" from number to number. This challenged the belief that such properties should exist on a smooth, continuous spectrum.
3. **Matter waves:** Matter can also behave as a wave. This was contrary to the understanding gathered from decades of experiments showing that matter (such as atoms and electrons) exists as particles.

Max Planck

Around the turn of the 20th century German physicist Max Planck sought to explain black body radiation. He proposed that in a solid, the electrons emitted or absorbed radiation only in discrete packets with the energy in each packet being proportional to the frequency of the radiation. He described mathematically the energy of these packets: $E = hf$ where f is the frequency of the radiation and h, is Planck's constant. However, the process by which radiation was emitted and absorbed remained a mystery for some time.

Planck's ideas helped to explain other mysteries of physics. Planck, along with Einstein, later developed the idea that we accept and use today, that light exists as photons that have particle-like behaviour. This accounts for both black body radiation and the photoelectric effect which could not be satisfactorily explained using existing theories of the time.

Qantum theory explained

Notes

Albert Einstein

In 1905, Einstein published a paper where he described light as "energy quanta." This quantum of energy could be absorbed or generated only as a whole when an atom "jumps" between quantised energy states. Under this model, Einstein's "energy quanta" contained the energy difference of the jump and, when divided by Planck's constant, the frequency of light carried by those quanta. It also explained how light could eject electrons off metal surfaces, a phenomenon known as the "photoelectric effect."

Twenty years after Einstein's paper the term "photon" was popularised for describing energy quanta thanks to the 1923 work of Arthur Compton. It had become clear that light could behave both as a wave and a particle, placing light's "wave-particle duality" into the foundation of quantum mechanics.

Niels Bohr

Scientists had observed that when hydrogen gas was heated above a specific temperature light was emitted light at distinct frequencies (now called emission lines). Further increase in temperature made no change to the emission lines. No visible light is emitted below this temperature. This was totally unexpected and could not be explained by classical physics.

In 1913 Niels Bohr, using Ernest Rutherford's 1911 "planetary" model of the atom, proposed that electrons were restricted to orbits around an atom's nucleus and could jump from one orbit to another. The orbits represent distinct energy levels and an electron that absorbs the right amount of energy jumps to a higher energy level. When this 'excited' electron falls back to its original energy level it emits the same amount of energy, creating an emission line. The concept of quantised properties explained so much that it became a founding principle of quantum mechanics.

Louis de Broglie

In 1924, a French physicist named Louis de Broglie hypothesised that, if light has both a particle and a wave nature, then matter (such as electrons) also has both types of properties.

De Broglie proposed that the wave nature of the electron determined the allowed orbits in Bohr's theory. He used a simple wave model to show that electron orbits must fit a whole number of wavelengths around the orbit. By doing this they undergo constructive interference and are stable whereas the electron waves in non-allowed orbits undergo destructive interference and cancel out. The concept that matter can also behave as a wave is the third founding principle of quantum mechanics.

Deriving the De Broglie Wavelength

De Broglie derived his wavelength equation as follows:

1. Einstein's famous equation relating matter and energy:
   $E=mc^2$ where: E = energy, m = mass and c = speed of light
2. Planck's equation elates energy to frequency:
   $E=hf$ where: h = Plank's constant (6.62607×10^{-34} J s) and f = frequency
3. De Broglie believed particles and waves have the same properties, he hypothesised that the two energies would be equal: $mc^2=hf$
4. Because real particles do not travel at the speed of light, De Broglie substituted velocity (v) for the speed of light (c). $mv^2=hf$
5. Substitute v/λ for f. The final expression relates the de Broglie wavelength and particle momentum.
   $mv^2 = \frac{hv}{\lambda}$ and $\lambda_{dB} = \frac{h}{mv}$

Notes

Werner Heisenberg and Erwin Schrödinger

In 1925, two scientists working independently and using separate lines of mathematical thinking applied de Broglie's reasoning to explain how electrons behaved within the atoms. In Germany, physicist Werner Heisenberg developed 'matrix mechanics' and Austrian physicist Erwin Schrödinger developed a similar theory called 'wave mechanics.' Later it was shown that these two approaches were equivalent.

The Heisenberg-Schrödinger model of the atom in which each electron acts as a wave (sometimes referred to as a 'cloud') around the nucleus of an atom replaced the Rutherford-Bohr model. In this model, electrons obey a 'wave function' and occupy 'orbitals' rather than orbits. Unlike the circular orbits of the Rutherford-Bohr model, atomic orbitals have a variety of shapes ranging from spheres to dumbbells to daisies.

The uncertainty principle

In 1927, Heisenberg made another major contribution to quantum physics now known as 'Heisenberg's uncertainty principle'. He reasoned that since matter acts as waves, some properties, such as an electron's position and speed, are 'complementary' meaning that there is a limit to how well the precision of each property can be known. The limit is related to Planck's constant. It was reasoned that the more precisely an electron's position is known, the less precisely its speed can be known, and vice versa.

Quantum Energy Levels

Electron Transitions

Bohr's model or description of the structure of the hydrogen atom explains that the electron can only exist at certain energy levels. These energies in a hydrogen atom can be calculated fairly accurately. This is more difficult for more complex atoms and compounds. Even so, many of the energy levels in these more complicated atoms and molecules have been determined.

When in what is known as the' ground state', the electrons in a compound are in the lowest energy orbitals possible. When a photon is absorbed by the compound an electron jumps from a low energy orbital to an unoccupied spot in a higher energy orbital. The compound is said to be in an excited state. When an electron falls back to the vacant low energy orbital a photon is released. If the energy difference is in the appropriate range visible light will be observed. If the energy difference is greater, an invisible ultra-violet photon or X-ray will be emitted.

One way of illustrating energy levels is to visualise them as steps on a ladder or shelves in a bookcase. Electrons can sit on shelves but not between shelves. To move from a lower level to a higher level, an electron must gain an amount of energy equal to the difference between the two levels. This can involve absorption of a photon. To move from a higher to a lower level, the electron will lose energy by emitting a photon with energy equal to the difference between the levels:

$$E_{photon} = E_{high} - E_{low}$$

The frequency (or wavelength) can be found as follows:

$$f = \frac{c}{\lambda} = \frac{E}{h}$$

Also: $E = hf = \frac{hc}{\lambda}$

Notes

Hydrogen spectra

When white light is shone on a sample of hydrogen gas, the hydrogen atom absorbs energy and an electron jumps to a higher energy level, see Figure 13.1. The light that passes through the hydrogen gas can be analysed and a continuous spectrum with black lines at 656, 468, 434, and 410 nm is observed. This indicates that these wavelengths have been absorbed and this spectrum is known as an absorption spectrum, see Figure 13.2. Similarly, when the light emitted from a hydrogen atom in an excited state, an emission spectrum is observed. All elements have characteristic emission spectrums and characteristic absorption spectra.

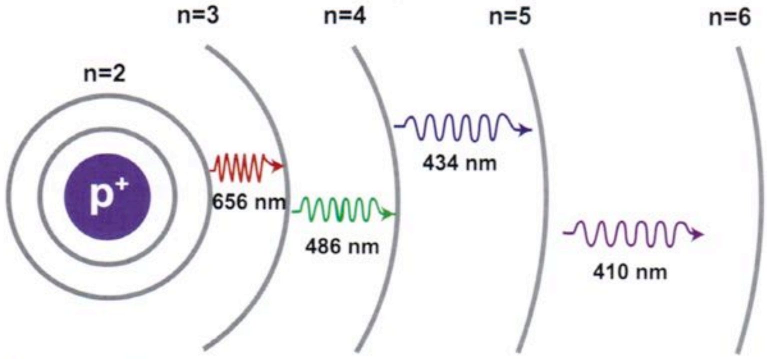


Figure 13.1: The emission of light by a hydrogen atom.

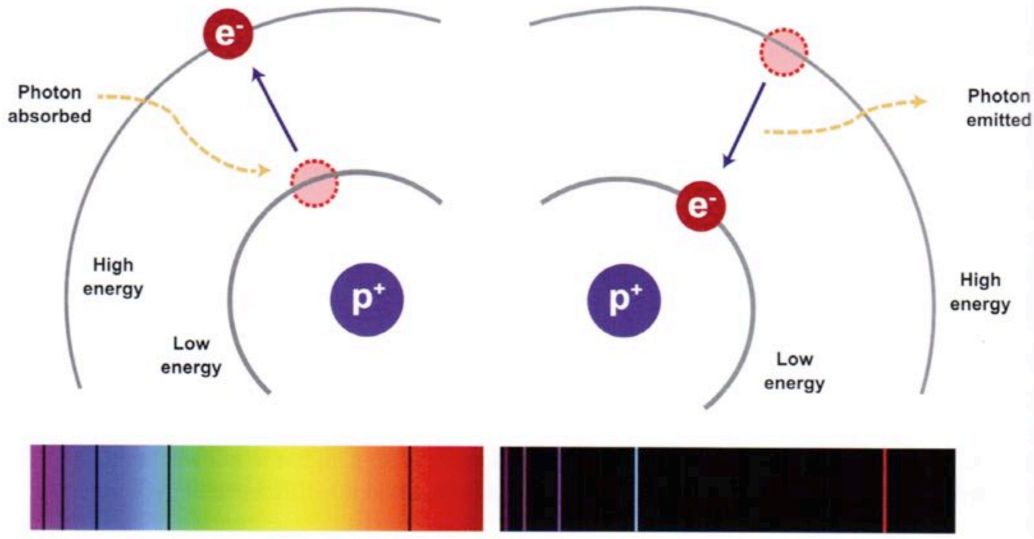


Figure 13.2: Hydrogen Absorption Spectrum (left) and emission spectrum (right).

Investigations 13.1: Applications of quantum mechanics

Background

Notes

X-rays

High energy particles, X-rays and gamma rays can deliver enough energy to expel tightly held electrons from the inner orbitals of an atom causing ionisation. Electrons in higher energy orbitals are able to 'fall' into the lower orbital releasing energy in the form of an X-ray photon. The energy of this photon is characteristic of the atom from where it originated. The term X-ray fluorescence is applied to this phenomenon. The wavelength of this fluorescent radiation can be calculated from Planck's Law:

$$\lambda = \frac{hc}{E}$$

The fluorescent radiation can be analysed either by sorting the energies of the photons (energy-dispersive analysis) or by separating the wavelengths of the radiation (wavelength-dispersive analysis). Once sorted, the intensity of each characteristic radiation is directly related to the amount of each element in the material. This is the basis of X-ray fluorescence analysis.

Task 1

X-ray analysis

X-ray fluorescence analysis and X-ray diffraction analysis are two very powerful and widely used material compositional and structural analysis techniques. Describe the two different techniques and their capabilities. Describe the X-ray detection systems used for each system. One method relies on the quantum nature of light, the other on the wave nature; discuss.

Task 2

Applications of quantum mechanics

Many applications of quantum physics have influenced society.

Describe the application and operation of the following technologies highlighting the importance of quantum theory:

1. Photo-voltaic cells.
2. Lasers.

Investigations 13.2: Microwaves

Notes

Background

This quantum energy level model does not only apply to the electrons within an atom. Atoms and molecules can also contain energy by way of molecular vibrations and/or rotations. Molecules have discrete energy levels and can jump between the different levels giving off photons. Infrared radiation originates from changing vibrational states within a molecule. When a molecule jumps from a high energy vibrational mode (or state) to a low energy mode an infrared photon is emitted. Similarly, microwave radiation is emitted when a molecule changes its rotational energy state

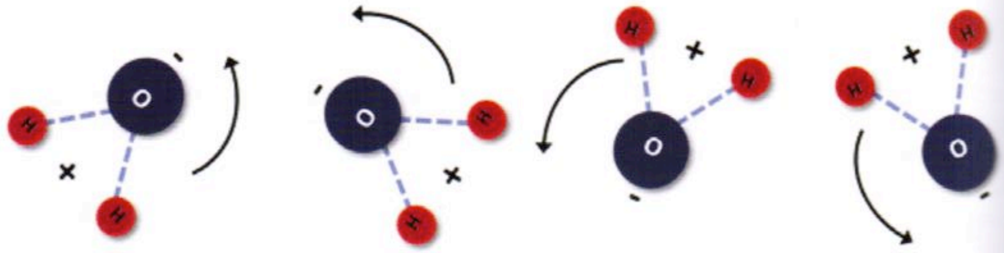


Figure 13.2: Schematic of a rotating water molecule. The oxygen has a net negative charge creating an electric dipole that oscillates due to the rotation of the water molecule.

The task

A modern application of microwave radiation is the everyday microwave oven. Microwaves are electromagnetic radiation associated with a corresponding change in the rotational energy level or state of a molecule. For a molecule to absorb a microwave photon it must have a rotating electric dipole. Water is a good example of a dipolar molecule. Although water molecules don't have an overall charge, their oxygen atom is slightly negative and their hydrogen atoms are slightly positive (the molecule has a positive and negative pole so is called polar). This means that in an electric field water molecules rotate to align with the field. When subjected to microwaves the electric field of a molecule will point upwards and then downwards about 2.5 billion times every second.

A. Microwave Ovens
   - Using appropriate physics understanding, explain how a microwave oven works.
   - What substance is most suitable for heating in a microwave oven?
   - Why is it difficult to heat dry rice in a microwave oven?
   - Discuss the statement: 'Frozen food should not be thawed in a microwave oven'

B. State and explain two other applications of microwave radiation.

Experiment 13.3: Quantum interference

Equipment

- Laser
- Needle
- Tape
- White card paper or cardboard
- 2 retort stands and clamps
- A room that can be darkened

Lab notes

1. Push a tiny hole in the card or cardboard with your needle.
2. Stand the card or cardboard upright in a retort stand and clamp at least 3 m away from the wall you will project your laser onto.
3. Mount your laser pointer in a second retort and clamp.
4. Predict what you expect to see when the laser light is directed through the hole. Turn the laser on and adjust its position and angle so that the light passes through the hole in the card and onto the wall. Record your observations. Do your observations match your prediction?
5. Push another hole in your card right next to the first one so that they are as close together as possible without creating one large hole.
6. Predict what you expect to see when the laser light is directed through both of the holes. Adjust your laser so that it passes through both holes. Observe and record the shapes created on the wall. Do your observations match your prediction?
7. Predict what you expect to see if you now cover one of the holes and use the laser setup as in step 6. Cover one of the holes with a small piece of paper, leaving the other open. Observe and record how the projected image on the wall changes. Do your observations match your prediction?

Post lab discussion

1. Explain why you should see a single blob of light from the laser when it was passing through one hole.
2. Explain why you should see a striped blob of light when it was passing through both holes.
3. Explain why you should have noticed that the stripes disappeared when you covered one of the holes.

Notes

Experiment 13.4: Measuring Planck's constant

Notes

Max Planck

The Planck constant plays a central role in understanding the properties of matter and energy. It is a cornerstone of the theory of quantum mechanics. Named after German physicist Max Karl Planck (1858–1947), the Planck constant tells us how the energy of individual photons relates to the wavelength of their radiation:

$$E_p = hc/\lambda$$

Where

E_p is the energy of a single photon (in joules), h is the Planck constant, c is the speed of light in a vacuum, and λ is the wavelength of the radiation.

How light emitting diodes work

Light emitting diodes or LEDs are produced by the junction of two 'doped' semiconductor materials, one of which has an excess of electrons (n-type) and the other a lack of electrons (p-type). When an electrical current passes through this junction, energy is released in the form of photons. The energy of each photon determines the colour of the light emitted. The amount of energy can be tailored by modifying the chemical composition of the semiconductor materials. LEDs can emit light in specific colours, such as red and green in the visible region of the electromagnetic spectrum, or beyond into the ultraviolet and infrared regions.

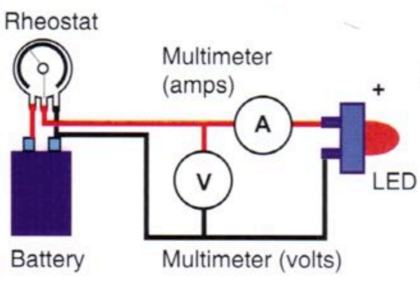
The wavelength determines the colour of the light emitted. For example, green-emitting LEDs typically produce light with a wavelength of around 567 nanometres. Each colour of LED has a different threshold voltage at which electrons start being produced. Measuring this voltage, together with known values for the emission wavelengths, provides a way to determine a value for the Planck constant.

Equipment

- Four LEDs emitting different colours - red, orange, green and blue. Make sure the LEDs have a clear, colourless casing surrounding the LED, so that the colour is determined by the device itself, not from the coloured casing.
- A battery pack or pure DC power supply capable of delivering 0–3 V.
- Rheostat or 1 kΩ potentiometer
- A voltmeter and an ammeter or two multimeters, or a data logger with voltage and current probes

Lab notes

1. Set up the circuit as shown in the diagram. Connect the ammeter in series with the LED to measure the current through it, and connect the voltmeter in parallel to the LED to measure the voltage across it. The applied voltage can be adjusted by using the potentiometer or the rheostat.



2. Change the voltage in steps of 0.05 V from 0 V to 3 V, and measure the resulting electrical current. Note that when the current flowing through the LED is small, the LED might not light up, but the ammeter can still measure the current. To protect the LED, take care to keep the current below 5 mA.

Post lab discussion

Notes

1. For each LED, plot a graph of current vs voltage. On each graph, find the straight line of 'best fit' to join up the points that slope up from the x-axis. If the points lie close to the line, a linear relationship holds between the applied voltage and the current in this region of the graph.
2. Determine the activation voltage (Va) from the collected data for each LED. It can be read from the graph by extrapolating a straight line through the current vs voltage graphs for each coloured LED where they intercept the x-axis.
3. Tabulate your findings in a table similar to the following:

LED colour	Wavelength, λ (nm)	Frequency, f $f = c/\lambda$	Activation voltage, V_a

4. Graph activation voltage (vertical axis) vs frequency (horizontal axis). Determine the slope of the graph, which is Planck's constant. How does your value compare with the accepted value for the Planck constant of 6.626×10^{-34} J s?

Problem Set 13: Quantum theory

Notes

1. The light from stars can be analysed by digitising and enhancing the spectrum produced by passing the starlight through a diffraction grating. The observed continuous spectrum contains distinct black lines.

   (a) Explain how these black lines are produced.

   Astronomers can use these lines to predict the elemental composition of the observed stars by comparison with line emission spectra produced by various elements under laboratory conditions.

   (b) Explain how this method gives accurate predictions of the elements in the observed stars.

   (c) What are two essential criteria needed to produce the line emission spectra.

2. White light is incident on a solution of chromium(III) chloride in a beaker and the resultant transmitted spectrum analysed.

   (a) Explain why the chromium(III) chloride solution appears green.

   (b) Give the name of the type of spectrum produced in the transmitted beam.

3. Aurora Australis, in the Southern Hemisphere, and Aurora Borealis, in the Northern Hemisphere, produce brilliant patterns of light in the upper atmosphere at the extreme latitudes of the magnetic poles of the Earth. This light is produced as a result of interactions between the magnetic field of the Earth, charged particles produced by solar winds and molecules and atoms of gas in the Earth's atmosphere.

   The predominant green colour has a wavelength of 557.7 nm and is a result of electron transitions between the n = 3 and n = 2 energy levels of oxygen.

   (a) Calculate the difference in energy between these two levels in both joules and electron volts.

   (b) Is this an example of fluorescence of phosphorescence? Explain.

4. An energy level diagram (not to scale) for the hydrogen atom is shown on the right. Consider each of the following downward transitions:

(i) E2 to E1	(ii) E4 to E2
(iii) E3 to E2	(iv) E5 to E3

   Calculate the following for each of these transitions.

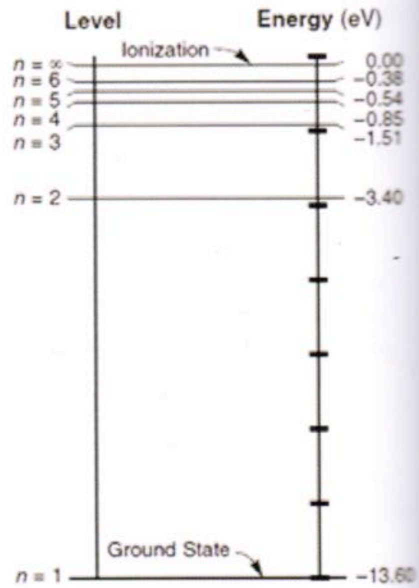
   (a) The frequency of the emitted photon.

   (b) The section of the electromagnetic spectrum to which the emitted photon belongs.

   A purple line in the visible emission spectrum of hydrogen has a wavelength of 434 nm.

   (c) Between which two levels must this electron fall to emit this photon?

   Note: 1eV = 1.6×10^{-19} J



5. An electron undergoes a transition from a higher to a lower energy level of 2.35 eV and in so doing emits a photon with an energy of 4.00×10^{14} Hz. In which energy level was this electron before it undertook this transition?

6. Explain why the spectrum from a gas such as hydrogen only shows the emision of certain wavelengths on excitation and why this same gas is capable of absorbing only some of these wavelengths.

13.87 eV ionisation

2.30 eV

1.38 eV

0.00 eV

7. At right is a diagram representing some of the energy levels in a caesium atom.
A beam of electrons with energy of 2.80 eV is incident on a gaseous sample of caesium in a sealed container.
   (a) What are the possible energies that electrons in the emerging beam can have?
   (b) What are the possible energies of any photons emitted?
   (c) What energy bombarding electrons would be needed to ionise a sample of caesium gas?

   This sample of caesium was bombarded with photons forming a continuous spectrum containing all energies between 1.00 eV and 14.5 eV.
   (c) What difference would be observed in this photon beam, after it emerged from the caesium sample?

Notes

8. Light-emitting diodes are semiconductor devices that emit light when a potential difference is applied across the junction of their semiconductor. A minimum potential difference is needed across this junction before they will emit light, and the colour emitted is determined by the value of this voltage. The applied potential raises the energy of the electrons in the semiconductor to an excited state and when they return to the ground state this energy is released as photons.
In an experiment it was found that a potential difference of 2.06 V across the diode junction resulted in light of wavelength 600 nm being produced.
   (a) Calculate the energy (in joules) absorbed by an electron in the ground state when this potential difference is applied.
   (b) What is the wavelength of the emitted photon?
   (c) Use this data to estimate a value for Planck's constant.

9. The wavelength of the red line in the Balmer (visible) series of the spectrum of atomic hydrogen is 656.3 nm. What is the difference in energy between the two energy levels responsible for this line.

10. Ground state helium atoms are irradiated with photons and it is noticed that the longest wavelength absorbed from the incident spectrum is 5.84×10^{-8} m. Calculate, in joules and electron volts, the energy difference between the ground state and this excited state of Helium.

11. Show that the separation of the energy levels of an excited atom is related to the wavelength, λ, of a photon released in the electron transition between these levels by the formula $E = 1.24 \times 10^{-6}/\lambda$

12. Three lines are observed on the emission spectrum from the first two excited states of a particular gas. The shortest wavelength of these was 1.042×10^{-7} m and one other was 1.235×10^{-7} m.
   (a) What is the wavelength of the third line observed in this spectrum and to what part of the visible or near visible spectrum does it belong?
   (b) Draw a labelled diagram showing these two energy levels for this atom.

13. Gaseous helium has a first excitation energy of 21.2 eV and an ionisation energy of 24.6 eV.
   (a) When electrons with an energy of 22.0 eV are fired at a sample of helium gas in a sealed tube photons are emitted that all have the same energy. What is the energy and wavelength of these photons and to what part of the electromagnetic spectrum do they belong?
   (b) What would you expect to occur to theses gas atoms or to observe in the emitted spectrum if these incident electrons had an energy of 26.0 eV? Explain your answer.
   (c) A beam of photons with a range of energies up to 26.0 eV was incident on this sample of helium. How would the transmitted beam differ from this incident beam and what is the maximum energy photon that might now be emitted?

Applications of special relativity

What gives gold its colour?

In discussions of special relativity, you occasionally encounter a claim like, "The effects of special relativity only matter to particle physicists and others working with extreme energies and velocities. Relativity has no consequences in everyday life." Well, these days, anybody who relies upon the Global Positioning System (GPS) to navigate their car or the airliner in which they're travelling uses both special and general relativity, because without correction for their effects, GPS would be so inaccurate as to be useless. But GPS is a recent innovation, and the relativistic corrections are both complicated and hidden from the user in the software in the receiver and on board the satellites. But there's an effect of special relativity which was observed, if not understood, by the ancients: the yellow gleam of gold.

With an atomic number of 79, gold is in the last row of the periodic table containing stable elements, and only four stable elements (mercury, thallium, lead, and bismuth) have greater atomic number. With 79 protons in its nucleus, the electrons of the gold atom are subjected to an intense electrostatic attraction. Using the naïve Bohr "solar system" model of the atom for the moment, electrons in the 1s orbital, closest to the nucleus, would have to orbit with a velocity v of 1.6×10^8 m s^{-1} to have sufficient kinetic energy to avoid "falling into" the nucleus. This is more than half the speed of light. At theses speeds the momentum of the electron increases causing a relativistic contraction of its orbit.

The colour of metals such as silver and gold is mainly due to absorption of light when a d electron jumps to an s orbital. For silver, the 4d→5s transition has an energy corresponding to ultraviolet light, so frequencies in the visible band are not absorbed. With all visible frequencies reflected equally, silver has no colour of its own; it's silvery. In gold, however, relativistic contraction of the s orbitals causes their energy levels to shift closer to those of the d orbitals (which are less affected by relativity). This, in turn, shifts the light absorption from the ultraviolet down into blue visual range. A substance that absorbs blue light will reflect the rest of the spectrum: the reds and greens which, combined, result in the yellowish hue we call golden.

Special relativity is also responsible for gold's resistance to tarnishing and other chemical reactions. Chemistry is mostly concerned with the electrons in the outermost orbitals. With a single 6s electron, you might expect gold to be highly reactive; after all, cæsium has the same 6s outer shell, and it is the most alkaline of natural elements: it explodes if dropped in water, and even reacts with ice. Gold's 6s orbital, however, is relativistically contracted toward the nucleus, and its electron has a high probability to be among the electrons of the filled inner shells. This, along with the stronger electrostatic attraction of the 79 protons in the nucleus, reduce the "atomic radius" of gold to about half of that for cæsium with its 55 protons and electrons. The gold atom is almost 50% heavier, yet only a little over half the size of cæsium giving gold its high density. Only the most reactive substances can tug gold's $6s^1$ electron out from where it's hiding among the others. The colour of gold and its immunity to tarnishing and corrosion are consequences of special relativity.

GPS systems

The Global Positioning System (GPS) is based on an array of 24 satellites, each carrying a precise atomic clock, orbiting the Earth. Using a hand-held GPS receiver which detects radio emissions from any of the satellites which happen to be overhead, users of even moderately priced devices can determine latitude, longitude and altitude to an accuracy currently reaching 15 metres, and local time to 50 billionths of a second. GPS has applications in aircraft navigation, oil exploration, wilderness recreation, bridge construction, sailing, and interstate trucking.

But in a relativistic world, things are not simple. The satellite clocks are moving at 14,000 km h^{-1} in orbits that circle the Earth twice per day, much faster than clocks on the surface of the Earth, and Einstein's theory of special relativity says that these rapidly moving clocks tick more slowly, by about seven microseconds (millionths of a second) per day.

Also, the orbiting clocks are 20,000 km above the Earth, and experience gravity that is one–quarter that on the ground. Einstein's general relativity theory says that gravity curves space and time, resulting in a tendency for the orbiting clocks to tick slightly faster, by about 45 microseconds per day. The net result is that time on a GPS satellite clock advances faster than a clock on the ground by about 38 microseconds per day.

To determine its location, the GPS receiver uses the time at which each signal from a satellite was emitted, as determined by the on-board atomic clock and encoded into the signal, together the with speed of light, to calculate the distance between itself and the satellites it communicated with. The orbit of each satellite is known accurately. Given enough satellites, it is a simple problem in Euclidean geometry to compute the receiver's precise location, both in space and time. To achieve a navigation accuracy of 15 metres, time throughout the GPS system must be known to an accuracy of 50 nanoseconds, which simply corresponds to the time required for light to travel 15 metres.

But at 38 microseconds per day, the relativistic offset in the rates of the satellite clocks is so large that, if left uncompensated, it would cause navigational errors that accumulate faster than 10 km per day! GPS accounts for relativity by electronically adjusting the rates of the satellite clocks, and by building mathematical corrections into the computer chips which solve for the user's location. Without the proper application of relativity, GPS would fail in its navigational functions within about 2 minutes.

Experimental evidence for time dilation

One of the first experiments to provide evidence of time dilation was done over seventy years ago by detecting muons Muons are particles created when incoming cosmic rays collide with air molecules in the outer reaches of the atmosphere. A constant stream of these particles travels towards the surface of the Earth at speeds very close to the speed of light. They are unstable particles, with a "half-life" of about 1.5 microseconds, which means that if you start with a thousand, 1.5 microseconds later you will have about 500 and so on.

In 1941, a detector placed near the top of Mount Washington (at 2000 m above sea level) measured muon flux of about 570 per hour. It would be expected that the number of muons would decrease as they fall, so if we move the detector to a lower altitude we expect it to detect fewer muons.

Knowing the half-life, and given that 570 per hour hit a detector near the top of Mount Washington, it would be expected that about 35 muons per hour would survive down to sea level. But with the detector at sea level about 400 muons per hour were detected! How do we explain the difference? The reason they didn't decay is that in their frame of reference, much less time had passed. The actual speed of the muons is about 0.994c, which corresponds to a time dilation factor of about 9. This means that in the time it takes to travel form the top of Mount Washington to sea level (6 microseconds), the time registered on the muons internal clock is about 0.67 microseconds (6/9) microseconds. In this time, only about one-quarter of them would decay leaving ¾ or about 430 to reach the detector.

Length contraction also plays its part. From the muon's point of view Mount Washington is less than 240m high. This explains why they can cover the distance so quickly.

In 1979 scientists carried out an experiment using a particle accelerator at CERN. They reported a similar experiment with muons accelerated to speeds 0.9994c. Trapped in a particle accelerator, muons were observed in the lab to have 29.3 times their rest half-life, completely consistent with time dilation.

Chapter 14: Special relativity

Special relativity explained

Notes

Main points

- Observations of objects travelling at very high speeds cannot be explained by Newtonian physics. These include the dilated half-life of high-speed muons created in the upper atmosphere, and the momentum of high-speed particles in particle accelerators.
- Einstein's special theory of relativity predicts significantly different results to those of Newtonian physics for velocities approaching the speed of light.
- The special theory of relativity is based on two postulates: that the speed of light in a vacuum is an absolute constant, and that all inertial reference frames are equivalent.
- Motion can only be measured relative to an observer; length and time are relative quantities that depend on the observer's frame of reference.

Equations:

The frequency f, wavelength λ, and wave speed v are related by the equation: $v = f\lambda$

The relationship between mass and energy is: $E = mc^2$

In a nuclear reaction: $E = \Delta m\, c^2$

The factor v/c is often referred to as β where: $\beta = \frac{v}{c}$

The Lorentz factor: $\gamma = \frac{1}{\sqrt{1-\beta^2}}$

If L_0 is the length of an object measured by an observer in the objects reference frame and L is the length as measured by the observer in a stationary reference frame then the two measurements are related as follows: $L=L_0 / \gamma$

$t = \gamma t_0$

Here t_0 is the time as measured in the frame of the moving 'light-clock' and t is the time as measured by the stationary observer.

Relative velocities: $u' = \dfrac{u - v}{1- \dfrac{uv}{c^2}}$ $\qquad u = \dfrac{u' + v}{1- \dfrac{u'v}{c^2}}$

Relativistic energy and momentum: $E_k = \gamma mc^2$ $\qquad p = \gamma mv$

To find a photon's momentum p, we can combine Planck's formula (E = hf) and Einstein's mass energy formula ($E = mc^2$):

$$p = mc = \frac{e}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

Special relativity

For a long time many scientists assumed that there must be some kind of substance through which light propagated similar to that observed with waves in water and with sound waves. They called this unknown substance the 'ether'. In 1887 Albert Michelson and Edward Morley carried out an experiment in which they tried to show the motion of Earth relative to the ether by measuring changes in light speed in different directions. To their surprise they found no change in the light speed regardless of the relative motion between Earth and the source of light or the ether.

Their experiment was a 'failure' but this 'failure' enabled scientists to abandon their ideas of the theory of 'ether' and to think differently. Without the ether theory there was now no absolute reference frame to determine what is at rest and what is moving. At this point Einstein started his work on special relativity.

Albert Einstein

Albert Einstein was born in Ulm, Germany on March 14, 1879. As a child, Einstein developed a curiosity for understanding the mysteries of science. Moving to Italy and then to Switzerland, he graduated from high school in 1896. In his later years, Einstein would write about two events that had a marked effect on his childhood. One was an encounter with a compass at age five, where he marvelled at the invisible forces that turned the needle. The other was at age 12, when he discovered a book of geometry which he read over and over.

In 1905, while working as a patent clerk in Bern, Switzerland, Einstein had what came to be known as his "Annus Mirabilis" or "miracle year". It was during this time that he obtained his doctorate degree and published four of his most influential research papers, including the special theory of relativity. This theory and his now world famous equation "$E = mc^2$" revolutionised our understanding of the Universe. In 1915, Einstein completed his general theory of relativity and in 1921 he was awarded the Nobel Prize in Physics for his explanation of the photoelectric effect.

Today, the practical applications of Einstein's theories include the development of modern electronics, GPS systems, lasers, and medical imaging techniques. Recognized as TIME magazine's "Person of the Century" in 1999, Einstein coupled his intellect with strong passion for social justice and dedication to pacifism, and gave the world both knowledge and pioneering moral leadership.

Einstein's special theory of relativity

The special theory of relativity changed forever ideas about space and time, energy and mass. The theory reveals to us that one person's interval of space is not the same as another person's, and time runs at different rates for different observers travelling at different speeds. A moving clock appears to run slower and a moving object measures shorter in its direction of motion. It also tells us that the momentum of a moving object increases exponentially as its velocity increases until, at the speed of light, it becomes infinite. The theory leads to the idea that energy and mass, once thought to be two distinctly different properties, are equivalent and interchangeable.

The reason that these predictions are not obvious in everyday observations is that the effect at everyday speeds for average size objects that we tend to deal with is very small. The effects only really become apparent at speeds approaching that of light itself.

The postulates of Einstein's special relativity

Einstein's theory is based on two simple postulates:

1. The laws of physics are the same in all inertial frames of reference.
2. The speed of light in vacuum has the same value in all inertial frames of reference.

The first postulate implies that there is equivalence between all inertial frames. An inertial frame is a place in space that is not experiencing any accelerating forces. It includes objects at rest and those moving at constant velocity – but then we need to ask, what does 'at rest' mean? There is no way of knowing this. There is no experiment that we can perform to determine our velocity or to ascertain whether we are at rest. All we can do is measure our velocity relative to some other object or reference frame. As we watch a train rush by we could say it has a velocity of 100 km h^{-1}. But an observer on a similar train passing in the opposite direction who suddenly looks out the window will see the first train pass at 200 km h^{-1}. An observer in an aircraft travelling overhead will observe a completely different velocity, as would someone on the surface of the moon peering down through a powerful telescope. The Earth moves across the solar system at high speed but we have no way of knowing this as we sit at our desk where we imagine we are 'at rest'.

Notes

Special relativity explained

Notes

There is also no such thing as an absolute reference frame. A fixed point in space in one frame is a moving point for another frame. People in two frames moving relative to each other will not agree about who is moving and at what velocity.

The first postulate was understood before Einstein. Einstein's revolutionary contribution is the new concept of the universality and constancy of the speed of light. The second postulate is the one that forces us to change the laws of physics as they were known before Einstein's relativity.

The universal speed limit

Surprising properties of light were discovered in the late nineteenth century. These properties form the basis of the theory of special relativity.

Experiments performed with radio and light waves emitted by pulsars, with light emitted from particles in accelerators, or with the light of gamma-ray bursts all show that the speed of the electromagnetic radiation does not depend on the frequency of the radiation, or on its polarisation, or on its intensity. After starting together and travelling together for thousands of millions of years across the Universe, light beams with different properties still arrive side by side. Other experiments show that the speed of light is the same in all directions of space.

But this invariance of the speed of light is puzzling. We all know that in order to throw a ball as fast as possible, we run as we throw it. We know instinctively that the ball's speed with respect to the ground is higher than if we do not run. We also know that hitting a tennis ball more forcefully makes it travel faster. But light behaves differently.

Experiments show that light emitted from a moving lamp has the same speed as light emitted from a resting one. One way to prove this is to look at the sky. The sky shows many examples of binary stars, stars that rotate around each other along ellipses. In some of these systems, we see the ellipses (almost) edge-on so that each star periodically moves towards and away from us. If the speed of light would vary with the speed of the source, we would see bizarre effects, because the light emitted from some positions would catch up with the light emitted from other positions. We would not be able to observe the elliptical shape of the orbits. However, such strange effects are not seen and perfect ellipses are observed. In other words, light in a vacuum will never travel faster than the speed of light. Experiments and theory show that no object can reach the speed of light. The speed of light is the universal speed limit; it is the maximum speed in nature. The velocity v of any physical system in nature is bound by c. The existence of an invariant limit speed c is not as surprising as we might think but, nevertheless it leads to many interesting results: it leads to observer-varying time and length intervals, to an intimate relation between mass and energy, to the existence of event horizons and to the existence of antimatter.

The complete theory of special relativity is contained within these statements.

- All light beams have the same speed.
- The speed of light in vacuum is invariant (it doesn't change).
- The speed of light is a universal limit speed.

Space and time

Because of Einstein's theory of relativity we can now say that space and time are related to each other by a common factor, the speed of light. Because it has the same value in all frames of reference it does not matter whether you are stationary with reference to a light source, travelling toward it or travelling away – the speed at which light reaches you is always the same. The constant velocity of light is used in our modern definitions of both time and distance.

Notes

Light moves extremely rapidly but with a finite speed. Today the speed of light is specified with a precision of nine significant figures. The metre is now defined in terms of the speed of light. Since 1983 the metre has been defined by international agreement as the distance travelled by light in vacuum during a time interval of 1/299,792,458 of a second. This makes the speed of light exactly 299,792.458 km s^{-1}.

Time is also defined in terms of the properties of light. One second is defined as the duration of 9 192 631 770 periods of the wavelength of light emitted by caesium-133 produced by electron transitions between the two hyperfine levels of the ground state of that atom.

Some astronomical distances are defined by their relationship to the speed of light. An example is the light year – the distance traversed by a photon in one year of travel through vacuum. The light that we see from our nearest neighbour star, Proxima Centauri, was transmitted 4.2 years ago so Proxima Centauri is 4.2 light years from Earth. Light produced by the Sun takes approximately 8 minutes to reach the Earth, so the diameter of the Earth's orbit around the Sun is about 16 light minutes.

Space-time

Space-time (also known as the space–time continuum) is a model that combines space and time into a single model. The Universe is usually interpreted from a Euclidean space perspective where space consists of three dimensions often described on a Cartesian system with x, y and z axes. In space-time a "fourth dimension" is introduced to enable time information to be included. Any event can now be described by knowing its location in space and the time at which it occurred. By multiplying time by the speed of light the time dimension will have the same units as the space dimensions.

Four dimensional space is difficult to visualise and even more difficult to draw on a two-dimensional screen or piece of paper. To simplify we can show just a single space dimension, such as distance in one direction which we could call 'x' and a time axis in the same units as the 'x' axis. For example if 'x' is measured in metres and time in seconds then time can be multiplied by the speed of light 'c' to give units of metres.

Figure 14.2 shows a space-time plot for a car travelling at 20 m s^{-1} (about 72 km h^{-1}). Notice that the horizontal axis is severely squashed. If the two axes were scaled equally the horizontal axis would be about 1500 km long.

For particles travelling at speeds close to the speed of light we can produce an equally scaled plot as shown in Figure14.3. This graph shows the space-time trajectories of two particles – one travelling at 0.95c and another at 0.99c. The solid line represents the speed of light so all events that we can experience will occur in the space-time region below this line. The space-time plot for the car in the previous figure is shown also – its space-time line is virtually horizontal.

The factor v/c is often referred to as β where: $\beta = \dfrac{v}{c}$

Notes

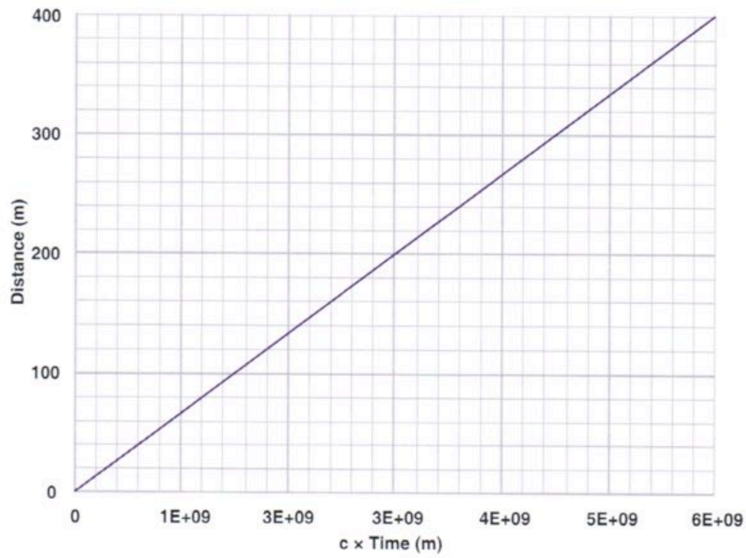


Figure 14.2: A simple space-time plot for a car travelling at 20 m s^{-1} (about 72 km hr^{-1}).

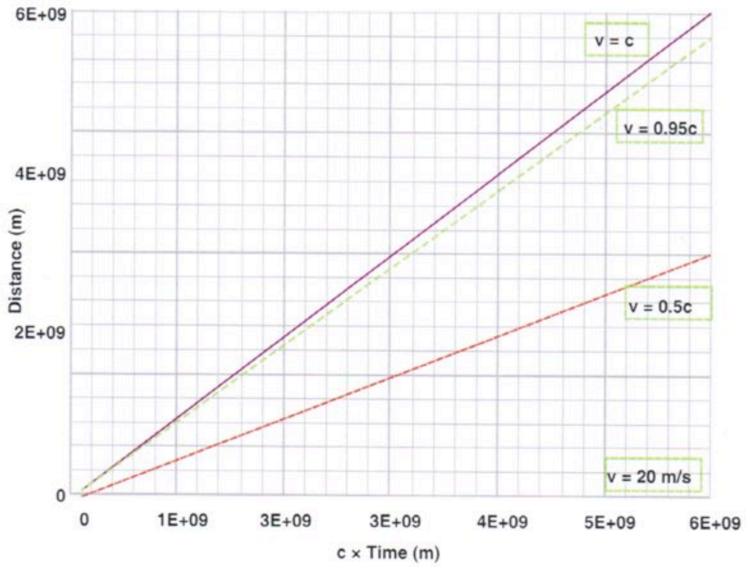


Figure14.3: The space-time trajectories of two particles – one travelling at 0.95c and another at 0.99c. The solid line represents the speed of light.

Hermann Minkowski

A mathematically rigorous description of space time was developed by mathematician Hermann Minkowski in the early 20th century. Now known as 'Minkowski space' or 'Minkowski space-time' this model comprises a four-dimensional manifold where the space-time interval between any two events is independent of the inertial frame of reference in which they are recorded. Although initially developed for Maxwell's equations of electromagnetism, the mathematical structure of Minkowski space-time was shown to be useful when adapted to Einstein's theory of special relativity, and is the most common mathematical structure on which special relativity is formulated. Because it treats time differently Minkowski space differs from simple four-dimensional Euclidean space. The model has significantly simplified a large number of physical theories.

Notes

Mass and energy

Mass can be defined as the measure of how much matter an object or body contains - the total number of sub-atomic particles (electrons, protons and neutrons) in the object. But also mass can be defined by Newton's second law, $F = ma$. It can be seen as the resistance to acceleration specifying the amount of force required to cause a body to accelerate.

Energy is the measure of a system's ability to make changes or in mechanics, the ability to perform "work". It exists in many forms: potential, kinetic, thermal etc. The law of conservation of energy tells us that energy can neither be created nor destroyed; it can only be converted from one form to another. It is the total amount of energy that is conserved. If you drop a rock from a bridge the rock has kinetic energy the moment it starts to move. Just before you dropped the ball, it had only potential energy. As the rock moves, the potential energy is converted into kinetic energy. Likewise, when the rock hits the ground, some of its energy is converted to thermal energy. If you find the total energy for the system, you will find that the amount of energy for the system is the same at all times.

The unification of energy and mass

The concept of mass has been fundamental to physics. Its definition goes back to Galileo and Newton who said that mass was that property of a body that enables it to resist externally imposed changes to its motion. Newton used mass to define momentum and force: he defined a body's momentum as $p = mv$ (where v is its velocity), and he defined force in terms of an object's acceleration: $F = ma$.

This definition of mass was applied in a straightforward way for almost two centuries. Then Einstein arrived on the scene and, in his theory of special relativity, he changed this way of thinking forever. Undoubtedly the most famous equation ever written is $E=mc^2$. This equation says that energy is equal to the mass of an object times the speed of light squared. This means that energy and mass are interchangeable – they are manifestations of the same thing. Since the speed of light is constant, an increase or decrease in the system's mass is proportional to an increase or decrease in the system's energy. The law of conservation of energy and the law of conservation of mass can be combined to give one law, the law of conservation of energy.

It is often stated that an object's mass increases as it approaches the speed of light. For example, consider a proton accelerated in a particle accelerator. The following occurs:

1) Energy must be added to the system to increase its speed.
2) More of the added energy goes towards increasing the particle's resistance to acceleration.
3) Less of the added energy goes into increasing the particle's speed.
4) Eventually, the amount of added energy required to reach the speed of light would become infinite. The proton never reaches the speed of light no matter how much energy is added. The speed of light can be considered the universal speed limit.

In step 2, the system's resistance to acceleration is a measurement of an object's mass, which increases when the object speeds up. This is called relativistic mass. It should be noted that many physicists have stopped using this concept of mass and now consider this effect in terms of an increase in momentum and energy. The Newtonian definition of mass still holds for a body at rest, and so has come to be called the body's *rest mass*, often denoted m_0.

Energy and Momentum

In classical mechanics, kinetic energy E_k and momentum p are expressed as

$E_k = ½mv^2$

$p = mv$

Special relativity explained

Notes

These relationships work well at low speeds and for objects of average mass, but at high speed we need to apply the relativistic corrections:

$E_k = \gamma mc^2$

$p = \gamma mv$

Where γ is the Lorentz factor as described on page 180.

In some relativity textbooks, the so called "relativistic mass" $m = \gamma m_0$ is used as well. Many authors prefer to use the expressions of relativistic energy and momentum to express the velocity dependence in relativity, which provide the same experimental predictions.

Relativistic energy and momentum increase significantly at speeds approaching the speed of light and at these speeds enormous amounts of energy are required. Therefore no massive particle can ever reach the speed of light.

Photons

We have seen that as we accelerate a massive particle up to the speed of light we find that the energy increases rapidly with little change in the particle's velocity. Einstein's formula predicts that, at the speed of light, the energy of the particle would become infinitely great. In other words, it would require an infinitely large amount of energy to accelerate the particle to the speed of light. This is, quite obviously, impossible so how then does a photon manage to travel with the speed of light? The answer is that photons have zero 'rest' mass, which means that the energy of a photon is all kinetic energy. If a photon is forced to come to rest in some absorbent material, it simply ceases to exist.

If individual photons have a definite energy and are able to behave like particles, we should expect them to carry momentum. It is natural to think that light carries energy as the Earth receives tremendous amounts of solar energy from the Sun. Einstein had used the hypothesis that light could be regarded as a stream of individual packets of energy to explain the 'photo-electric effect', the fact that light shining on a metal surface can cause electrons to be ejected. Einstein showed that, if Planck's law of black-body radiation is accepted, photons must also carry momentum $p=h/\lambda$. This photon momentum was observed experimentally by Arthur Compton, for which he received the Nobel Prize in 1927.

To find a photon's momentum we can combine Planck's formula ($E = hf$) and Einstein's mass – energy formula ($E = mc^2$):

$$p = mc = \frac{e}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

Simultaneity

How do we know two events happen at the same time? When we see a flash of lightning we know its associated sound, thunder, will arrive shortly after. This time delay is a result of the different rates at which the information is conveyed to us – the flash of lightning travels at the speed of light, the thunder at a pedestrian pace equal to the speed of sound. The time delay can be used to calculate how far away a lightning strike is from the place where we are located.

If we observe two events at locations where we know the distance to our point of observation we can carry out a simple calculation to determine if the two events are simultaneous – that is, did they happen at exactly the same time? But this is not so easy in Einstein's world. Whether or not two events occur simultaneous depends upon your frame of reference. The time order of events that are close together in time but distant in space can be different in different frames.

It was common for Einstein to create simple thought experiments to help illustrate the concepts of his theories. One such thought experiment illustrates the point of simultaneity. Examples similar to this are discussed in many textbooks.

Imagine a train moving with uniform high velocity. A light source located in the centre of the train transmits a light pulse in all directions. A detector (or clock) at the front and rear of the train record the moment a pulse of light is detected. Marie, an observer on board the train recognises that the pulses strike each detector simultaneously. At this moment an observer named Albert on a 'stationary' platform observes the train pass by just as the light pulses are emitted.

As light travels out from the source, according to Albert, the stationary observer, it must be travelling at the speed of light in both directions. After the pulses are emitted the rear of the train has moved closer to the source and therefore has less distance to travel. The forward going pulse has further to travel. Albert perceives that the light pulse has reached the rear detector first and he concludes that the two pulse detection events are not simultaneous.

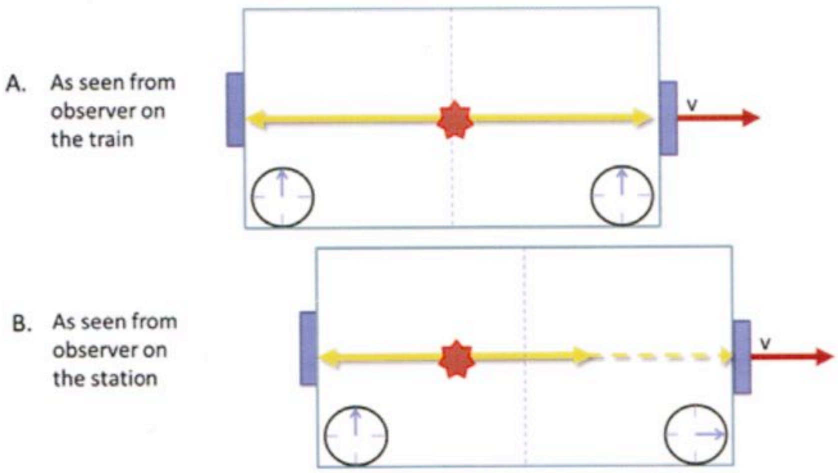


Figure 14.4: A light source located in the centre of the train transmits a light pulse in all directions. An observer on the train sees the pulses strike each detector simultaneously. A stationary observer sees the light pulse reach the rear detector first.

Notes

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This thought experiment demonstrates that the two events that appear to be simultaneous to one observer do not appear to be simultaneous to another observer. In other words, two events that are simultaneous in one reference frame in general do not appear to be simultaneous in a second frame moving relative to the first. Simultaneity is not an absolute concept but rather one that depends on the state of motion of the observer.

Einstein's thought experiment demonstrates that two observers can disagree on the simultaneity of two events. Visualising events in space-time can help us understand this concept. Imagine you are looking at a row of trees in an orchard. Standing at a position at the end of the row you can see the trees in a line in front of you and you could say they all share the same y-coordinate. From another vantage point, say some distance perpendicular to the line, we can see the trees separated by 2 metres. But if you think of time as just another "direction" you can believe that your time coordinate could have one value in one reference frame, and another value in a different frame.

Time dilation and length contraction follow from this in a straightforward way. And they are much easier to visualise if you can see that time is another "direction", and therefore is relative to the observer, just like position is.

Discussion: Sound waves

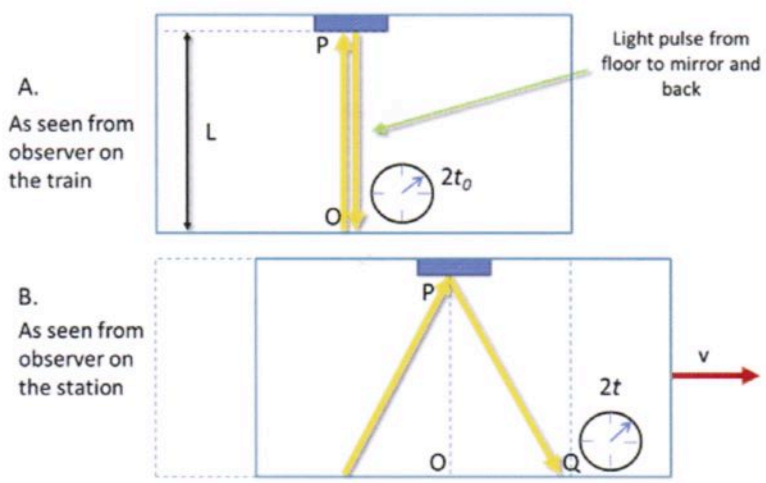
Consider the previous experiment but with the light source replaced by a sound source. When the sound reaches the two detectors a flash of light is given off. Will the two observers agree on the simultaneity of the sound pulse? Discuss.

Time dilation

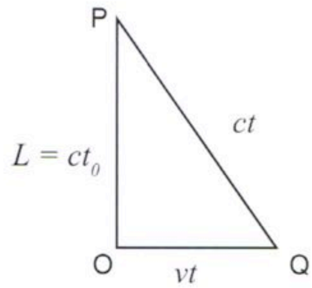
Another typical thought-experiment is the analysis of the "light-clock". The basic idea of a light-clock is to use the distance travelled by a pulse of light and the known speed of light to mark out intervals of time. The following example is discussed in many textbooks and can be used to derive the time dilation formula. The thought experiment proceeds as follows:

Albert, inside a train carriage, sets up an experiment where he directs a pulse of light to a mirror on the roof of the train. The beam returns to its starting position and the time for the return trip is measured. This is shown in part 'A' of the following diagram.

The next step in this experiment is to imagine the train moving at high velocity through the station from left to right and consider how the light pulse would appear to Marie who is standing on the platform of a railway station. She would observe the path of the light pulse as two diagonal paths as shown in part 'B'.



The triangular path OPQ is shown below. Knowing that for constant velocity - distance = velocity multiplied by time - we can determine the length of the sides of the triangle: From part A the length L is equal to the velocity of light c multiplied by the time taken, t_0: That is, $L = ct_0$. Similarly the diagonal edge of the triangle is ct and the base of the triangle is vt as shown. Note that t_0 is known as the 'proper time' and is the time measure in the frame containing the light clock, in this case the train carriage and t is the time measured relative to the proper time. The length of the light path PQ as viewed by Marie on the platform is longer than the path PO as observed by Albert in the train carriage. The speed of light 'c' is the same for both observers so therefore time as measured by Albert, the moving observer, must be ticking 'slower' than time as observed for Marie, the stationary observer.



If we analyse the triangle using Pythagoras' theorem we get:

$(ct)^2 = (vt)^2 + (ct_0)^2$

$(ct_0)^2 = (ct)^2 - (vt_0)^2$

$$t_0 = t\sqrt{1 - \frac{v^2}{c^2}} \qquad t = t_0 \frac{1}{\sqrt{1-\beta^2}}$$

Using $\gamma = \dfrac{1}{\sqrt{1-\beta^2}}$ we get: $t = \gamma . t_0$

Here t_0 is the time as measured in the frame of the moving 'light-clock' and t is the time as measured by the stationary observer. γ is the Lorentz factor and will be described in the next section.

The Lorentz Transform

Hendrik Lorentz (18 July 1853 – 4 February 1928) was a Dutch physicist who shared the 1902 Nobel Prize in Physics with Pieter Zeeman for the discovery and theoretical explanation of the Zeeman Effect - the splitting of a spectral line into several components in the presence of a static magnetic field. He also derived the transformation equations subsequently used by Albert Einstein to describe space and time. The Lorentz transform adapted from his work is a way of comparing observations from different reference frames. It is a way to bring observers of different velocities at different places together so they can 'compare notes'. It takes into account the fact that the speed of light is constant, and finite, but distance and time are not constant.

For example, if you are observing a building from the front entrance and a friend two streets away observes the same building how do you compare your observations about the size and shape of the building? You need to make an adjustment, some sort of a transform, to reflect your different viewpoints. In special relativity this becomes complicated since neither distance nor time are constant between observers moving relative to each other.

In the Lorentz transform measurements in the direction of motion are adjusted by a factor γ (gamma) known as the Lorentz factor. Its value is given by:

$$\gamma = \sqrt{1 - \frac{v^2}{c^2}} \qquad = \frac{1}{\sqrt{1-\beta^2}}$$

Where v is the relative velocity of the two reference frames and c is the speed of light. Gamma is always greater than one because v is always less than c.

Notes

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The following graph is a plot of gamma and 1/gamma for speeds up to the speed of light.

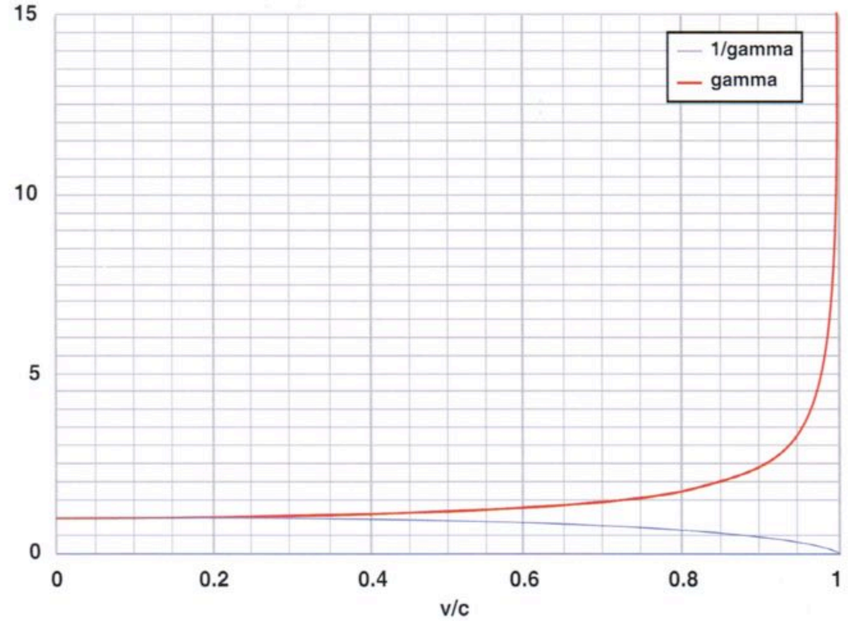


Figure 14.6: A plot of gamma and 1/gamma for speeds up to the speed of light

The relativity of length

As objects move through space-time, space as well as time changes. As an object travels at relativistic speeds it contracts or gets shorter. The term "length contraction" appears in many textbooks but what does it mean? Do fast-moving objects really shrink? Or does an object only appear to shrink, or does the observer only "perceive" a contraction?

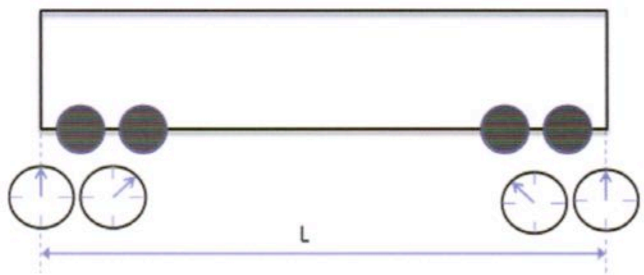


Figure14.7 Measuring the length of a moving train by locating its front and back at the same time

Figure14.7 shows the difficulty of trying to measure the length of a moving train by locating its front and back at the same time. Because simultaneity is relative and it enters into length measurements, length should also be a relative quantity. It is.

A suitable thought experiment is to compare the length of the train with a known external length such as the length of a tunnel.

Marie is on the train, with synchronised clocks placed at each end. Albert is on the station. By carefully setting up the clocks Marie sees the front clock strike noon as the train exits the tunnel and the back clock strike noon as the train enters the tunnel. To Marie the clocks strike noon simultaneously and she concludes that the train fits exactly in tunnel. For Albert the back clock strikes noon first and the front clock a little later so he concludes that the train is shorter than the tunnel.

The key to understanding this is to ask how, exactly, one might measure the length of a moving object. We can do another thought experiment using the example of a very fast train and determine how we can measure its speed. We need a set of stationary clocks spread out at known positions. The measurement of length consists of recording the simultaneous positions of the two ends of the train – we may need multiple observers to do this. The instructions might be to report in if you see either end of the train at your location at precisely noon. We can work out, by knowing who reported in, where the ends of the train were at the chosen time.

Moving objects are length-contracted – they appear shorter to an observer in a stationary frame of reference. Note that length contraction occurs only along the direction of relative motion.

If L_0 is the length of train measured by an observer in the train and L is the length as measured by the observer in a stationary reference frame then the two measurements are related through the formula used in most textbooks:

$$\frac{L}{L_0} = \sqrt{1-\beta^2}$$

$$L = L_0 / \gamma$$

Thoughts on length and time

Does a moving object really shrink? Reality is based on observations and measurements. If the results are always consistent and if no error can be determined, then what is observed and measured is real. In that sense, the object really does shrink. However, a more precise statement is that motion affects the measurement and thus reality. To an observer on the ground the train does shrink. In another observer's reality the amount of shrinking may be different. And for observers on the moving train the reality is that everything is as normal.

The relativity of velocities

No two objects can have a relative velocity greater than c. But what if a spacecraft traveling at 0.9c and it fires a missile which it observes to be moving at 0.8c with respect to it!? Velocities must transform according to the Lorentz transformation, and that leads to a rather non-intuitive result called Einstein velocity addition.

To analyse this situation we can consider two observers in relative motion with respect to each other who are both observing the motion of the missile. How do they measure the velocity of the object relative to each other if the speed of the object is close to that light? We can consider a reference frame S' moving at a speed v relative to S. The missile has a velocity u' measured in the S' frame. The velocity u is the speed of the missile relative to frame S.

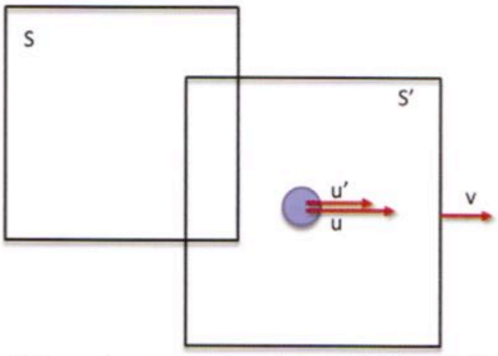


Figure 14.8: A reference frame S' is moving at a speed v relative to S. The missile shown by the blue circle has a velocity u' measured in the S' frame. The velocity u is the speed of the missile relative to frame S.

Notes

Notes

Then $u' = \dfrac{u - v}{1 - \dfrac{uv}{c^2}}$ and $u = \dfrac{u' + v}{1 - \dfrac{u'v}{c^2}}$

When v is much less than the speed of light c the denominator in the equation for u' approaches unity, and so $u' = u - v$, which is the Galilean velocity transformation equation. It is exactly what we would expect in the non-relativistic case. However, when u approaches the speed of light the equation becomes:

$$u' = \frac{c - v}{1 - \frac{cv}{c^2}} = \frac{c - v}{1 - \frac{v}{c}} = \frac{c\left(1 - \frac{v}{c}\right)}{1 - \frac{v}{c}} = c$$

From this result, we see that the speed of a particle travelling close to the speed of light measured by an observer in frame S is also measured as c by an observer in S'. This result is independent of the relative motion of S and S'. This s consistent with Einstein's second postulate, that the speed of light must be c relative to all inertial reference frames. Furthermore, we find that the speed of an object can never be measured to be greater than c.

What can two observers agree on?

Two observers do agree on:
(1) their relative speed of motion with respect to each other
(2) the speed of any ray of light, and
(3) the simultaneity of two events which take place at the same position and time in some frame.

We have seen several measurements that the two observers do not agree on:
(1) the time interval between events that take place in one of the frames,
(2) the distance between two fixed points in one of the frames,
(3) the velocity of a moving particle, and
(4) whether two events are simultaneous or not.

Experiment 14.1: Measuring the speed of light

Background

Visible light is one form of electromagnetic radiation (emr). Other forms exist that we cannot detect with our eyes, including infrared, ultraviolet and microwave radiations. All forms of emr travel at the same speed in vacuum, and almost the same speed in air.

Microwave ovens contain a device that emits microwaves of a single frequency. Note that many ovens contain a diffuser whose job is to break up the standing waves. This will make the pattern harder to detect.

Electromagnetic waves interact with materials in different ways, depending on the nature of the material and the frequency of the electromagnetic wave. Microwaves work well for cooking because their energy can be efficiently absorbed by molecules commonly found in food, including water, sugars, and fats. The absorbed microwave energy is converted to thermal energy and this cooks the food.

In this experiment you will use some of the properties of waves to estimate the speed of light. These properties are interference and the relationship between a wave's speed, its frequency, and its wavelength. Interference is what happens when multiple waves interact. In a microwave oven, interference occurs between waves that are reflected from the inside surfaces of the oven. The interference patterns can create "hot" and "cold" spots in the oven-areas where the microwave energy is higher or lower than average. This is why many microwave ovens have rotating platters to promote more even cooking of the food.

The spacing of the hot spots will be equal to one-half of the wavelength of the microwaves. Microwave ovens produce microwaves in a special configuration, called a standing wave. A standing wave is a wave that so perfectly fits its container that the wave pattern looks like it is standing still.

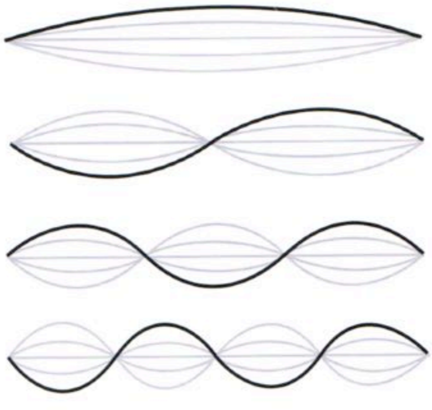


Figure14.1: Standing Wave patterns

The distance between hot-spots is equal to half of the wavelength of the microwaves. You will be able to measure the distance between the hot spots by measuring the distance between melted sections in chocolate. The frequency of the microwaves can be found on a label on the back of the oven. The frequency f, wavelength λ, and wave speed v are related by the equation: $v = f\lambda$.

Notes

Experiment 14.1: Measuring the speed of light

Notes

Aim

To measure the speed of EMR using microwaves

Equipment

- microwave oven
- two plates, or one plate and a shallow bowl
- bread and butter or margarine, or a large slab of chocolate or other low-melting material
- metre rule

Pre-lab

- Remove the turntable from the microwave oven.
- Cover the turntable spindle (the the rotating parts) using an inverted plate or the shallow bowl.
- Balance the other plate on top of the inverted one.
- Completely cover all the pieces of bread with butter or margarine (not necessary if using chocolate).
- Arrange the buttered bread on the plate so there are no large gaps between them; or place the chocolate slab so that none overhangs the edge of the plate.

Lab notes

- Turn on the oven and observe the butter or chocolate. As soon as it starts to melt, turn the power off and remove it from the oven. This should take only a few seconds.
- The butter or chocolate should begin to melt in bands or rows. Measure and record the distance between the centres of two adjoining rows.
- Check the manufacturer's plate on the back of the oven. Record the frequency of the microwaves in MHz or GHz. If this is not given you will need to do some research.

Post-lab discussion

1. Determine the wavelength of the microwaves produced in the oven.
2. Use the wavelength and the frequency to determine the wave speed.
3. Estimate your uncertainty in measuring the wavelength. Does your measured value agree (within experimental uncertainty) with the accepted value of the speed of emr?
4. Why do microwave ovens have a turntable to rotate the food as it cooks?
5. Other devices that use microwaves include mobile telephones and radar. Is there any hazard in using these devices?

Investigation 14.2: Plotting a space-time graph

3ackground

Space-time graphs are usually constructed for fast-moving particles, but you probably have imited access to these.

The task

Consider an everyday journey, such as your normal trip to school. Make a space-time graph of this journey. Make the x-axis 'space-time' in units of 'light-minutes'. (A light minute is the listance travelled by light in one minute. It is found by taking the time in minutes multiplied by he speed of light). The y-axis will the distance travelled in metres or kilometres whichever is nore convenient.

Plan your work carefully. You need to work out (and record) the answers to some apparently simple questions.

(i) How do you define your starting and finishing points?
(ii) Will you be working with scalar quantities, or vector quantities? Why?
(iii) How will you find out the distance (or displacement) travelled?
(iv) Will you be using your speed or your velocity to create your graph?
(v) Does it matter that for some parts of the journey, you travel at constant speed, while for other parts you are accelerated (or decelerated)?
(vi) How do you determine the values to use on the x- and y-axes?
(vii) The speed of light is expressed to nine decimal places. Are error bars important for your graph? Why?

Post-lab discussion

After you have created your graph, use it to answer these questions, using calculations where appropriate.

1. What is the gradient of your graph? What is the maximum gradient it could have? How do you know?
2. How do you find your instantaneous velocity from the graph? How do you find your average velocity? Explain your answer.
3. What is the maximum value of β from your graph?
4. What is the minimum value of β from your graph?
5. If the horizontal axis used the same scale as the vertical axis, how wide would your graph need to be?

Notes

Problem Set 14.1: Special relativity explanation questions

Notes

1. (a) What is meant by the term "inertial reference frames"
   (b) Are two vehicles moving at different but constant velocities in the same inertial reference frame?

2. State Einstein's postulates in his special theory of relativity.

3. The term "proper time" is used in special relativity. What is meant by this term?

4. Light does not undergo any effects like length contraction and time dilation so is it subject to the theories of special relativity?

5. A photon has energy but does not obey Einstein's mass/energy equation $E = mc^2$. Explain.

6. Two trains are moving at different but constant velocities. Are there any conditions under which they are in the same inertial reference frame? Do two non-inertial reference frames imply that one frame is accelerating?

7. Two spaceships are launched from the same place at the same time in opposite directions, both eventually reaching a velocity of 0.70c, in their respective directions. The technicians at the launch site on see both of these spaceships as travelling away from them at 0.70c. When the second spaceship is viewed from the first and vice versa what would the velocity of the other ship be? Numerically it would appear that the speed at which either ship is moving away from the other is 1.40c. Discuss the validity of this supposition.

8. Given a jet fighter can fly at supersonic speed (say Mach 3) does design allowance need to be incorporated to accommodate any shrinkage in length? Would this be necessary in spacecraft design if the spacecraft could travel at near light speed? Explain.

9. Is the density of the material from which a relativistic space ship is constructed itself relative?

10. Alpha Centauri is a star 4.367 light years from Earth. A time traveller taking this journey at near light speed in a starship was confused by the fact that it he made the journey in less than 4 years based on his clock. How would you explain this situation to the traveller? How would this dilemma be viewed by an observer on Earth?

11. Explain if or how the density of a material is affected when it is travelling at relativistic velocities.

12. A diagram of a beam of light bouncing off mirrors shows that time in a moving spacecraft must run slow as seen by a stationary observer.
    (a) Explain why there must be length contraction.
    (b) Is this contraction real or an optical illusion?

13. When an object travels at near light speed we talk about the effects of time dilating relative to an observer in a different reference frame and length contracting to approach zero as its velocity approaches light speed. Why is it that light itself not subject to these two effects?

14. Special relativity considers the speed of light as being constant in all reference frames. How does this explain refraction of a beam of light by a glass prism when this is said to occur because the velocity of the light has decreased?

Problem Set 14.2: Special relativity calculation questions

Notes

1. At what velocity is a spaceship travelling if a clock on it runs at a rate which is one-half the rate of a clock at rest relative to the spacecraft?

2. Calculate the speed of a spaceship that is measured by an observer at rest at 0.70 of its actual length.

3. Calculate the momentum of a spacecraft with a rest mass of 2.5 tonne travelling at a velocity of 0.92c.

4. Two vehicles, both travelling at 0.80c, are moving apart from each other in exactly opposite directions. Calculate the velocity of one vehicle relative to the other.

5. A spacecraft is moving past a stationary observer at 0.92c. How long is one second of proper time on the spacecraft as measured by the stationary observer?

6. A train with a length measured at rest of 200 m is approaching a mountain tunnel of length 160 m. An observer at rest relative to the train sees that all of the train is inside the tunnel at the same time. Calculate the speed at which the train is approaching the tunnel.

7. A spacecraft is travelling to a distant galaxy 250 light years from Earth at 0.995c. How long would this spacecraft take to reach this galaxy
   (a) relative to the occupants of the spacecraft?
   (b) relative to an observer on Earth?

8. While you are on Earth, you observe that the spaceship Centauri-1 travels past you at 0.994c in 30 ns. This spacecraft is normally stored in a hanger at the local intergalactic base. What is the minimum length this hanger would need to be to completely enclose the Centauri-1?

9. The half-life of a π-meson (pion) is 26 μs and it travels at a velocity of 0.95c towards Earth. What is its lifetime measured relative to a stationary point on Earth?

10. Two manned spaceships, Enterprise and Discovery, are launched so that they finish up travelling in exactly opposite directions away from each other. Enterprise has a velocity of 0.70c relative to Earth in its direction and Discovery a velocity of 0.85c relative to Earth in its direction.
    (a) What velocity would an observer on Earth see each of their velocities as being?
    (b) From the reference frame of an occupant of Discovery, at what velocity would they say the Earth was moving away from them at?
    (c) An occupant of Enterprise says Discovery was moving away from them at a velocity of 1.55c. Explain why this person is wrong and give a better value for the separation velocity. You must show all equations used and calculations performed.

11. Our solar system is part of is the Milky Way galaxy which is generally considered to have a diameter of around 1.2×10^5 light years. If a particle travelling at a velocity of 0.98c entered this galaxy, how long would it take to traverse the diameter in the reference frame of:
    a) the particle b) a stationary observer

12. Identical clocks are placed with you on Earth and in a spaceship travelling away from you at a velocity of 0.95c and at a particular instant they are both showing 9.00 am. When your clock shows a time of 12.00 midday, what time would the astronaut observe on his clock?

13. A space fighter, with a length of 600 m, leaves its mothership and moves away from it at a constant velocity of 0.8c. The mothership needs to communicate with the fighter so it sends out a laser beam carrying the signal to the fighter. The crew on the fighter and the communications officer on the mothership both record zero time at the instant the laser beam arrives at the rear of the fighter.
   (a) Can each of these frames of reference be considered inertial frames?
   (b) How long after this would the beam reach the front of the fighter as measured by the crew on the fighter?
   (c) How long after this would the beam reach the front of the fighter as measured by the communications officer on the mothership?

   On reaching the front of the fighter the laser beam is reflected back through the fighter in the direction from which it came. The reflected laser beam is again viewed by both the crew on the fighter and the communications officer on the mothership.
   (d) Using the initial time as when the laser beam first reached the rear of the fighter, how long would it be before it again reached the rear as measured by the crew on the fighter?
   (e) Using the initial time as when the laser beam first reached the rear of the fighter, how long would it be before it again reached the rear as measured by the communications officer on the mothership?

14. Two identical spacecraft leave the Earth at the same velocity but in directly opposite directions. If the velocity of each spacecraft was 0.84c, what value would an observer on Earth obtain when she calculated their relative velocities?

15. You are standing on Earth observing a dogfight between two fighter jets. One of them, flying at 3.5 times the speed of sound, fires a missile at 700 m s^{-1} when directly overhead of your position. Calculate the velocity of the missile as observed by you using each of the following.
   (a) Classical physics principles. (b) Relativity theory.

16. A radioactive nucleus travelling away from you at 0.25c in your frame of reference undergoes decay and emits a beta particle in the direction of its travel at 0.65c relative to the remaining nucleus. What is the velocity of the emitted beta particle relative to you?

17. What is the relativistic mass of a space vehicle traveling at 2.25×10^8 m s^{-1} if it has a rest mass of 3400 kg?

18. A train that has a proper length of 158 m and a rest mass of 8.00×10^5 kg is traveling at 0.925c. What is its mass and length as measured by a stationary observer?

19. Einstein said that mass and energy are the same and as a particle's velocity increases so does its mass. At what speed would a particle be travelling for its rest mass to increase to three times its rest mass?

Notes

13, 14

The birth of the Universe

The Big Bang

By the mid-20th century, there were two competing theories for the origin of the Universe. The Steady State theory held that matter is continuously created as the Universe expands, the overall density of the Universe remains the same, and the Universe has existed forever.

Most scientists now believe that we live in a finite expanding Universe which has not existed forever, and that all the matter, energy and space in the Universe was once squeezed into an infinitesimally small volume, which erupted in a cataclysmic "explosion" which has become known as the Big Bang. The term, 'The Big Bang', was invented by the English astronomer Fred Hoyle during a 1949 radio broadcast as a derisive description of a theory he disagreed with.

The theory implies that space, time, energy and matter all came into being at an infinitely dense, infinitely hot gravitational singularity, and began expanding everywhere at once. Modern measurements place this event at approximately 13.8 billion years ago and thus this is considered the age of the Universe. The model offers a comprehensive explanation for a broad range of observed phenomena, including the abundance of light elements, the cosmic microwave background, large scale structure, and Hubble's Law.

According to prevailing scientific thinking, if we were to look at the Universe one second after the Big Bang, what we would see is a 10-billion degree sea of neutrons, protons, electrons, anti-electrons (positrons), photons, and neutrinos. Some time later we would see the Universe cool; the neutrons would decay forming protons and electrons or would combine with protons to make deuterium (an isotope of hydrogen). Continued cooling would eventually lead to electrons combining with nuclei to form simple atoms. Giant clouds of these primordial elements would later coalesce through gravity to form matter and eventually stars and galaxies.

The Cosmic Microwave Background

In 1963, Arno Penzias and Robert Wilson were studying faint microwave signals from the Milky Way galaxy. They found a mysterious noise of unknown origin. At first the noise was thought to be interference caused by pigeon droppings on the antenna equipment. Pigeons were trapped and dung was cleaned from the antenna. Ultimately Penzias and Wilson realized that the noise was an actual signal. Penzias and Wilson theorised that if the Big Bang theory was correct, the Universe would be filled with background radiation left over from the creation event. This radiation is now called the cosmic microwave background, or CMB.

The CMB was created at a time in cosmic history called the Recombination Era. About 378,000 years after the Big Bang the Universe was a hot, dense and opaque plasma containing both matter and energy. Photons could not travel freely, so no light escaped. The Universe then cooled to a temperature of about 2,700 °C which enabled electrons and protons to form stable hydrogen atoms. This process released photons, creating the radiation that is now called the CMB.

The Expanding Universe

In 1925, the American astronomer Edwin Hubble stunned the scientific community by demonstrating that there was more to the Universe than just our Milky Way galaxy and that there were in fact many separate islands of stars - thousands, perhaps millions of them, and many of them huge distances away from our own. Then, in 1929, Hubble announced a further dramatic discovery. Using improved telescopes, Hubble observed that the light coming from these galaxies was shifted a little toward the red end of the spectrum, which indicated that the galaxies were moving away from us. When the source of a wave is moving toward an observer the wavelength is shortened (called 'blue shift') and when the source is moving away from the observer the wavelength is lengthened ('red shift'). Hubble observed that the emission spectra of distant galaxies were all red-shifted, and the further away they were the greater the red shift.

After a detailed analysis Hubble concluded that the galaxies and clusters of galaxies were in fact flying apart from each other at a speed that was in direct proportion to its distance. This is known as Hubble's Law. A galaxy that is twice as far away as another is receding twice as fast, one ten times as far away if receding ten times as fast, etc. The law is usually stated as $v = H_0D$, where v is the velocity of recession, D is the distance of the galaxy from the observer and H_0 is the Hubble constant which is around 22 km/s/million light years.

Edwin Hubble

Individual galaxies themselves are not expanding but space itself is expanding. Imagine a balloon inflating, if tiny dots are painted on the balloon to represent galaxies, then as the balloon expands so the distance between the dots increases and the further apart the dots the faster they move apart. In such an expansion the Universe continues to look more or less the same from every galaxy.

Comprehension task

Draw a time line starting at the Big Bang to show when and how matter evolved from sub-atomic particles to heavy nuclei.

At points along the time line, there are great changes in the nature of the Universe and the matter in it. Explain what caused these changes.

The standard model explained

Notes

Main points

- The Big Bang theory describes the early development of the Universe, including the formation of subatomic particles from energy and the subsequent formation of atomic nuclei.
- A variety of evidence supports the Big Bang theory, including cosmic background radiation, the abundance of light elements and the red shift of light from galaxies that obey Hubble's law.
- Alternative theories exist, including the Steady State theory, but the Big Bang theory is the most widely accepted theory today.
- The standard model is used to describe the evolution of forces and the creation of matter in the Big Bang theory.
- The expansion of the Universe can be explained by Hubble's law and cosmological concepts, such as red shift and the Big Bang theory.

The big questions are, "What is the world made of?" and "What holds it together?"

- The standard model is the most complete explanation of the fundamental particles and interactions to date.
- The standard model is based on the premise that all matter in the Universe is made up from elementary matter particles called quarks and leptons; quarks experience the strong nuclear force, leptons do not.
- The world is made of six quarks and six leptons. Everything we see is a conglomeration of quarks and leptons.
- Baryons are composite particles made up of quarks.
- Names and descriptions are only a small part of any physical theory; the concepts, rather than physics vocabulary, are the critical elements.
- A particle's state (set of quantum numbers) can affect how it interacts with other particles.
- Lepton number and baryon number are conserved in all reactions between particles; these conservation laws can be used to support or invalidate proposed reactions.
- There are four fundamental forces, and force carrier particles are associated with each force.
- The standard model explains three of the four fundamental forces (strong, weak and electromagnetic forces) in terms of an exchange of force carrying particles called gauge bosons; each force is mediated by a different type of gauge boson.
- High-energy particle accelerators are used to test theories of particle physics, including the standard model.
- The magnitude of the force experienced by a particle travelling in a magnetic field depends on the charge of the particle, the velocity of the particle and the strength of the field.

Physicists have developed a theory called the standard model that explains what the world is made of, and what holds it together. Developed since the middle of the 20th century, the theory holds that all matter in the Universe is made up of combinations of elementary particles called quarks and leptons. It describes all of the particles and the interactions between. It explains the strong, weak and electromagnetic forces as a result of the exchange of various types of force carrier particles between the elementary matter particles. All the known matter particles are composites of quarks and leptons, and they interact by exchanging force carrier particles.
The Standard Model has been verified by experiments; all the particles predicted by this theory have been found. But it does not explain everything. For example, gravity is not included in the Standard Model. Dark energy and dark matter are not yet understood, but are believed to be cosmological properties required to explain the expanding Universe.

Structure within the atom
Protons and neutrons vibrate within the nucleus, and quarks vibrate within the protons and neutrons.
Figure 15.1 is quite distorted. If we drew the atom to scale and made protons and neutrons a centimetre in diameter, then the electrons and quarks would be smaller than the diameter of a human hair and the entire atom's diameter would be greater than the length of thirty football fields; 99.999999999999% of an atom's volume is just empty space!

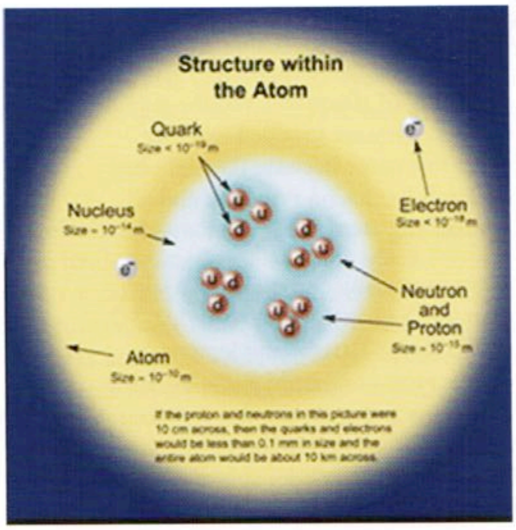


Figure 15.1: This is the modern atom model. Electrons are in constant motion around the nucleus, protons and neutrons vibrate within the nucleus, and quarks vibrate within the protons and neutrons (ParticleAdventure.org).

While an atom is tiny, the nucleus is ten thousand times smaller than the atom and the quarks and electrons are at least ten thousand times smaller than that. We don't know exactly how small quarks and electrons are; they are definitely smaller than 10^{-18} metres, or they might literally be points, but we just do not know. It is also possible that quarks and electrons are not fundamental after all, and will turn out to be made up of other, more fundamental particles ... and on it goes. Relative sizes are shown in Figuire 15.2.

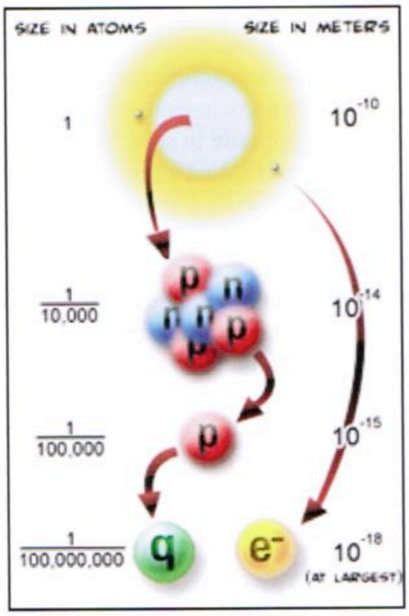


Figure 15.2

Physicists are constantly look for new particles. When they find a new particle, they find out its properties, trying to find patterns that tell us what the fundamental building blocks of the Universe are, and how they interact. We now know of about two hundred particles most of which aren't fundamental. These particles are named using letters from the Greek and Roman alphabets. Of course, the names of particles are but a small part of any physical theory. You should not be discouraged if you have trouble remembering them. Take heart: even the great Enrico Fermi once said to his student (and future Nobel Laureate) Leon Lederman, "Young man, if I could remember the names of these particles, I would have been a botanist!"

Notes

The standard model explained

Notes

The Pauli Exclusion Principle

We can use these quantum particle properties to categorise the particles we find. Physicists once thought that no two particles in the same quantum state could exist in the same place at the same time. This is called the Pauli Exclusion Principle, and it explains much about chemistry. But certain particles do not obey this principle. Particles that do obey the Pauli Exclusion Principle are called fermions, and those that do not are called bosons.

Imagine a large family of identical fermion siblings spending the night at the Fermion Motel, and another large family of identical boson siblings spending the night at the Boson Inn. Fermions behave like squabbling siblings, and not only refuse to share a room but also insist on rooms as far as possible from each other. On the other hand, boson siblings prefer to share the same room.

Fermions and bosons

These are the matter particles consisting of six quarks and the six leptons. They are grouped together under this name because they all obey the Pauli Exclusion Principle and all have an anti-particle.

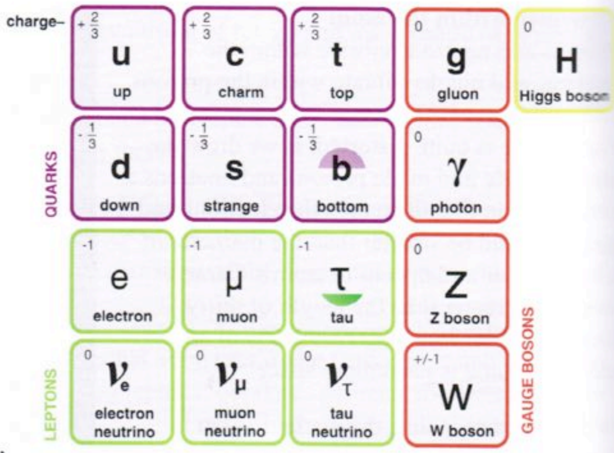


Figure 15.3: Quarks, leptons and bosons (ParticleAdventure.org)

A fermion is any particle whose spin is an odd half-integer (such as 1/2, 3/2, and so forth). Quarks and leptons, as well as most composite particles, such as protons and neutrons, are fermions. For reasons we do not fully understand, having odd half-integer spin means that fermions obey the Pauli Exclusion Principle (i.e. two fermions cannot co-exist in the same state at same location at the same time).

Bosons have an integer spin (0, 1, 2...). All force carrier particles are bosons, as are those composite particles with an even number of fermion particles (such as mesons).

Matter and antimatter

For every type of matter particle we know, there exists a corresponding antimatter particle, or antiparticle. The antiparticle is identical in mass to the particle from which it derives its name but opposite in sign. The antiparticle of the electron is called a positron. Antiparticles behave just like their corresponding matter particles, except they have opposite charges. For instance, a proton is electrically positive whereas an antiproton is electrically negative. When a matter particle and antimatter particle meet, they annihilate into pure energy.

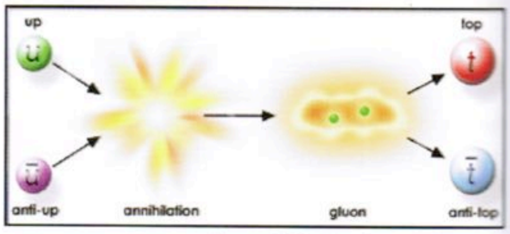


Figure 15.4: Fermions and Bosons (ParticleAdventure.org)

The Universe appears to be composed entirely of matter. If antimatter and matter are exactly equal but opposite, then why is there so much more matter in the Universe than antimatter? Well ... that is a question that keeps physicists up at night.

The usual symbol for an antiparticle is a bar over the corresponding particle symbol. For example, the "up quark" u has an "up" antiquark" designated by $\overline{u}$, pronounced u-bar. The antiparticle of a quark is an antiquark, the antiparticle of a proton is an antiproton, and so on. The antielectron is called a positron and is designated e+.

Quarks

There are six quarks. They are never found alone but as combinations of two or three in particles called hadrons. Three quarks having charge of +2/3 are called up, charm and top; and three having charge -1/3 are called down, strange and bottom. The up and down quarks together account for both the proton and neutron.

All matter from galaxies to mountains to molecules is made from quarks and leptons. But that is not the whole story. Quarks behave differently than leptons, and for each kind of matter particle there is a corresponding antimatter particle. Quarks are one type of matter particle. Most of the matter we see around us is made from protons and neutrons, which are composed of quarks.

There are six quarks, but physicists usually talk about them in terms of three pairs: up/down, charm/strange, and top/bottom. (Also, for each of these quarks, there is a corresponding antiquark.) Quarks have the unusual characteristic of having a fractional electric charge, unlike the proton and electron, which have integer charges of +1 and -1 respectively. Quarks also carry another type of charge called colour charge, which we will discuss later. The most elusive quark, the top quark, was discovered in 1995 after its existence had been theorized for 20 years.

The naming of quarks.

In 1964, Murray Gell-Mann and George Zweig suggested that hundreds of the particles known at the time could be explained as combinations of just three fundamental particles. Gell-Mann chose the name "quarks,"pronounced "kworks," for these three particles, a nonsense word used by James Joyce in the novel Finnegan's Wake. In order to make their calculations work, the quarks had to be assigned fractional electrical charges of 2/3 and minus 1/3. Quarks are never observed by themselves, and so initially these quarks were regarded as fiction. Experiments have since convinced physicists that not only do quarks exist, but there are six of them, not three.

There are six 'flavors' of quarks which just means different kinds. The two lightest are called up and down. The third quark is called strange. It was named after the "strangely" long lifetime of the K particle, the first composite particle found to contain this quark. The fourth quark type, the charm quark was discovered in 1974 almost simultaneously at both the Stanford Linear Accelerator Centre (SLAC) and at Brookhaven National Laboratory.

The fifth and sixth quarks 'top' and 'bottom' were sometimes called 'truth' and 'beauty'. The bottom quark was first discovered at Fermi National Lab (Fermilab) in 1977. The top quark was discovered last, also at Fermilab, in 1995. It is the most massive quark. It had been predicted for a long time but had never been observed successfully until then.

Hadrons

These are particles made up of two or more quarks, are capable of existence on their own (as opposed to in combination) and can interact strongly with each other. Quarks only exist in groups with other quarks and are never found alone. Composite particles made of quarks are called **Hadrons**. Only a very small part of the mass of a hadron is due to the quarks in it.

Although individual quarks have fractional electrical charges, they combine such that hadrons have a net integer electric charge. Another property of hadrons is that they have no net colour charge even though the quarks themselves carry colour charge.

There are two classes of hadrons: baryons and mesons:

- A baryon is any hadron made of three quarks (qqq). Protons are baryons, made of two up quarks and one down quark (uud). So are neutrons (udd).
- A meson is a hadron made from a quark and its anti-quark. One example of a meson is a pion (+), which is made of an up quark and a down anitiquark. The antiparticle of a meson just has the quark and antiquark switched, so an antipion (-) is made of a down quark and an up antiquark. Mesons, made of a particle and an antiparticle, are very unstable.

Notes

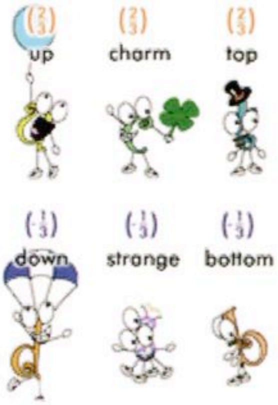


Figure 15.5: Six quarks (ParticleAdventure.org)

The standard model explained

Notes

The K meson lives much longer than most mesons, which is why it was called "strange" and gave this name to the strange quark, one of its components.

Leptons

The other group of matter particles is the leptons. There are six leptons, three being electrically charged and three being neutral. Leptons appear to be point-like particles without internal structure. The best known lepton is the electron (e-). The other two charged leptons are the muon and the tau, which like electrons are charged but with a lot more mass. The other leptons are the three types of neutrinos. These have no electrical charge, very little mass, and are very hard to detect.

Each pair of leptons is intimately connected to a pair of quarks – the electron and its neutrino are connected to the up and down quarks, the muon and its neutrino to the strange and charm quarks and the tau and its neutrino to the top and bottom quarks.

Leptons are solitary particles. Each lepton has a corresponding antilepton. The heavier leptons, the muon and the tau, are not found in ordinary matter at all. This is because when they are produced they very quickly decay, or transform, into lighter leptons. Sometimes the tau lepton will decay into a quark, an antiquark, and a tau neutrino. Electrons and the three kinds of neutrinos are stable.

When a heavy lepton decays, one of the particles it decays into is always its corresponding neutrino. The other particles could be a quark and its antiquark, or another lepton and its antineutrino.

Physicists have observed that some types of lepton decays are possible and some are not. In order to explain this, they divided the leptons into three lepton families: the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino. The number of members in each family must remain constant in a decay; a particle and an antiparticle in the same family "cancel out" to make the total of them equal zero. Although leptons are solitary, they are always loyal to their families!

Lepton type conservation

Leptons are divided into three lepton families: the electron and its neutrino, the muon and its neutrino, and the tau and its neutrino. The terms "electron number," "muon number," and "tau number" to refer to the lepton family of a particle. Electrons and their neutrinos have electron number +1, positrons and their antineutrinos have electron number -1, and all other particles have electron number 0. Muon number and tau number operate analogously with the other two lepton families.

	muon		muon neutrino		electron		e^- antineutrino
equation	μ		ν_μ	+	e^-	+	$\bar{\nu}_e$
electron number	0	=	0	+	1	+	-1
muon number	1	=	1	+	0	+	0
Tau number	0	=	0	+	0	+	0

One important thing about leptons, then, is that electron number, muon number, and tau number are always conserved when a massive lepton decays into smaller ones. Let's take an example decay. A muon decays into a muon neutrino, an electron, and an electron antineutrino (*see left*)

As you can see, electron, muon, and tau numbers are conserved. These and other conservation laws are what we believe define whether or not a given hypothetical lepton decay is possible.

Neutrinos

Neutrinos are a type of lepton. Since they have no electrical or strong charge they almost never interact with any other particles. Most neutrinos pass right through the earth without ever interacting with a single atom of it.

They are produced in a variety of interactions, especially in particle decays. In fact, it was through a careful study of radioactive decays that physicists hypothesized the neutrino's existence. For example:

- In a radioactive nucleus, a neutron at rest (zero momentum) decays, releasing a proton and an electron.
- Because of the law of conservation of momentum, the resulting products of the decay must have a total momentum of zero, which the observed proton and electron clearly do not. (Furthermore, if there are only two decay products, they must come out back-to-back.)
- Therefore, we need to infer the presence of another particle with appropriate momentum to balance the event.
- We hypothesize that an antineutrino was released; experiments have confirmed that this is indeed what happens.

Because neutrinos were produced in great abundance in the early Universe and rarely interact with matter there are a lot of them in the Universe. Their tiny mass but huge numbers may contribute to total mass of the Universe and affect its expansion.

Gauge bosons

Gauge bosons are massless and are referred to as the force carriers because they are the particles responsible for mediating the strong and weak interactions. Particles subject to either the strong or the weak interaction exchange bosons as they interact. The W-positive, W-negative and Z0 mediate the weak interactions between the different flavours of quarks and leptons, the eight gluons mediate the strong force between the quarks and the photon mediates the electromagnetic interaction.

Photons

Photons are different from the other bosons and particles because they do not have a rest mass and travel at the speed of light. Depending on its energy a photon can be transformed into a particle/anti-particle pair. Conversely, a collision between a particle and its anti-particle will result in the annihilation of those particles and the formation of photons. The relationship between the mass and energy interchanged can be calculated from Einstein's equation E = mc2, where all of the energy becomes mass or all of the mass will become energy.

Flavour

An alternative name is generation. Flavour is a property that separates the different types of leptons and quarks. Each of the charged leptons and its associated neutrino has a distinct flavour, as do the three flavours of quarks, with two per flavour for both. The first flavour of both leptons and quarks (the electrons, protons and neutrons) does not undergo decay, with the electrons orbiting the atomic nuclei containing the protons and neutrons which are composed of up and down quarks. The second flavour (charm and strange quark; muon and muon neutrino) and third flavour (top and bottom quark; tau and tau neutrino) have short half-lives and are only observed in very high energy particle accelerators. The masses of the particles in each successive flavour are greater than that of corresponding particles in the flavour before. This is why successive flavours were discovered only when more powerful particle accelerators were built.

Notes

The standard model explained

Notes

The four interactions
Matter is made of quarks and leptons but what holds all these particles together?

Matter exists because of the ways in which the fundamental particles interact. These interactions include attractive and repulsive forces, decay, and annihilation. There are four fundamental interactions between particles, and all forces in the world can be attributed to these four interactions. Any force you can think of - friction, magnetism, gravity, and so on - is caused by one of these four fundamental interactions.

How do things interact without touching! How do two magnets "feel" each other's presence and attract or repel accordingly? How does the Sun attract the Earth? Generally the answers given to these questions are "magnetism" and "gravity," but how do these interactions work? At a fundamental level, a force is not just something that happens to particles, it is a thing that is passed from one particle to another.

Interactions that affect matter particles arise from an exchange of force carrier particles, a different type of particle altogether. What we normally think of as "forces" are actually the effects of force carrier particles on matter particles. We see examples of attractive forces in everyday life (such as magnets and gravity), and so we generally take it for granted that an object's presence can just affect another object. The deeper question, "How can two objects affect one another without touching?" leads us to propose that the invisible force could be an exchange of force carrier particles. Particle physicists can explain the force of one particle acting on another to incredible precision through the exchange of force carrier particles.

One important thing to know about force carriers is that a particular force carrier particle can only be absorbed or produced by a matter particle which is affected by that particular force. For instance, electrons and protons have electric charge, so they can produce and absorb the electromagnetic force carrier, the photon. Neutrinos, on the other hand, have no electric charge, so they cannot absorb or produce photons.

The electromagnetic force
The electromagnetic force causes like-charged things to repel and oppositely-charged things to attract. Many everyday forces, such as friction, and even magnetism, are caused by the electromagnetic force. For instance, the force that keeps you from falling through the floor is the electromagnetic force which causes the atoms making up the matter in your feet and the floor to resist being displaced.

The carrier particle of the electromagnetic force is the photon. Photons of different energies span the electromagnetic spectrum of x rays, visible light, radio waves, and so forth. Photons have zero mass, as far as we know, and always travel at the "speed of light", c, which is about 300,000,000 metres per second in a vacuum.

Atoms usually have the same numbers of protons and electrons. They are electrically neutral, therefore, because the positive protons cancel out the negative electrons. Since they are neutral, what causes them to stick together to form stable molecules? The answer is that the charged parts of one atom can interact with the charged parts of another atom. This allows different atoms to bind together, an effect called the residual electromagnetic force. This is what allows atoms to bond and form molecules, allowing the world to stay together and create the matter you interact with all of the time. All the structures of the world exist simply because protons and electrons have opposite charges!

The Strong Nuclear Force
What then binds the nucleus together? The nucleus of an atom consists of a bunch of protons and neutrons crammed together. Since neutrons have no charge and the positively-charged protons repel one another, why doesn't the nucleus blow apart?

We cannot account for the nucleus staying together with just electromagnetic force. What else could there be?

Notes

To understand what is happening inside the nucleus, we need to understand more about the quarks that make up the protons and neutrons in the nucleus. Quarks have electromagnetic charge, and they also have an altogether different kind of charge called colour charge. The force between colour-charged particles is very strong, so this force is called 'the strong force'. The strong force holds quarks together to form hadrons, so its carrier particles are called gluons because they so tightly "glue" quarks together.

Colour

'Colour' or 'colour charge' is a label and has nothing to do with actual colour. It is a name given to the three states of quarks labelled red, blue and green. Anti-quarks are labelled anti-red, anti-blue and anti-green. Gluons, which hold quarks together, are also coloured. When a gluon is emitted or absorbed by a quark the quark may change colour (state) but the large composite particle is always colourless. In order to be colourless, baryons (protons and neutrons), are comprised of three quarks, and must therefore have one of each colour. Mesons are comprised of two quarks, and must comprise a quark/anti-quark pair.

Quarks and gluons are colour-charged particles, they exchange gluons in strong interactions. When two quarks are close to one another, they exchange gluons and create a very strong colour force field that binds the quarks together. The force field gets stronger as the quarks get further apart. Quarks constantly change their colour charges as they exchange gluons with other quarks.

There are three colour charges and three corresponding anti-colour (complementary colour) charges. Each quark has one of the three colour charges and each antiquark has one of the three anti-colour charges. Just as a mix of red, green, and blue light yields white light, in a baryon a combination of "red," "green," and "blue" colour charges is colour neutral, and in an antibaryon "anti-red," "anti-green," and "anti-blue" is also colour neutral. Mesons are colour neutral because they carry combinations such as "red" and "anti-red."

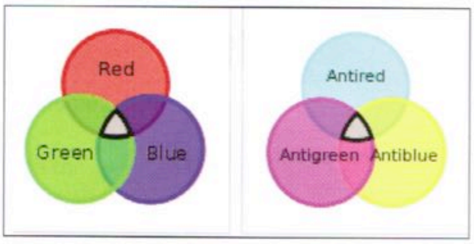


Figure 15.7: Three colours or anti-colours combine to be colourless.

Because gluon-emission and -absorption always changes colour, and -in addition - colour is a conserved quantity - gluons can be thought of as carrying a colour and an anti-colour charge. Since there are nine possible colour-anti-colour combinations we might expect nine different gluon charges, but it works out that there are only eight combinations.

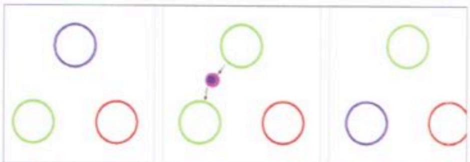


Figure 15.8: A. A hadron with three quarks (red, green, blue) before a colour change

B. Blue quark emits a blue-antigreen gluon

C. Green quark has absorbed the blue-antigreen gluon and is now blue; colour remains conserved

Colour-charged particles cannot be found individually. For this reason, the colour-charged quarks are confined in groups (hadrons) with other quarks. These composites are colour neutral.

The development of the Standard Model's theory of the strong interactions reflected evidence that quarks combine only into baryons (three quark objects), and mesons (quark-antiquark objects), but not, for example, four-quark objects. Now we understand that only baryons (three different colours) and mesons (colour and anti-colour) are colour-neutral. Particles such as ud or uddd that cannot be combined into colour-neutral states are never observed.

The standard model explained

Notes

Residual strong force

The strong force binds quarks together because quarks have colour charge. But that still does not explain what holds the nucleus together, since positive protons repel each other with electromagnetic force, and protons and neutrons are colour-neutral. So what holds the nucleus together? The answer is that, in short, they don't call it the strong force for nothing. The strong force between the quarks in one proton and the quarks in another proton is strong enough to overwhelm the repulsive electromagnetic force. This is called the residual strong interaction, and it is what "glues" the nucleus together.

The Weak Force

Weak interactions are responsible for the decay of massive quarks and leptons into lighter quarks and leptons. When fundamental particles decay we observe the particle vanishing and being replaced by two or more different particles. Although the total of mass and energy is conserved, some of the original particle's mass is converted into kinetic energy, and the resulting particles always have less mass than the original particle that decayed. The only matter around us that is stable is made up of the smallest quarks and leptons, which cannot decay any further.

When a quark or lepton changes type (a muon changing to an electron, for instance) it is said to change flavour. All flavour changes are due to the weak interaction. The carrier particles of the weak interactions are the W+, W-, and the Z particles. The W's are electrically charged and the Z is neutral.

Gravity

What about gravity? Gravity has been considered one of the fundamental interactions, but the Standard Model cannot satisfactorily explain it. This is one of those major unanswered problems in physics today. In addition, the gravity force carrier particle has not been found. Such a particle may someday be found: the graviton.

Fortunately, the effects of gravity are extremely tiny in most particle physics situations compared to the other three interactions, so theory and experiment can be compared without including gravity in the calculations. Thus, the Standard Model works without explaining gravity.

Experiment 15.1: Detecting the world - wavelength and resolution

Background

When using waves to detect the physical world the quality of the image is limited by the wavelength you use. Our eyes are attuned to visible light, which has wavelengths of about 0.5 micrometres which means that we can resolve objects larger than about a micrometre. However, the wavelength of visible light is too long to analyse anything smaller than a cell. To observe things under higher magnification, you must use waves with smaller wavelengths. That's why scientists use scanning electron microscopes when studying sub-microscopic things such as viruses. However, even the best scanning electron microscope can only show a fuzzy picture of an atom.

A good example of the wavelength vs. resolution issue is a swimming pool. If you have a swimming pool with waves which are 1 metre apart (a 1 metre wavelength) and push a stick into the water, the pool's waves just pass around the stick because the large wavelength ensures that the waves are not affected by such a tiny target. What physical effect is responsible for this?

All particles have wave properties. So, when using a particle as a probe, we need to use particles with short wavelengths to get detailed information about small things. As a rough rule of thumb, a particle can only probe down to distances equal to the particle's wavelength. To probe down to smaller scales the probe's wavelength has to be made smaller.

Notes

Lab notes

Part A

Use a pool or a ripple-tank to investigate the relationship between wavelength and resolution. Set up the tank according to the instructions, and begin generating waves.

Insert a thin upright wire into the water, downstream from the wave source – does the wire affect the wave pattern? Would you know the wire was there if you could only observe the wave pattern downstream? Repeat with thicker wires, rods and tubes etc. and with different wavelengths, to obtain a relationship between wavelength and resolution (the ability to observe a small object).

Part B

Different sized balls can be used to obtain an image of an object. With an object placed on the ground use balls to surround the object and then remove the object to observe the 'image' created. How does the size of the balls affect the detail of the image?

Investigation 15.2: Detecting the world - particle beams

Background

Most of the experiments that have given rise to our current conception of particle physics have occurred relatively recently. But the story of how physicists experiment to test and create theories in modern particle physics is one which starts less than a hundred years ago. In 1909 a man named Ernest Rutherford set up an experiment to test the validity of the prevailing theory of the atom. In doing so he established a way, by using particle beams, that for the first time physicists could "look into" tiny particles they couldn't see with microscopes.

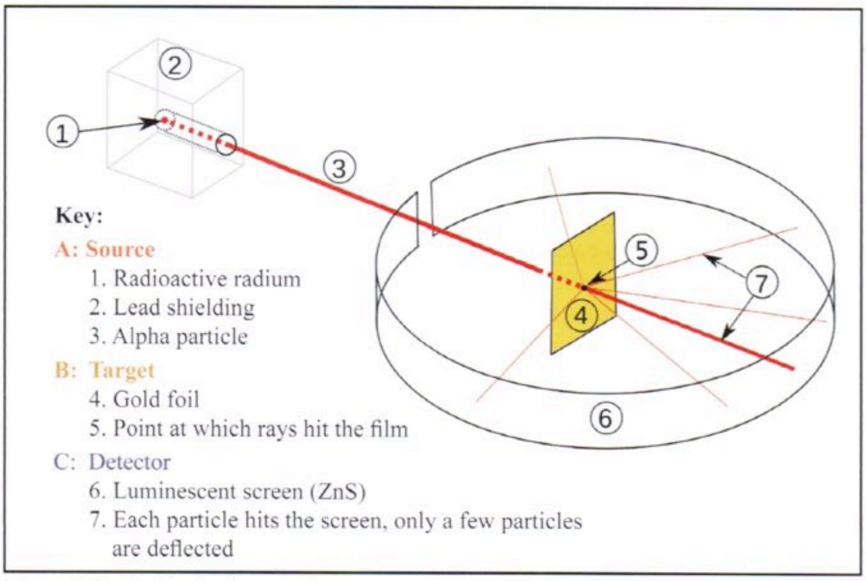


Figure 15.1: Rutherford's experiment

Rutherford's experiment is shown in Figure 15.1. The alpha particles were expected to pass right through the very thin gold foil and make their marks in a small cluster on the screen. If atoms were permeable, neutral balls, then the alpha particles should simply pass through the gold foil and strike the back of the screen. But much to everyone's surprise, some of the alpha particles were deflected at large angles to the foil; some even hit the screen in front of the foil. The deflection of the particles is shown in Figure 15.2.

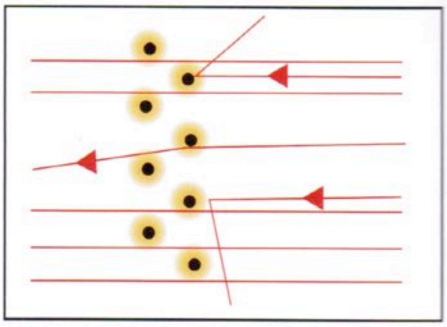


Figure 15.2: Target, gold foil atoms, magnified

Notes

Almost all particle physics experiments today use the same basic elements that Rutherford did:

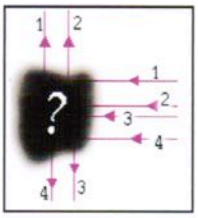
- A source (in this case, a beam of alpha particles)
- A target (the gold atoms in the foil)
- A detector (the zinc sulfide screen)

In addition, Rutherford established the practise of "seeing" into the sub-atomic realm by using particle beams and particle physicists today follows his experimental lead by inferring the actual nature of particles and interactions from the frequently counterintuitive results they find.

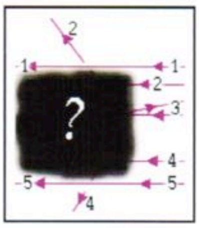
The task

In the pictures (left), there is a target hidden by a black cloud. To figure out the shape of the target, we shot some beams into the cloud and recorded where the beams came out. Can you figure out the shape of each target? What assumptions have you made when deciding the shape?

(a)



(b)



In modern laboratories, experimenters use computers to analyse and visualise the data.

In terms of the experimental setup above, describe how you, personally, perceive the world. Note that you have more than one way to 'observe' your surroundings.

(a) If the target is the object that you observe, what is the source?
(b) How does the 'detector' work?
(c) What are the limitations to what you can perceive?
(d) How can (or do) you use technology to improve your perception of the world?

Investigation 15.3: Accelerators

Background

Notes

The physicists tool: The accelerator

Physicists can't use visible light to explore atomic and sub-atomic structures because the wavelengths are too long. However, since particles have wave properties, physicists can use particles as their probes. In order to see the smallest particles, physicists need a particle with the shortest possible wavelength, but most particles in the natural world have fairly long wavelengths. So how do physicists decrease a particle's wavelength so that it can be used as a probe?

A particle's energy and its wavelength are inversely related. High-energy physicists apply this principle when they use particle accelerators to increase the energy of a probing particle, thus decreasing its wavelength. Steps:

- Put your probing particle into an accelerator.
- Give your particle lots of energy by speeding it up to very nearly the speed of light.
- Since the particle now has a lot of energy, its wavelength is very short.
- Slam this probing particle into the target and record what happens.

Mass and energy

Quite often, physicists want to study massive, unstable particles that have only a fleeting existence (such as the very massive top quark.) However, all that physicists have around them in the everyday world are very low-mass particles. How does one use particles with lesser mass to obtain particles of greater mass?

Albert Einstein's famous equation $E = mc^2$ says that mass is just a form of energy. To produce particles with a greater mass, all one has to do is put the low-mass particles into an accelerator, give them a lot of kinetic energy (i.e. speed them up), and then collide them together. During this collision, the particle's kinetic energy results in the formation of new massive particles. It is through this process that we can create massive unstable particles and study their properties.

What makes particles go in a circle?

To keep any object going in a circle there needs to be a constant force on that object towards the centre of the circle. In a circular accelerator an electric field makes the charged particle accelerate, while large magnets provide the necessary inward force to bend the particle's path in a circle.

Figure 15.3.1: A magnet bends the direction of a moving charged particle

The presence of a magnetic field does not add or subtract energy from the particles. The magnetic field only bends the particles' paths along the arc of the accelerator. Magnets are also used to direct charged particle beams toward targets and to "focus" the beams, just as optical lenses focus light.

The Force a Magnetic Field Exerts on a moving Charged Particle

The magnitude of the force experienced by a particle travelling in a magnetic field depends on the charge of the particle, the velocity of the particle, the strength of the field, and, importantly, the angle between their relative directions. The right hand rule can show the direction of the force on a positive charge in a magnetic field. Point your index finger along the direction of the particle's velocity. If your middle finger points along the magnetic field, your thumb will point in the direction of the force.

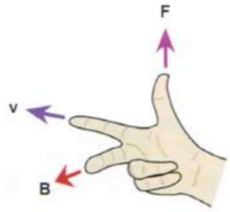


Figure 15.3.2 Right hand rule
Note: For negative charge reverse the direction of the velocity (or use your left hand).

Key Equations:
The force on a charged particle: $F_B = qvB \sin \Theta$

where q is the charge of the particle, v is the velocity of the particle, B is the magnetic field value and Θ is the angle between the velocity vector and the magnetic field vector. Note that where the direction of the particle and the direction of the magnetic field are perpendicular then

$$F_B = qvB$$

also, recall that to make a charged particle traverse a circular path of radius r a centripetal force: $F_C = F_B$ is required.

$$\frac{mv^2}{r} = qvB$$

Investigation 15.3: Accelerators

Measuring charge and momentum

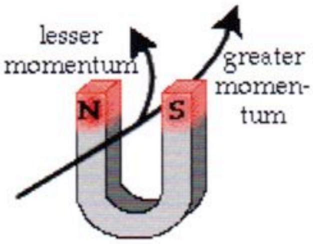


Figure 15.3.4: A magnet is used to bend the path of a particle.

One important function of the detector is to measure a particle's charge and momentum. For this reason, the inner parts of the detector, especially the tracking device, are in a strong magnetic field. The signs of the charged particles can easily be read from their paths, since positive and negative particles that are initially traveling in the same direction curve in opposite directions in the same magnetic field.

The momenta of particles can be calculated since the paths of particles with greater momentum bend less than those of lesser momentum. A particle with greater momentum spends less time in the magnetic field or has greater inertia than the particle with lesser momentum.

To summarise, physicists use accelerators to "peek" into the structure of particles. Detectors collect data which is then analysed by computers and then by people.

Detectors

Rutherford used zinc sulfide to test for the presence of invisible alpha particles and used this knowledge to determine the path of alpha particles. To look for these various particles and decay products, modern physicists have designed multi-component detectors that test different aspects of an event. Each component of a modern detector is used for measuring particle energies and momenta, and/or distinguishing different particle types.
Following each event, computers collect and interpret the vast quantity of data from the detectors and present the extrapolated results to the physicist. Modern detectors consist of many different pieces of equipment each of which tests for a different aspect of an event. These many components are arranged in such a way that physicists can obtain the most data about the particles spawned by an event. The reason that detectors are divided into many components is that each component tests for a special set of particle properties. These components are stacked so that all particles will go through the different layers sequentially. A particle will not be evident until it either interacts with the detector in a measurable fashion, or decays into detectable particles.

A few important things to note:

- Charged particles, such as electrons and protons, are detected both in the tracking chamber and the electromagnetic calorimeter.

- Neutral particles, such as neutrons and photons, are not detectable in the tracking chamber; they are only evident when they interact with the detector. Photons are detected by the electromagnetic calorimeter, while neutrons are evidenced by the energy they deposit in the hadron calorimeter.

- Each particle type has its own "signature" in the detector. For example, if a physicist detects a particle only in the electromagnetic calorimeter, then she is fairly certain that she observed a photon.

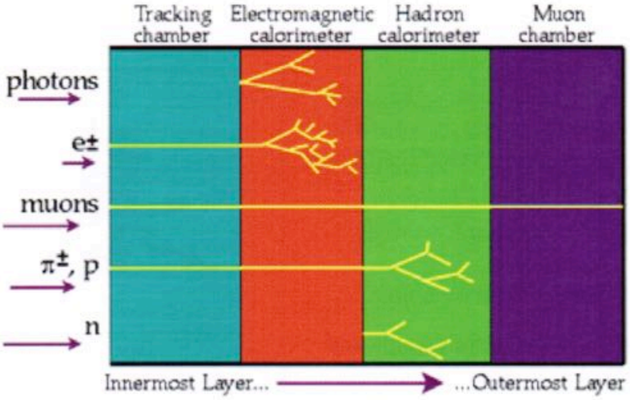


Figure 15.3.5: The interaction of various particles with the different components of a detector. Neutrinos are not shown on this chart because they rarely interact with matter, and can only be detected by missing matter and energy.

Accelerators solve two problems. Since all particles behave like waves, physicists use accelerators to increase a particle's energy, thus decreasing its wavelength. Second, the energy of speedy particles is used to create the massive particles that physicists want to study. Basically, an accelerator takes a particle, speeds it up using electromagnetic fields, and bashes the particle into a target. Surrounding the collision point are detectors that record the many pieces of the event.

Notes

How to obtain particles to accelerate

How do physicists get the particles they want to study?

- Electrons: Heating a metal causes electrons to be ejected. A television, such as a cathode ray tube, uses this mechanism.
- Protons: They can easily be obtained by ionizing hydrogen.
- Antiparticles: To get antiparticles, first have energetic particles hit a target. Then pairs of particles and antiparticles will be created via virtual photons or gluons. Magnetic fields can be used to separate them.

Accelerators speed up charged particles by creating large electric fields which attract or repel the particles. This field is then moved down the accelerator, "pushing" the particles along, as shown in Figure 15.3.6

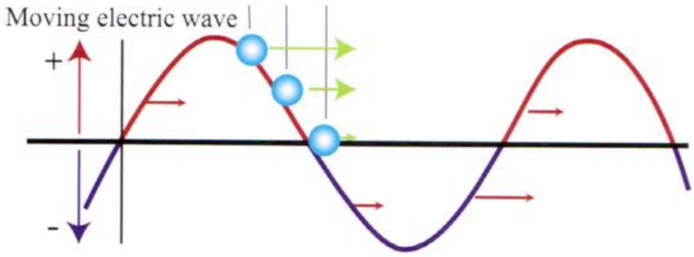


Figure 15.3.6: In a linear accelerator the field is due to travelling electromagnetic (E-M) waves.

Task 1 **Accelerator design**

There are several different ways to design these accelerators, each with its benefits and drawbacks.

(a) Research and describe the following target arrangements:
- Fixed target
- Colliding beams

(b) What are the advantages and disadvantages of each target arrangement?

(c) Research and describe the following accelerator layouts:
- Linac
- Synchrotron

(d) What are the advantages and disadvantages of each layout?

Task 2 **Major accelerators**

Explore the basic plans of the world's major accelerators and the differences in accelerator designs. Write a brief synopsis of each of the following, stating their basic design, advantages and main achievements.

- SLAC: Stanford Linear Accelerator Centre, in California
- Fermilab: Fermi National Laboratory Accelerator, in Illinois.
- CERN: European Laboratory for Particle Physics, crossing the Swiss-French border
- BNL: Brookhaven National Lab, in New York
- CESR: Cornell Electron-Positron Storage Ring, in New York.
- DESY: Deutsches Elektronen-Synchrotron, in Germany.
- KEK: High Energy Accelerator Research Organization, in Japan
- IHEP: Institute for High-Energy Physics, in the People's Republic of China

Problem Set 15.1: The standard model

Notes

1. The hundreds of known particles are all made from how many fundamental particles?

2. What are protons and electrons made of?

3. Baryons and mesons are made of quarks. Describe their make up

4. When a muon and an anti-muon collide they can annihilate each other and release their mass-energy as two photons. Assuming that these two photons are identical,
(a) What will each of their energies be?
(b) What wavelength will they have?
(c) Why does there need to be two photons produced and not just one?
(d) In what directions would they have to travel relative to each other and why?
(e) In what part of the electromagnetic spectrum are they located?

5. Fill in the missing baryons or leptons in each of the following equations. Assume that charge, baryon number and lepton number are all conserved, and that the mass of the reactants cannot be less than the mass of the products.
(a) $n \rightarrow p + e^- + \_\_\_\_$
(b) $\_\_\_\_ + n \rightarrow \_\_\_\_ + e^-$
(c) $\pi^+ \rightarrow \mu^+ \rightarrow + \_\_\_\_$
(d) $p \rightarrow n + \nu_e + \_\_\_\_$

6. An electron and a positron undergo pair annihilation. If they initially had no kinetic energy, what is the energy of each γ produced by the annihilation.? Why must there be two gamma rays produced?

7. If a magnetic field makes electrons go clockwise, in which direction does it make positrons go?

8. Can an object accelerate while keeping the same speed?

9. An electron and a positron were produced when a particle and its antiparticle collided head-on, perpendicular to this page. The diagram below shows the outcome of the collision. What conservation law appears to have been broken? Explain.
- charge
- number of leptons
- momentum
- energy

10. Which fundamental interaction is responsible for:
(a) friction? (b) nuclear bonding? (c) planetary orbits?

11. Which interactions or interactions
(a) act on neutrinos? (b) has heavy carriers? (c) act on the protons in you?

12. Which force carriers cannot be isolated? Why?

13. Which force carriers have not been observed?

Problem Set 15.2: General revision questions

Notes

1. Protons are accelerated in the LHC to an energy of 7.00 TeV and a velocity of 0.999997c. What is their wavelength under these conditions?

2. In the Australian synchrotron electrons are travelling with an average energy of 3.00 GeV in the main ring.
   (a) What is their average velocity in the main ring?
   (b) What wavelength do they have at this velocity?
   (c) Calculate the relativistic mass of each of these electrons.

3. In an experiment at the LHC at CERN two protons travelling in opposite directions with an energy of 7.00 Tev each are forced to collide. What is the relativistic mass, in kilograms, of each of these protons if they are travelling at 0.999999c?

4. An atomic nucleus decays emitting an alpha particle with a kinetic energy of 4.7 MeV. What is the mass equivalent of this energy?

5. A particular electron gun accelerates an electron from rest to a velocity of 0.965c. Calculate, in both joules and electron volts:
   (a) The rest energy of the electron.
   (b) The energy of the moving electron.
   (c) The kinetic energy of the electron.

6. Electrons in the beam of an X-ray machine are accelerated from rest through a potential difference of 40.0 kV. Calculate:
   (a) The maximum velocity that these electrons can achieve under these conditions.
   (b) The maximum relativistic kinetic energy of an electron in this beam.

7. Protons in a bubble chamber are bombarded with energetic antiparticles known as negative pions. At collision points, a proton and a pion transform into a negative kaon and a positive sigma:

   $$\pi^- + p \rightarrow K^- + \Sigma^+$$

   The rest energies of these particles are

π^- 139.6 MeV	K^- 493.7MeV	P 938.3 MeV	Σ^+ 1189.4 MeV

   How much energy is released in this reaction?

8. The element protactinium-236 is known to undergo beta decay to uranium-236 with a half-life of 9.00 minutes. A protactinium-236 nucleus at rest undergoes such a decay and recoils with a velocity of 5200 m s^{-1}. Assuming the anti-neutrino leaves with minimum momentum after decay:
   (a) Calculate the velocity of the ejected beta-particle.
   (b) Is this value reasonable? Justify your answer with an explanation and calculations.

9. In an experiment at the LHC at CERN two protons travelling in opposite directions with energies of 7 Tev each are forced to collide. What is the relativistic mass, in kg, of each of these protons if they are travelling at 0.999999c?

10. A proton in the LHC, circumference 27 km, was accelerated to 99.9999997c.
    (a) Calculate its apparent mass at this speed.
    (b) How long would the path in the LHC appear to the particle?

Problem Set 15.2: General revision questions

Notes

11. In the Synchrotron electrons are accelerated to velocities approaching the velocity of light. On the same set of axes sketch graphs of both the non-relativistic energy and the relativistic energy against the velocity of the electron, with the electron velocity being in units of "c".

12. Stanford University in the USA has a linear accelerator 3.00 km in length and in which electrons are accelerated to 0.9999999997c.
    (a) Calculate the rest energy of an electron in MeV.
    (b) Calculate the relativistic momentum of an electron in this tube and compare it to the non-relativistic momentum.
    (c) Calculate the total energy, in joules and eV, possessed by an electron in this accelerator.

13. In the Australian synchrotron electrons are travelling with an average energy of 3 GeV in the main ring.
    (a) What is their average velocity in the main ring?
    (b) What wavelength do they have at this velocity?
    (c) Calculate the relativistic mass of each of these electrons.

14. A discharge lamp in a stationary reference frame emits light with a wavelength of 240 nm. The same wavelength from a distant galaxy is observed to be Doppler shifted to 600 nm. Is this galaxy moving towards or away from us? Justify your answer with relevant calculations.

15. A spaceship captain was charged for going through a red traffic light. He argued in court that due to his motion the red was Doppler shifted so he saw it as green. Estimate his speed at this time.

16. Beta particles are released from a carbon-14 nucleus when it undergoes decay. One such beta particle is measured to be travelling at 0.89c. Calculate this beta particle's
    (a) relativistic mass.
    (b) kinetic energy on release.

17. When a particle and its antiparticle collide they annihilate each other and all of their mass is converted to a pair of photons.
    (a) Explain why these two photons would be expected to travel in opposite directions.
    In one particular case these two particles are a positron and an electron, each travelling at 0.7c in a research facility. Calculate the total momentum and total energy in each of the following.
    (b) The frame of reference of the research facility.
    (c) The rest frame of the electron.

18. The half-life of a π-meson (pion) is 26 μs and it travels at a velocity of 0.95c towards Earth. What is its lifetime measured relative to Earth?

19. A scientist working in a particle research facility fired pi-mesons (pions) at a speed of 0.950c towards a target in a particle accelerator. Pions are radioactive with a half-life of 2.60×10^{-8} s in their own reference frame.
    (a) How long will their half-life be from the point of view of the physicists?
    (b) How far will the pions travel in the particle accelerator during their lifetime?
    (c) How far will they travel in their own reference frame?

20. The spectrum from a distant galaxy, H15, is measured from Earth and a spectral line of 550 nm is found to be blue shifted to 450 nm.
    (a) Relative to the Earth, in what direction is galaxy H15 moving?
    (b) What is H15's velocity relative to Earth?
    The same spectral line from H15 is measured at 700 nm relative to another galaxy G10.
    (c) In what direction is H15 moving relative to G10?
    (d) What is galaxy H1's velocity relative to G10?

Measurement and uncertainties

The *maximum* uncertainty of a measurement is usually ± 1 scale division. Thus, on a ruler that measures to 1 mm, a reading of 14.5 cm would be shown as **14.5 ± 0.1 cm**. On a *digital* instrument (stopwatch, balance) this is the best you'll get.

On an *analogue* instrument (ruler, thermometer, measuring cylinder) a skilled user may be able to estimate to less than this. For example, a thermometer having a fairly big spacing between the degree markings might be readable to ± 0.2 degree, if you were good at using it, or to ± 0.5 degree if you are not so skilled.

Other factors such as the reliability of the instrument itself are also important.

Example:

- Use a ruler to measure this page to ± 0.1 cm.
- Now measure it to the best (most accurate) value that you can, and show your result accordingly.
- How can we show which of these measurements has the lesser uncertainty (i.e. is 'more accurate')?

Adding or subtracting uncertainties:

If you *add* two measurements, you also add their uncertainties. Thus,

4.5 ± 0.1 cm + 5.5 ± 0.1 cm = **10.0 ± 0.2 cm**.

(Note that a simple rule about significant figures does not apply here; 2 SF + 2 SF but the answer is to 3 SF. *Significant figures give a general idea of uncertainties* instead of the more thorough treatment of uncertainties shown here.)

If you subtract measurements, you also add the uncertainties. Thus,

5.5 ± 0.1 cm - 4.5 ± 0.1 cm = **1.0 ± 0.2 cm**.

If you *multiply or divide* measurements, you convert to % uncertainty, then add these.

Example:

1. A toy car travelled 6.25 ± 0.05 metres in 22.51 ± 0.01 seconds. The speed is distance divided by time. So, we convert to % uncertainty:

$$\frac{\pm 0.05}{6.25} \times 100 = \pm 0.8\%$$

so we can now write the distance as 6.25 cm ± 0.8% .

The % uncertainty in the time is:

$$\frac{\pm 0.01}{22.51} \times 100 = \pm 0.04\%$$

So we can now write the time as **22.51 s ± 0.04%**.

Then when we calculate the average speed of the car, we can show an estimate of the uncertainty of the speed in the answer.

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{6.25\text{ m}}{22.51\text{ s}} = 0.27765...\text{m s}^{-1}$$

uncertainty = 0.8 + 0.04 = ± 0.84%

0.84% of 0.27765 ... = 0.002

thus the speed is 0.278 ± 0.002 m s^{-1}

Note that a significant figure 'rule of thumb' works in this case. But note also that for actual measurements, showing the uncertainty estimate is much better than just blindly following a rule.

Exercise: Use your measurements of this page (above) to calculate its area, and show the result with an estimate of the uncertainty.

Measurement and uncertainties

Minimising uncertainties by making repeat measurements:

You can reduce the uncertainty in a measurement by making lots of measurements of the same thing, each independent of the others, then finding the mean value and the standard deviation of the distribution. The uncertainty in this case is ± the standard deviation. Another name for standard deviation is 'standard error of the mean'.

For example, a group of students measuring "g" got the following:

Run	1	2	3	4	5	6	7	8	9	10
Value (m s^{-2})	9.36	9.67	9.64	9.41	9.88	10.21	9.55	9.74	9.96	9.92

Calculate the mean and the standard deviation of these values, and hence quote "g" with an estimate of the experimental uncertainty.

Using a spreadsheet to calculate the mean and standard deviation, we get:

Mean = 9.734

St dev = 0.250

We would quote the mean value to be:

9.7 ± 0.2 m s^{-2}, or 9.7 ± 0.3 m s^{-2}; note that either way, the "expected" value of 9.8 m s^{-2} falls within the experimental uncertainty.

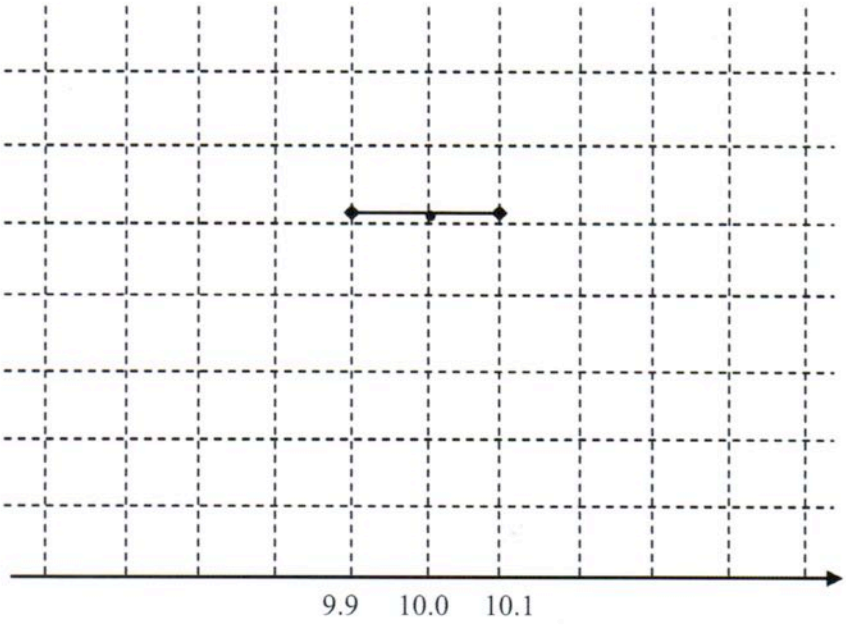
The more values you include, the more likely it is that your mean is close to the expected or actual value.

Why does this reduce the experimental uncertainty? Try using any two or three consecutive values in this table to calculate an average value for "g" and then compare it with the expected value. Note that the standard deviation is a feature of large samples and is not a valid measure for small samples, eg two or three.

Showing uncertainties on a graph:

You can graphically represent uncertainty in a measurement by plotting the value, and then adding 'error bars' that extend along the axis to show the ± values.

For example you would graph a value of 10.0 ± 0.1 m s^{-1} as a dot at 10.0, with a bar extending 0.1 unit in the positive direction (to show that the value could be as high as 10.1) and a bar extending in the negative direction (to show that the value could be as low as 9.9).



When drawing a line of best fit, it is worth keeping in mind that the central dot is not the measurement – anywhere along the bars could be correct. That is what an uncertainty means. A line of best fit should reflect your understanding of the physics of the situation.