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PHYSICS

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IB DIPLOMA PROGRAMME

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Contents

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1 MEASUREMENTS AND UNCERTAINTIES

1.1 MEASUREMENTS IN PHYSICS

You must know:

- ✔ the definitions of fundamental and derived SI units
- ✔ what is meant by scientific notation
- ✔ the meaning of metric multipliers
- ✔ that significant figures are used to indicate levels of precision in measurements
- ✔ what is meant by an order of magnitude
- ✔ what is meant by an estimation.

You should be able to:

- ✔ use SI units in a correct format when expressing measurements, final calculated answers and when you are presenting raw and processed data
- ✔ use scientific notation in conjunction with metric multipliers to express answers and data in as concise a way as possible
- ✔ quote and compare ratios, values, estimations and approximations to the nearest order of magnitude
- ✔ estimate quantities to an appropriate number of significant figures.

The change in definitions of the SI fundamental units in May 2019 does not affect your IB Diploma Programme (DP) learning as you are not required to know the definitions except as indicated in the subject guide. However, you should be aware that textbooks written before this date may give the older definitions.

Assessment tip

In physics, unless you are providing a final answer as a ratio or as a fractional difference, you must **always** quote the correct unit with your answer. Marks can be lost in an examination when a unit is missing or is incorrect.

You should always link your answer value to its unit (together with the prefix where appropriate).

Scientists need a shared language to communicate between themselves and with the wider public. Part of this language involves agreeing the units used to specify data. For example, if you are told that your journey to school has a value of 5000 then you need to know whether this is measured in metres (originally a European measure) or fet (an old Icelandic length measure).

The agreed set of units and rules is known as the *Système Internationale d'Unités* (almost always abbreviated as SI). In this system, seven *fundamental (base) units* are defined and all other units are derived from these. You are required to use six of the seven fundamental units; the seventh is the unit of luminous intensity, the candela, that is not used in the IB Diploma Programme physics course.

The six fundamental units you will use in the DP physics course are shown in this table.

Measure	Unit	Abbreviation
mass	kilogramme	kg
length	metre	m
time	second	s
quantity of matter	mole	mol
temperature	kelvin	K
current	ampère	A

There are many other derived units used in the course and the expression of these in fundamental units is usually given in this book when you meet the derived unit for the first time. Examples of these derived units include joule, volt, watt, pascal.

Often, the use of a derived unit avoids a long string of fundamental units at the end of a number, so $1\,\text{volt} \equiv 1\,\text{J}\,\text{C}^{-1} \equiv 1\,\text{kg}\,\text{m}^2\,\text{s}^{-3}\,\text{A}^{-1}$.

There are also some units used in the course that are not SI. Examples include $\text{MeV}\,c^{-2}$, light year and parsec. These have special meaning in some parts of the subject and are used by scientists in those fields. Their meaning is explained when you meet them in this book.

The SI also specifies how data in science should be written. Numbers in physics can be very large or very small. Expressing the diameter of an atom as 0.000 000 000 12 m is unhelpful; 1.2×10^{-10} m is much better. This format of $n.nn \times 10^n$ is known as *scientific notation* and should be used whenever possible. It can also be combined with the SI prefixes that are permitted.

SI prefixes are added in front of a unit to modify its value, so 1012 s can be written as 1.012 ks. The full list of prefixes that you are allowed is included in the data booklet and you can refer to it during examinations.

Prefix	Symbol	Factor	Decimal number
deca	da	10^1	10
hecto	h	10^2	100
kilo	k	10^3	1 000
mega	M	10^6	1 000 000
giga	G	10^9	1 000 000 000
tera	T	10^{12}	1 000 000 000 000
peta	P	10^{15}	1 000 000 000 000 000
deci	d	10^{-1}	0.1
centi	c	10^{-2}	0.01
milli	m	10^{-3}	0.001
micro	µ	10^{-6}	0.000 001
nano	n	10^{-9}	0.000 000 001
pico	p	10^{-12}	0.000 000 000 001
femto	f	10^{-15}	0.000 000 000 000 001

There are some rules here too.

- Only one prefix is allowed per unit, so it would be incorrect to write 2.5 µkg for 2.5 mg.
- You can put one prefix per fundamental unit, so $0.33\,\text{Mm}\,\text{ks}^{-1}$ would be acceptable for $330\,\text{m}\,\text{s}^{-1}$ (the speed of sound in air) but nowhere near as meaningful.

Significant figures (sf) can lead to confusion. It is important to distinguish between significant figures and decimal places (dp). For example:

- 2.38 kg has 3 sf and 2 dp
- 911.2 kg has 4 sf and 1 dp.

The rule for the number of sf in a calculated answer is quite clear. Specify the answer to the same number as the quantity in the question with the smallest number of sf.

Assessment tip

Many marks are lost through careless use of units in every DP physics examination. When a question begins 'Calculate, in kg, the mass of…', if you do not quote a unit for your answer then the examiner will assume that you meant kg. If you worked the answer out in g and did not say so, then you will lose marks.

Example 1.1.1

A snail travels a distance of 33.5 cm in 5.2 minutes.

Calculate the speed of the snail.

State the answer to an appropriate number of significant figures.

Solution

The answer, to 7 sf, is $1.073718 \times 10^{-3}\,\mathrm{m\,s^{-1}}$.

It is incorrect to quote the answer to this precision as the time is only quoted to 2 sf (the fact that 5.2 minutes is 312 s is not important). The appropriate answer is $1.1 \times 10^{-3}\,\mathrm{m\,s^{-1}}$ (or $1.1\,\mathrm{mm\,s^{-1}}$ if you prefer).

Assessment tip

In Example 1.1.1, rounding up is needed. You should do this for every calculation– *but only at the very end of the calculation*. Rounding answers mid-solution leads to inaccuracies that may take you out of the allowed tolerance for the answer. Keep all possible sf in your calculator until the end and only make a decision about the sf in the last line. In Example 1.1.1, an examiner would be very happy to see …

$= 1.073718 \times 10^{-3}\,\mathrm{m\,s^{-1}}$ so the speed of the snail is $1.1 \times 10^{-3}\,\mathrm{m\,s^{-1}}$ (to 2 sf) … as your working is then completely clear.

Sometimes estimations are required in physics. This is because either:

- an educated guess is needed for all or some of the quantities in a calculation, or
- there is an assumption involved in a calculation.

Often it will be appropriate to express your answer to an order of magnitude, meaning rounded to the nearest power of ten. The best way to express any order of magnitude answers is as 10^n, where n is an integer.

Assessment tip

You may see order of magnitude answers in Paper 1 (multiple choice) written as a single integer. When the response is, say, 7, this will mean 10^7.

It is also permissible to talk about 'a difference of two orders of magnitude'; this means a ratio of 100 (10^2) between the two quantities.

Example 1.1.2

Estimate the number of air molecules in a room.

Solution

The calculation is left for you, but you should use the following steps.

- Estimate the volume of a room by making an educated guess at its dimensions, in metres.
- The density of air is about $1.3\,\mathrm{kg\,m^{-3}}$—call it $1\,\mathrm{kg\,m^{-3}}$ to make the numbers easy later.
- The mass of 1 mol of oxygen molecules is 32 g and 1 mol of nitrogen is 28 g—call the answer 30 g for both gases combined.
- Each mole contains 6×10^{23} molecules.

The volume and density → mass of gas in room and molar mass → number of moles and Avogadro's number → answer.

Assessment tip

If the command term 'Estimate' is used in the examination, it will always be clear what is required as you will lack some or all data for your calculation if an educated guess is needed. In estimation questions, such as Example 1.1.2, make it clear what numbers you are providing for each step and how they fit into the overall calculation.

1.2 UNCERTAINTIES AND ERRORS

You must know:

- ✔ what is meant by random errors and systematic errors
- ✔ what is meant by absolute, fractional and percentage uncertainties
- ✔ that error bars are used on graphs to indicate uncertainties in data
- ✔ that gradients and intercepts on graphs have uncertainties.

You should be able to:

- ✔ explain how random and systematic errors can be identified and reduced
- ✔ collect data that include absolute and/or fractional uncertainties and go on to state these as an uncertainty range
- ✔ determine the overall uncertainty when data with uncertainties are combined in calculations involving addition, subtraction, multiplication, division and raising to a power
- ✔ determine the uncertainty in gradients and intercepts of graphs.

All measurement is prone to error. The Heisenberg uncertainty principle (Topic 12) reminds us of the fundamental limits beyond which science cannot go. However, even when the data collected are well above this limit, then two basic types of error are implicit in the data you collect: *random error* and *systematic error*.

Random errors lead to an uncertainty in a value. One way to assess their impact on a measurement is to repeat the measurement several times and then use half the range of the outlying values as an estimate of the *absolute uncertainty*.

Uncertainty in measurement is expressed in three ways.

Absolute uncertainty: the numerical uncertainty associated with a quantity. For example, when a length of quoted value 5.00 m has an actual value somewhere between 4.95 m and 5.05 m, the absolute uncertainty is ± 0.05 m.

The length will be expressed as (5.00 ± 0.05) m.

Fractional uncertainty $= \dfrac{\text{absolute uncertainty in quantity}}{\text{numerical value of quantity}}$.

A fractional uncertainty has no unit.

Percentage uncertainty $=$ fractional uncertainty $\times 100$ expressed as a percentage. There is no unit.

Random errors are unpredictable changes in data collected in an experiment. Examples include fluctuations in a measuring instrument or changes in the environmental conditions where the experiment is being carried out.

Systematic errors are often produced within measuring instruments. Suppose that an ammeter gives a reading of +0.1 A when there is no current between the meter terminals. This means that every reading made using the meter will read 0.1 A too high. The effect of a systematic error can produce a non-zero intercept on a graph where a line through the origin is expected.

Example 1.2.1

Five readings of the length of a small table are made. The data collected are:

0.972 m, 0.975 m, 0.979 m, 0.981 m, 0.984 m

a) Calculate the average length of the table.

b) Estimate, for the length of the table, its:

i) absolute uncertainty

ii) fractional uncertainty

iii) percentage uncertainty.

Solution

a) The average length is:

$$\frac{(0.972 + 0.975 + 0.979 + 0.981 + 0.984)}{5} = 0.978(2)\,\text{m}$$

b) i) The outliers are 0.972 and 0.984 which differ by 0.012 m. Half this value is 0.006 m and this is taken to be the absolute uncertainty.

The length should be expressed as (0.978 ± 0.006) m.

(This absolute error is an estimate; another estimate is the standard deviation of the set of measurements which in this case is 0.004 m. 0.006 m is thus an overestimate.)

ii) The fractional uncertainty is $\frac{0.006}{0.9782} = 0.006(13) = 0.006$.

This is a ratio of lengths and has no unit.

iii) The percentage uncertainty is $0.006 \times 100 = 0.6\%$.

You will often need to combine quantities mathematically: a pair of lengths, both with uncertainty, may need to be added to give a total length. This derived quantity will also have an uncertainty.

Combining uncertainties

The two sides of a table have lengths (180 ± 5) cm and (60 ± 3) cm. What is the total perimeter of the table?

The **absolute uncertainties are added** when quantities are **added and subtracted**.

When $y = a \pm b$ then $\Delta y = \Delta a + \Delta b$

In this case, the perimeter of the table is $180 + 180 + 60 + 60 = 480$ m. The absolute uncertainty is $5 + 5 + 3 + 3 = 16$ cm.

The perimeter is (480 ± 16) cm or 4.8 ± 0.2 m.

Notice that when the quantities themselves are subtracted, the uncertainties are still added.

What is the area of the table?

When $y = \frac{ab}{c}$ then $\frac{\Delta y}{y} = \frac{\Delta a}{a} + \frac{\Delta b}{b} + \frac{\Delta c}{c}$

The **fractional uncertainties are added** when quantities are **multiplied or divided**.

The area is $1.8 \times 0.60 = 1.08\,\text{m}^2$. The two fractional uncertainties are

$\frac{0.05}{1.8} = 0.028$ and $\frac{0.03}{0.6} = 0.050$.

The sum is 0.078 and this is the fractional uncertainty of the answer.

The absolute uncertainty in the area $= 0.078 \times 1.08 = 0.084$.

The answer should be expressed as $(1.08 \pm 0.08)\,\text{m}^2$.

When the answer is found by division, the fractional uncertainties are still added.

Raising quantities to a power

When $y = a^2$, this is the same as $a \times a$ so using the algebraic rule above: $\frac{\Delta y}{y} = \frac{\Delta a}{a} + \frac{\Delta a}{a} = \frac{2\Delta a}{a}$.

In the general case, when $y = a^n$, $\frac{\Delta y}{y} = \left|n\frac{\Delta a}{a}\right|$, where $||$ means the absolute value or magnitude of the expression.

When **a quantity is raised to a power n, the fractional uncertainty is multiplied by n**.

The radius of a sphere is (0.20 ± 0.01) m. What is the volume of the sphere?

Volume of sphere is: $\frac{4}{3}\pi r^3 = 0.0335\,\text{m}^3$

where r is the radius.

Fractional uncertainty of radius $= \frac{0.01}{0.20} = 0.05$

So, the fractional uncertainty of the radius cubed is $3 \times 0.05 = 0.15$.

The absolute uncertainty is $0.335 \times 0.15 = 0.0050\,\text{m}^3$.

The volume of the sphere is $(0.335 \pm 0.005)\,\text{m}^3$.

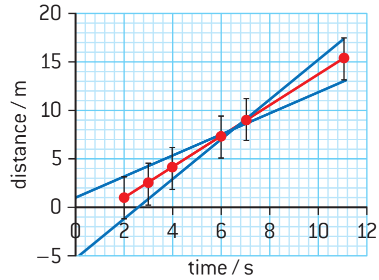
There is more information about this topic in Chapter 13, which deals with Paper 3, Section A.

It is possible that data points, all with an associated error, are presented on a graph. Therefore, there are errors associated with the gradient and any intercept on the graph. The way to treat these errors is to add *error bars* to the graph. These are vertical or horizontal lines, centred on each data point, that are equal to the length of the absolute errors.

Maximum and minimum best-fit lines can then be drawn each side of the true best-fit line. The gradients of these maximum–minimum lines give a range of values that corresponds to the error in the gradient. The intercepts of the maximum–minimum lines also have a range in values that can be associated with the error in the true intercept.

For the graph in Figure 1.2.1, the gradient is 1.6 with a range between 2.1 and 1.1, so $(1.6 \pm 0.5)\,m\,s^{-1}$.

The intercept is –2.4 with a range of 1.0 to –5.8, so $(-2.4 \pm 3.4)\,m$.



▲ Figure 1.2.1. Maximum and minimum best-fit lines each side of a true best-fit line

1.3 VECTORS AND SCALARS

You must know:

- ✔ what are meant by vector and scalar quantities
- ✔ that vectors can be combined and resolved (split into two separate vectors).

You should be able to:

- ✔ solve vector problems graphically and algebraically.

Quantities in DP physics are either *scalars* or *vectors*. (There is a third type of physical quantity but this is not used at this level.)

A vector can be represented by a line with an arrow. When drawn to scale, the length of the line represents the magnitude, and the direction is as drawn.

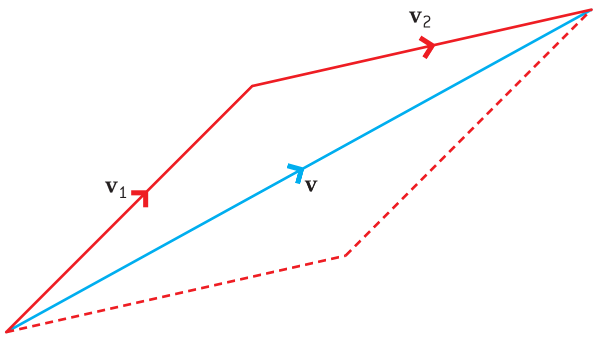
Both scalars and vectors can be added and subtracted. Scalar quantities add just as any other number in mathematics. With vectors, however, you need to take the direction into account.

Figure 1.3.1 shows the addition of two vectors. The vectors must be drawn to the same scale and the direction angles drawn accurately too. A further construction produces the parallelogram with the red solid and dashed lines. Then the magnitude of the new vector $\mathbf{v}_1 + \mathbf{v}_2$ is given by the length of the blue vector with the direction as shown.

Scalars are quantities that have magnitude (size) but no direction. They generally have a unit associated with them.

Vectors are quantities that have both magnitude and a physical direction. A unit is associated with the number part of the vector.

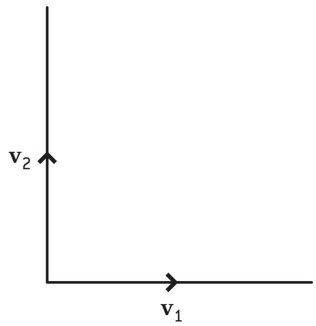
For example, the scalar quantity speed is written as v; the vector quantity velocity is written as $\mathbf{v}$ (sometimes as $\underset{\sim}{v}$ or $\vec{v}$, but this notation is not used in this book).

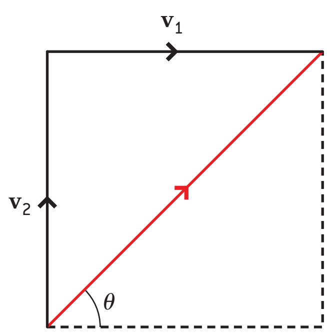


▲ Figure 1.3.1. Adding vectors $\mathbf{v}_1$ and $\mathbf{v}_2$

Vectors can also be added algebraically. The most common situation you meet in the DP physics course is when the vectors are at 90° to each other (Figure 1.3.2).

As before, addition by drawing gives the red vector which is the sum of $\mathbf{v}_1$ and $\mathbf{v}_2$. Algebraically, the use of trigonometry gives the magnitude of the resultant (added) vector as $\sqrt{\mathbf{v}_1^2 + \mathbf{v}_2^2}$ and the direction θ as $\tan^{-1}\left(\frac{\mathbf{v}_2}{\mathbf{v}_1}\right)$.





▲ Figure 1.3.2. Adding two vectors at right angles

Example 1.3.1

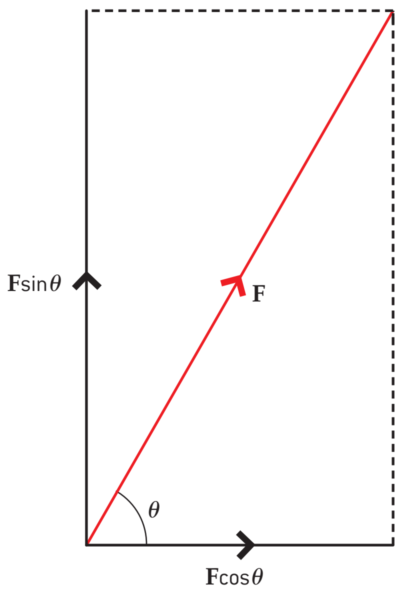
A girl walks 500 m due north and then 1200 m due east. Calculate her position relative to her starting point.

Solution

This is similar to the situation in Figure 1.3.2 where the first vector has a magnitude of 500 m and the second a magnitude of 1200 m.

The magnitude of the resultant is $\sqrt{500^2 + 1200^2} = 1300\,\text{m}$.

θ is $\tan^{-1}\left(\frac{500}{1200}\right) = 22.6°$.



▲ Figure 1.3.3. Resolving a vector

Another skill required in the DP physics course is that of breaking a vector down into two components at right angles to each other – this is known as resolving the vector. A right angle is chosen because the two resolved components will be independent of each other. Figure 1.3.3 shows the process.

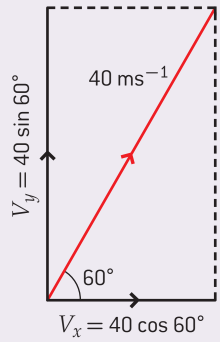
The vector **F** points upwards from the horizontal at θ. This length **F** is the hypotenuse of the right-angled triangle. The other sides have lengths $\mathbf{F}\cos\theta$ and $\mathbf{F}\sin\theta$.

Example 1.3.2

An object moves with a velocity $40\,\text{m}\,\text{s}^{-1}$ at an angle N30°E. Determine the component of the velocity in the direction:

a) due east

b) due north.



Solution

a) The angle between the vector and east is 60°

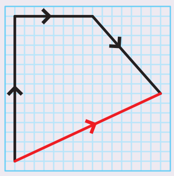
So the component due east $= 40\cos 60° = 20\,\text{m}\,\text{s}^{-1}$

b) Due north, the component is $40\cos 30° = 40\sin 60° = 34.6\,\text{m}\,\text{s}^{-1}$

Example 1.3.3

A girl cycles 1500 m due north, 800 m due east and 1000 m in a south-easterly direction. Calculate her overall displacement.

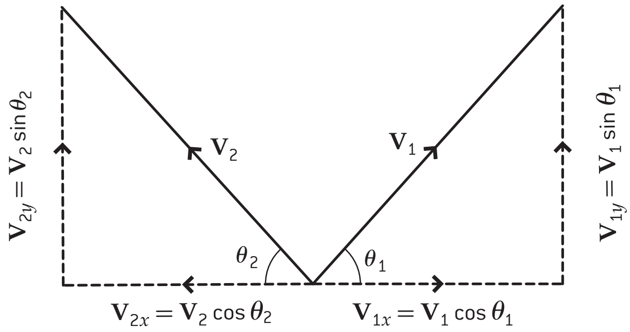
Solution



A drawing of the journey is shown. The total horizontal component of the displacement is $800 + 1000\cos 45° = 1510\,\text{m}$. The total vertical component is $1500 - 1000\cos 45° = 790\,\text{m}$.

The displacement is 1700 m at $\tan^{-1}\left(\frac{790}{1510}\right) = 28°$.

You can now add or subtract any non-parallel vectors algebraically. Figure 1.3.4 shows the method.



▲ **Figure 1.3.4.** Algebraic method for adding or subtracting non-parallel vectors

Horizontally the addition gives $\mathbf{V}_x = \mathbf{V}_{1x} + \mathbf{V}_{2x}$ which is $\mathbf{V}_1 \cos\theta_1 - \mathbf{V}_2 \cos\theta_2$.

Vertically the addition gives $\mathbf{V}_y = \mathbf{V}_{1y} + \mathbf{V}_{2y}$ which is $\mathbf{V}_1 \sin\theta_1 + \mathbf{V}_2 \sin\theta_2$. These new vector lengths can be added to give the new vector length $\mathbf{V} = \sqrt{\mathbf{V}_x^2 + \mathbf{V}_y^2}$ with an angle to the horizontal of $\tan^{-1} = \left(\frac{\mathbf{V}_y}{\mathbf{V}_x}\right)$.

To subtract two vectors, simply form the negative vector of the one being subtracted (by reversing its original direction but leaving the length unchanged) and add this to the other vector.

Practice problems for Topic 1

Problem 1

You will need to have covered the relevant topic before answering this question.

a) Express the following derived units in fundamental units: watt, newton, pascal, tesla.

b) Give a suitable set of fundamental units for the following quantities:
acceleration, gravitational field strength, electric field strength, energy.

Problem 2

Express the following physical constants (all in the data booklet) to the specific number of significant figures.

Quantity	Significant figures required
Neutron rest mass	3
Planck's constant	2
Coulomb constant	2
Permeability of free space	5

Problem 3

Express the following numbers in scientific notation to three significant figures.

a) 4903.5

b) 0.005194

c) 39.782

d) 9273844.45

e) 0.035163

Problem 4

Estimate these quantities.

a) Length of a DP physics course in seconds.

b) Number of free electrons in the charger lead to your computer.

c) Volume of a door.

d) Number of atoms in a chicken's egg (assume it is made of water).

e) Number of molecules of ink in a pen.

f) Energy stored in an AA cell.

g) Number of seconds you have been alive.

h) Thickness of tread worn off a car tyre when it travels 10 km.

Problem 5

Determine, the following, with their absolute and percentage uncertainties.

a) The kinetic energy of a mass (1.5 ± 0.2) kg moving at (21.5 ± 0.3) m s^{-1} (use $E_k = \frac{1}{2}mv^2$).

b) The force acting on a wire of length (3.5 ± 0.4) m carrying a current (2.5 ± 0.2) A in a magnetic field of strength (5.2 ± 0.3) mT (use $F = BIL$).

c) The quantity of gas, in mol, in a gas of volume (1.25 ± 0.03) m^3, pressure (2.3 ± 0.1) × 10^5 Pa at a temperature of (300 ± 10) K (use $pV = nRT$).

Problem 6

A car is driven at 30 m s^{-1} for 30 minutes due east and then at 25 m s^{-1} for 45 minutes northeast.

Calculate the final displacement of the car from its starting point.

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PHYSICS

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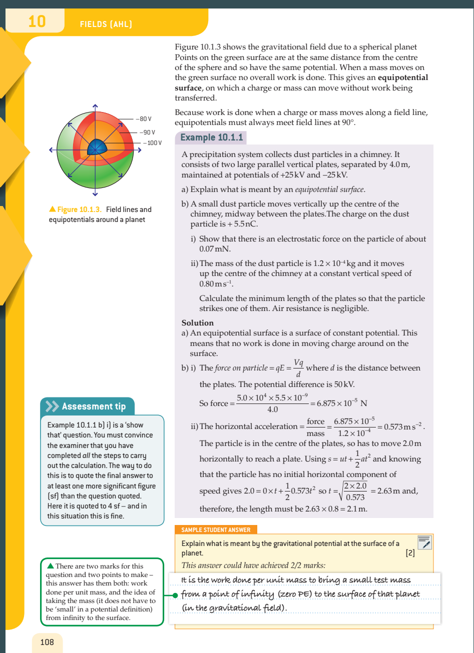
Key syllabus material is explained alongside **key definitions**

Assessment tips **offer guidance** and warn against common errors

Assessment questions and **sample student responses** provide practice opportunities and useful feedback



10 FIELDS (AHL)

Figure 10.1.3 shows the gravitational field due to a spherical planet Points on the green surface are at the same distance from the centre of the sphere and so have the same potential. When a mass moves on the green surface no overall work is done. This gives an **equipotential surface**, on which a charge or mass can move without work being transferred.

Because work is done when a charge or mass moves along a field line, equipotentials must always meet field lines at 90°.

−80 V
−90 V
−100 V

▲ Figure 10.1.3. Field lines and equipotentials around a planet

Example 10.1.1

A precipitation system collects dust particles in a chimney. It consists of two large parallel vertical plates, separated by 4.0 m, maintained at potentials of +25 kV and −25 kV.

a) Explain what is meant by an *equipotential surface*.

b) A small dust particle moves vertically up the centre of the chimney, midway between the plates. The charge on the dust particle is + 5.5 nC.

i) Show that there is an electrostatic force on the particle of about 0.07 mN.

ii) The mass of the dust particle is 1.2×10^{-4} kg and it moves up the centre of the chimney at a constant vertical speed of $0.80\ m\,s^{-1}$.

Calculate the minimum length of the plates so that the particle strikes one of them. Air resistance is negligible.

Solution

a) An equipotential surface is a surface of constant potential. This means that no work is done in moving charge around on the surface.

b) i) The *force on particle* $= qE = \frac{Vq}{d}$ where d is the distance between the plates. The potential difference is 50 kV.

So force $= \frac{5.0 \times 10^4 \times 5.5 \times 10^{-9}}{4.0} = 6.875 \times 10^{-5}$ N

ii) The horizontal acceleration $= \frac{\text{force}}{\text{mass}} = \frac{6.875 \times 10^{-5}}{1.2 \times 10^{-4}} = 0.573\ m\,s^{-2}$.

The particle is in the centre of the plates, so has to move 2.0 m horizontally to reach a plate. Using $s = ut + \frac{1}{2}at^2$ and knowing that the particle has no initial horizontal component of speed gives $2.0 = 0 \times t + \frac{1}{2}0.573t^2$ so $t = \sqrt{\frac{2 \times 2.0}{0.573}} = 2.63$ m and, therefore, the length must be $2.63 \times 0.8 = 2.1$ m.

Assessment tip

Example 10.1.1 b) i) is a 'show that' question. You must convince the examiner that you have completed *all* the steps to carry out the calculation. The way to do this is to quote the final answer to at least one more significant figure (sf) than the question quoted. Here it is quoted to 4 sf – and in this situation this is fine.

SAMPLE STUDENT ANSWER

Explain what is meant by the gravitational potential at the surface of a planet. [2]

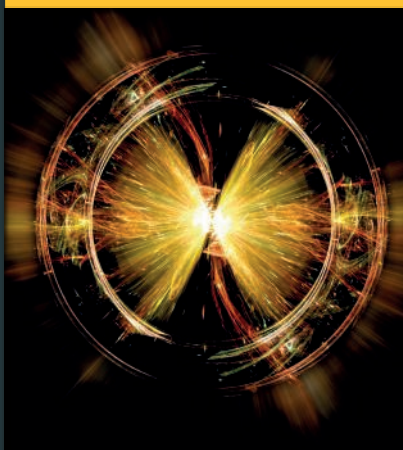
This answer could have achieved 2/2 marks:

It is the work done per unit mass to bring a small test mass from a point of infinity (zero PE) to the surface of that planet (in the gravitational field).

▲ There are two marks for this question and two points to make – this answer has them both: work done per unit mass, and the idea of taking the mass (it does not have to be 'small' in a potential definition) from infinity to the surface.

108

What's on the cover?
A visual representation of the Higgs boson particle



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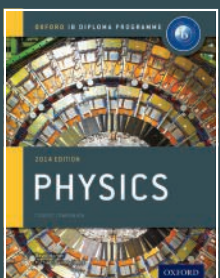

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