Subject	Qualification	Examination Board
Physics	A Level	AQA
Additional Information:		

Task Overview:

1. Experiment Design
2. Data Analysis
3. Presenting Data
4. Maths Skills
5. YouTube Physics video links
6. Physics GCSE-standard Exam Questions
7. Physics in the News
8. Physics Key Vocabulary
9. Astrophysics Research Project
10. Applications of Physics Case Study
11. Chernobyl Newspaper Article
12. Physics Popular Literature

Success Criteria:

See further task details below

Resources:

Internet, GCSE revision materials, calculator, ruler, pencil, graph paper.

How will the work produced will fit into subsequent work and the specification as a whole?

The range of activities allow you to demonstrate your knowledge in various key areas vital to the study of Physics. Some will also give you the opportunity to discover more about the content you will learn whilst studying A Level Physics as well as developing other skills.

How should the work should be presented?

Once each assignment has been completed, you should email (if possible) to Mr Alker (see address below). For assignments that can only be completed on paper, these should be filed so that they can be handed in when you are next in school.

Who should you contact if you should require further assistance with the work before the end of term?	Mr Alker (Head of Science/Physics) m.alker@gildredgehouse.org.uk
Length of time expected to complete tasks:	2 – 3 hours per task
Submission Requirements:	Email work when completed, or store in a file.

What equipment will be needed for the subject?

This is our course text book: AQA Physics A Level Second Edition Year 1 Student Book Author: Jim Breithaupt, ISBN: 978 0 19 835186 3, Publisher: Oxford University Press, www.global.oup.com

Optional Extension Task/Further Reading

http://www.physics.org/
http://www.iop.org/education/student/youth_membership/page_41684.html
https://www.iop.org/

Task Details

1. **Experiment Design**

On Earth, the acceleration due to gravity, 'g', is 9.81 ms^{-2}. You may be more familiar with using g = 10 ms^{-2}.

How did scientists work this out?

Design an experiment to determine the value of the acceleration due to gravity, 'g'.
- Research the required Physics to be able to calculate 'g'.
- Design an experiment that could be carried out using standard laboratory equipment to experimentally determine the value of 'g'.
- Draw a clear diagram of your apparatus.
- Write a detailed set of instructions in your plan, ensuring you describe the exact measurements to take.
- Explain how you would make your results as ACCURATE as possible.
- Explain how you would make your results as RELIABLE as possible.
- Explain how you would process your data to determine the value of 'g'.

2. **Data Analysis**

Using the provided data, write a report analysing the patterns and trends of Nuclear Power generation in the UK.
- Ensure you analyse the graphs carefully to fully describe the patterns shown
- Comment on the sources provided – how reliable do you think they are?
- Provide a context to your analysis by discussing any global trends

3. **Presenting Data**

For each set of data provided, display the information on an appropriate graph.

4. **Maths Skills**

Complete the exercises provided covering a range of essential maths skills.

5. **YouTube Physics Video Links**

Using the provided list of website URLs, watch each of the short YouTube video links to review the key topics from GCSE that form the foundations of the A Level course. If you would like the links emailed to you, please contact m.alker@gildredgehouse.org.uk

6. **Physics GCSE-standard Exam Questions**

Complete the GCSE-standard exam style questions provided in your pack.

7. **Physics in the News**

Read the provided articles of examples of recent advances of Physics and Engineering.

8. **Physics Key Vocabulary**

Learn the definitions of the list of key Physics vocabulary, provided in your pack.

9. **Astrophysics Research Project**

Pick **one** of the following research questions to form the basis of an in-depth research project. Present your research in a format of your choosing (eg: written report, powerpoint presentation, etc):

1. How do Astrophysicists measure vast distances, such as those between stars?
2. What is a black hole?
3. How is our Universe changing and what evidence do we have?
4. How have telescopes evolved over time?

10. **Application of Physics Case Study**

Choose one mode of transport (aeroplane/boat/car/bike/rocket). Research the Physics involved in making your chosen mode of transport move. Summarise your findings into a short case study report.

11. **Chernobyl Newspaper Article**

Watch a (factual!) documentary on the Chernobyl nuclear disaster (such as National Geographic's: https://www.youtube.com/watch?v=AZ4qOMN527s)

Then write a newspaper article about the incident.

12. **Physics Popular Literature**

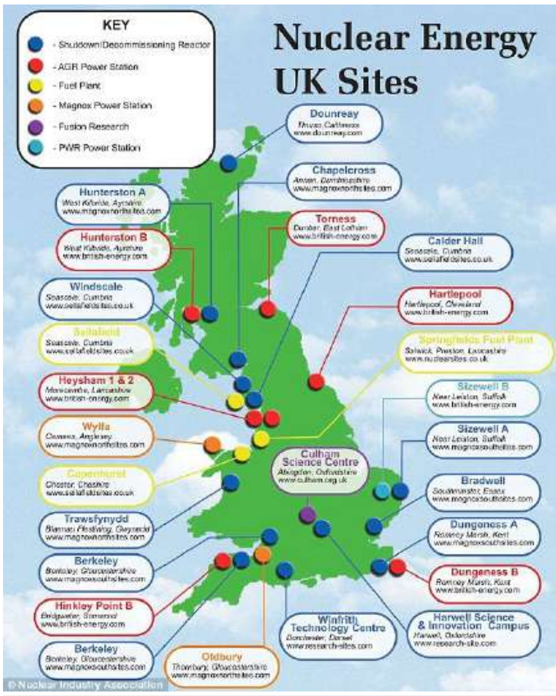
Find a copy of at least one of the following books in your local library and read it.

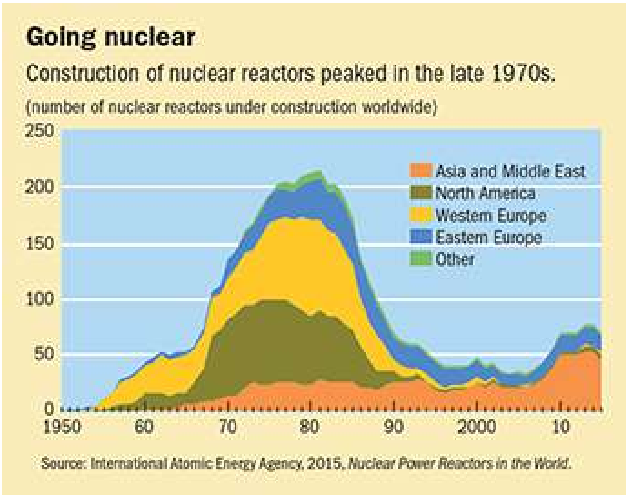
- Cosmos, by Carl Sagan
- A Brief History of Time, by Stephen Hawking
- The Road to Reality, by Roger Penrose
- The Tragedy of the Moon, by Isaac Asimov
- The Elegant Universe, by Brian Greene
- Introduction to Quantum Mechanics, by David J Griffiths
- 13 Things That Don't Make Sense: The Most Intriguing Scientific Mysteries of Our Time, by Michael Brooks
- Goldilocks and the Water Bears: The Search for Life in the Universe, by Louisa Preston

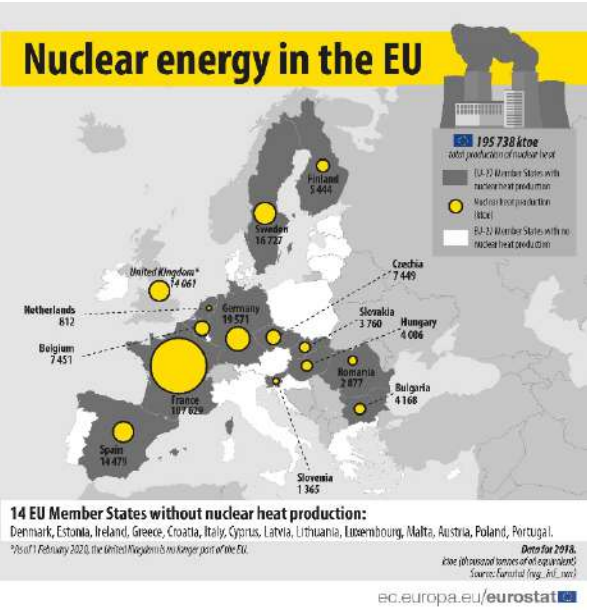
Physics Task 2: Data Analysis

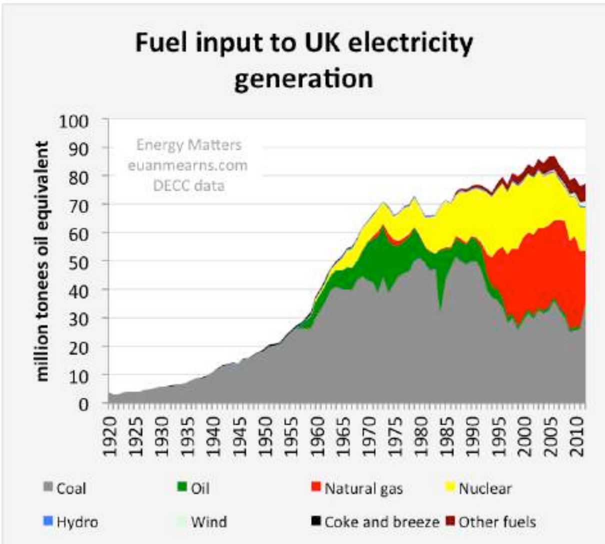
Using the provided data, write a report analysing the patterns and trends of Nuclear Power generation in the UK.

- Ensure you analyse the graphs carefully to fully describe the patterns shown
- Comment on the sources provided – how reliable do you think they are?
- Provide a context to your analysis by discussing any global trends









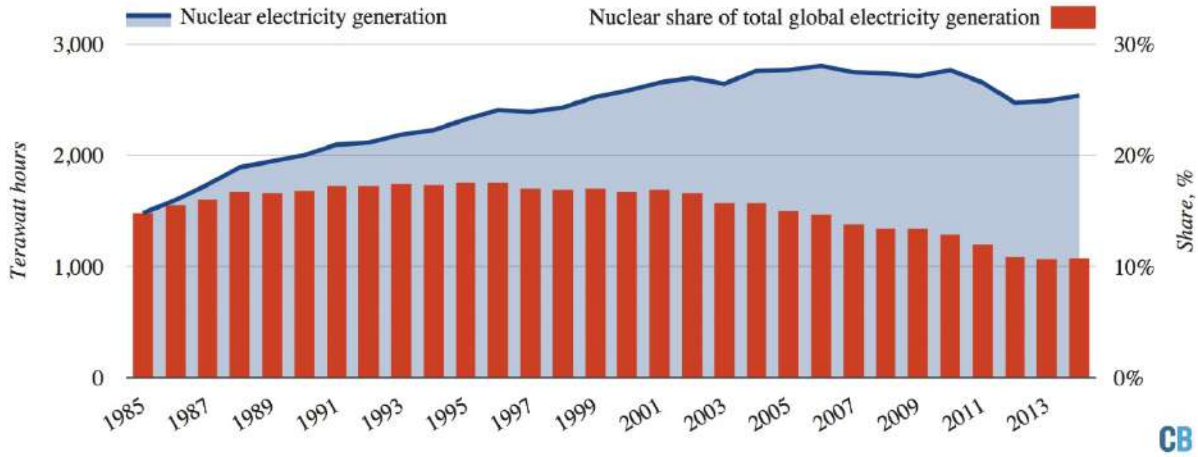
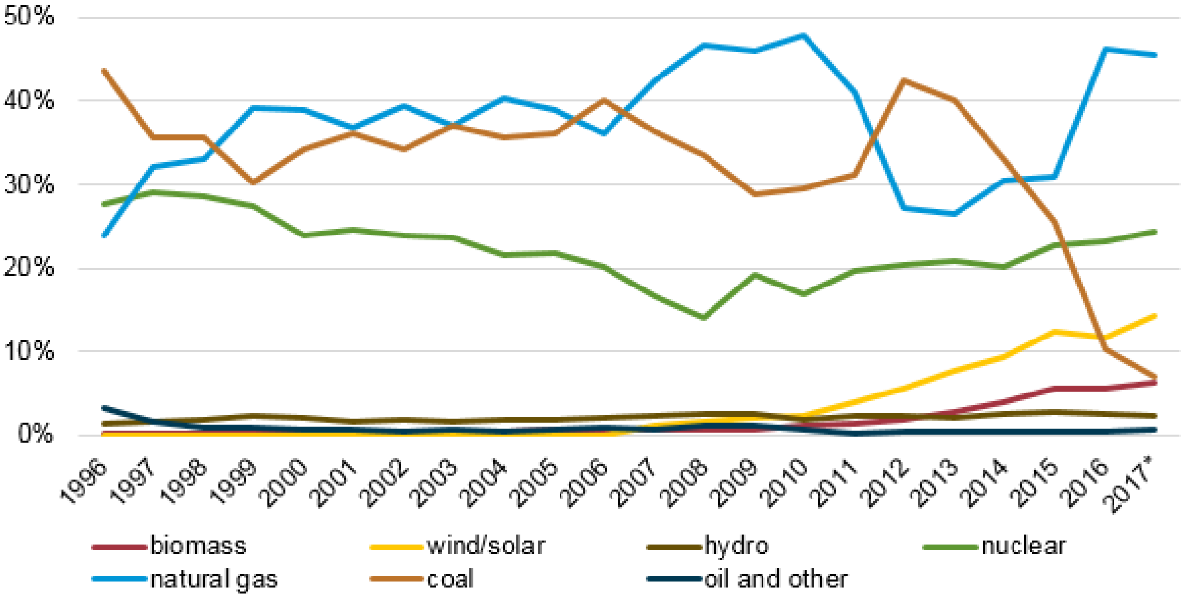


Figure 12. United Kingdom electricity generation share by fuel source



* note 2017 values are estimates based on data through September

Source: U.S. Energy Information Administration based on Digest of UK Energy Statistics and National Statistics: Energy Trends

Task 3: Presenting Data

For each set of data below, display the information on an appropriate graph.

Data set 1:

Table 2: Mass of balls and diameters of crater formed

	mass(±0.01g)	Diameter of crater(±0.1cm)					Average diameter(±0.2cm)
ball1	27.92	8.0	8.0	8.3	8.4	8.3	8.2
ball2	46.53	9.3	9.4	9.3	9.1	9.4	9.3
ball3	65.37	9.7	9.4	9.5	9.5	9.7	9.6
ball4	105.44	9.9	10.5	10.2	9.9	10.4	10.2
ball5	112.01	10.6	10.6	10.8	10.5	10.6	10.6
ball6	136.74	10.7	10.7	10.9	10.9	11.4	10.9
ball7	174.45	11.2	11.4	11.6	11.2	11.2	11.3

Table 2: The largest average deviation of the trials was used as the uncertainty of the average diameter.

Data set 2:

Length of wire (cm)	Volts (Volts)			Current (amps)			Resistance (ohms)		
	1	2	3	1	2	3	1	2	3
10	0.47	0.47	0.47	0.24	0.23	0.23	1.96	2.04	2.04
20	0.6	0.59	0.58	0.16	0.17	0.17	3.75	3.47	3.41
30	0.65	0.64	0.64	0.14	0.13	0.13	4.64	4.92	4.92
40	0.69	0.69	0.68	0.11	0.11	0.11	6.27	6.27	6.18
50	0.72	0.72	0.72	0.1	0.09	0.08	7.2	8	9.13
60	0.76	0.76	0.76	0.07	0.07	0.07	10.9	10.9	10.9
70	0.82	0.82	0.82	0.06	0.06	0.06	13.67	13.67	13.67

Data set 3:

Angle between the spring gun and the horizon (degrees)	Range (meters)
20	6.4
30	8.6
40	9.8
50	9.6
60	8.7
70	6.3
80	3.4

Data set 4:

Table 1		
Velocity of Sound in Various Media		
Media	Density (kg per cubic meter)	Velocity (m/s)
Air	1.0	343.0
Pure Water	1,000.0	1,493.0
Sea Water	1,020.0	1,533.0
Glass	2,600.0	4,540.0
Iron	7,870.0	5,130.0
Lead	11,350.0	1,158.0

Data set 5:

Table 2		
Velocity of Sound in Water		
Temperature (°C)	Density (kg per cubic meter)	Velocity (m/s)
0	999.8395	1,402.39
10	999.7026	1,447.28
20	998.2071	1,482.36
30	995.6502	1,509.14
40	992.2	1,528.88
50	988.04	1,542.57
60	983.2	1,552.00
80	971.8	1,555.00
100	958.37	1,543.05

In questions 17 to 32, $a = 4, b = -2, c = -6$

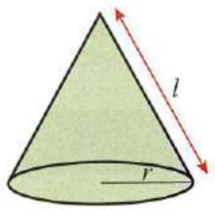
17 $\frac{1}{4}bc$	18 $3b$	19 c^2	20 $\frac{2}{9}c^2$
21 $5a^2$	22 $(4b)^2$	23 $9b^2$	24 $a^2 + c^2$
25 $ab + c$	26 $\frac{1}{3}bc - \frac{1}{2}a$	27 $\frac{1}{8}abc$	28 $\frac{3a}{2b}$
29 $\frac{c}{b} + \frac{5a}{2b}$	30 $(2a)^2 - \frac{1}{2}a^2$	31 $b^2(2a - c)$	32 $\frac{1}{2}(a - b) - \frac{1}{3}c$

In questions 33 to 48, $x = -3, y = 5, z = -1$

33 $z(2x + y)$	34 $x^2 - \frac{1}{4}z$	35 $\frac{1}{3}x^2 + 2x$	36 $\frac{3}{5}y^2 - 2x^2$
37 z^3	38 $x^2(2y + 3z)$	39 $\frac{4y + 2x^2}{z^2}$	40 $x^2(y^2 - z^2)$
41 $z^2 - 3z + 2$	42 $\frac{2}{3}x^3 + z^3$	43 $\frac{2y - 5z}{5x}$	44 $\frac{x(x^2 - z)}{3y}$
45 $\frac{(2x)^2 + z}{y}$	46 $(2x + 4z)(3y + z)$	47 $x^3z^3(x^2 - z)$	48 $\frac{4}{5}xy + \frac{2}{3}xz$

M Formulas

M4.2

1 

The surface area A of a cone is roughly given by the formula

$$A = 3rl$$

Find the value of A when

(a) $r = 2, l = 10$ (b) $r = 5, l = 3$ (c) $r = 8, l = 5$

2 The position P of the middle value of some numbers is found from the formula

$$P = \frac{1}{2}(n + 1)$$

where n is how many numbers there are.

Find P when (a) $n = 7$ (b) $n = 99$

3 The interest I made by some money P is given by the formula

$$I = \frac{PTR}{100}$$

where T is the time and R is the rate of interest. Find the value of I when

(a) $P = 800, T = 2, R = 5$ (b) $P = 40, T = 5, R = 8$

4 

The volume V of an orange is roughly given by the formula

$$V = 4r^3$$

where r is the radius of the orange.

Find the value of V when (a) $r = 5$ (b) $r = 10$

5 A ball is dropped. The distance s it travels is given by the formula

$$s = 4.9t^2$$

where t is the time taken.

Find the value of s when

(a) $t = 10$ (b) $t = 2$

6 The temperature in degrees Fahrenheit F can be changed into degrees Centigrade C by using the formula

$$C = \frac{5}{9}(F - 32)$$

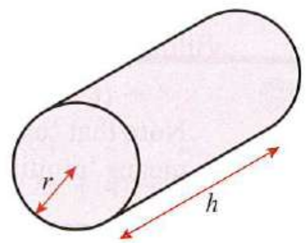
Find the value of C when

(a) $F = 50$ (b) $F = 68$

7 Using the formula $h = \sqrt{(a^2 - b^2)}$ find the value of h when

(a) $a = 13, b = 12$

(b) $a = 25, b = 24$

8 

The surface area A of a cylinder is roughly given by the formula

$$A = 6rh + 3r^2$$

Find the value of A when

(a) $r = 2, h = 5$

(b) $r = 4, h = 20$

Can you still?

Mixed

1. Some chocolates are shared between Gianna and Vitali in the ratio 3 : 7. Gianna gets 12 chocolates less than Vitali. Vitali eats two-thirds of his share. How many chocolates does Vitali now have?

2. Work out

   (a) $\frac{(-7)^2 + 11}{1 - (-4)}$

   (b) $\frac{(-2 - 3)^3 - 5^2}{2{\cdot}5^2 + 3{\cdot}75}$

3. An exterior angle of a regular polygon is 18°. Work out the sum of the interior angles.

4. Simplify

   (a) $\frac{(4m^2)^2}{8m^3}$

   (b) $\sqrt[3]{(8x^{12}y^9)}$

   (c) $\frac{(2y^3)^2}{(2y^2)^3}$

In questions 9 to 12, you may *use a calculator* if you wish.

9 The formula $v = \sqrt{u^2 + 2as}$ gives the final speed v of a car whose initial speed is u, acceleration is a and displacement is s. Find the value of v (to 3 significant figures if necessary) when

(a) $u = 10, a = 3, s = 7$
(b) $u = -3{\cdot}6, a = 9{\cdot}8, s = 15{\cdot}3$

10 The formula $s = vt - \frac{1}{2}at^2$ gives the displacement s of a particle after time t. The final speed is v and acceleration is a.
Find s (to 3 significant figures if necessary) when

(a) $v = 5, a = 3, t = 2$ (b) $v = 0, a = 9{\cdot}81, t = 1{\cdot}03$

11 The formula $A = \sqrt{s(s-a)(s-b)(s-c)}$ gives the area A of a triangle with sides a, b and c where s is half the perimeter.
Find the area A (to 2 significant figures if necessary) of the following triangles (by first finding and stating the value of s).

(a) $a = 3, b = 4, c = 5$ (b) $a = 7.8,\ b = 18.72,\ c = 20{\cdot}28$

12 The total resistance R in a circuit with resistors R_1 and R_2 in parallel is given by the formula

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

Find R in the following cases (to 3 significant figures if necessary).

(a) $R_1 = 2$ ohms and $R_2 = 2$ ohms
(b) $R_1 = 3$ ohms and $R_2 = 4$ ohms

M Multiplying out brackets

Multiply out $2(a + b)$ means $2 \times a$ add $2 \times b = 2a + 2b$

Expand $5n(2n + 3)$ means $5n \times 2n$ add $5n \times 3 = 10n^2 + 15n$

Note that 'expand' means 'multiply out'.

M4.3

1 Simplify:

(a) $4y \times 2$	(b) $6 \times 8x$	(c) $2a \times 4b$	(d) $c \times 5c$
(e) $7a \times 2a$	(f) $24x \div 4$	(g) $42n \div 6$	(h) $64p \div 8$
(i) $6c \times 9c$	(j) $3a \times 2b \times 2c$	(k) $-9y \times 4$	(l) $-4c \times 5d$
(m) $-6c \times -3d$	(n) $-9y \div 3$	(o) $28q \div -4$	(p) $-7p \times -5p$

In questions 2 to 10, answer 'true or false'.

2 $3 \times a = a \times 3$	**3** $3a - a = 3$	**4** $8n \times 4n = 32n^2$
5 $4n + 4n = 8n^2$	**6** $2 \times 3n = 5n^2$	**7** $10a \div 2 = 5a$
8 $a \times 3a = 3a^2$	**9** $a + a^2 = a^3$	**10** $12p \div 3 = 9p$

Multiply out

11 $2(a + 3)$	**12** $6(4x - 2)$	**13** $7(3x - 5)$	**14** $5(a - b)$
15 $7(3x + y)$	**16** $6(3x + 2)$	**17** $4(p + 2q)$	**18** $9(4c + 8d)$
19 $x(2x + y)$	**20** $a(b + a)$	**21** $c(2c + d)$	**22** $a(a - 7)$
23 $a(3a - 4)$	**24** $5x(y + 2)$	**25** $4a(a + 2b)$	**26** $6a(4b - 8c)$

Expand

27 $-2(x + 6)$	**28** $-3(a - 2)$	**29** $-5(c + 10)$	**30** $-4(3p - 5)$
31 $-3(2c + 4)$	**32** $-a(b + c)$	**33** $-p(2p + q)$	**34** $-a(a + b)$
35 $-x(2x - y)$	**36** $-m(m - n)$	**37** $-(2p + 5q)$	**38** $-6a(4 - 2b)$

Expand

39 $a(a^2 - 2b)$	**40** $x^2(4x + y)$	**41** $5b^2(2b + 3)$	**42** $3p(pq + 2p^2)$

M Expanding and simplifying brackets

(a) Simplify $2(3n + 1) + 3n$

multiply out brackets first

$= 6n + 2 + 3n$

now collect like terms

$= 9n + 2$

(b) Simplify $5(2a + 1) - 3(a - 2)$

$= 10a + 5 - 3a + 6$

⇧ Note

$= 7a + 11$

M4.4

Expand and simplify:

1 $2(x + 3) + 5$	**2** $5(2x + 1) + 3$
3 $4(3x + 2) + 2x$	**4** $9(2x + 3) - 14$
5 $3(2a + 4) - 2a$	**6** $9(3y + 2) - 6$

Expand and simplify:

7 $5(a + 2) + 2(2a + 1)$
8 $3(x + 4) + 6(x + 2)$
9 $6(x + 1) + 3(2x + 4)$
10 $3(4a + 8) + 2(a - 3)$
11 $7(2x + 3) + 4(3x + 1)$
12 $4(2d + 2) + 6(3d + 4)$

Can you still?

Mixed

1 Simplify (a) $\frac{4}{\sqrt{2}}$ (b) $\frac{(5 + \sqrt{2})(5 - \sqrt{2})}{(\sqrt{3} + \sqrt{2})(\sqrt{3} - \sqrt{2})}$

2 A population of 900 increases by 10% then decreases by 10% of its current size. How large is the population now?

3 Evaluate (a) 6^{-2} (b) $9^{-\frac{1}{2}}$ (c) $64^{\frac{1}{3}}$

Simplify

13 $3(4a + 2) - 2(a - 2)$ **14** $5(3x + 1) - 3(3x + 2)$ **15** $6(2x + 3) - 4(2x + 2)$

16 $5(3a + 2) - 3(2a + 1)$ **17** $3(4d + 1) - 2(6d - 5)$ **18** $7(2c + 6) - 4(c + 5)$

Expand and simplify:

19 $9y - 5(y + 2) - 3$ **20** $11x + 2 - 3(2x - 5)$ **21** $6a + 2(3a + 1) - 7 + 2a$

22 $15(n + m) - 6(2n - m)$ **23** $8(2a + b) - 3(3a + 2b)$ **24** $8x + 6(2 - x) + 2(3x + 5)$

Simplify:

25 $a(3a + 2) + 5a(2a + 1)$ **26** $4x(3x + 2) - 3x(x - 3)$

27 $2y(4y + 5) - 5y(y + 2)$ **28** $3a(a + 2b) + 2b(5a + 2b)$

29 $4m(3m + 2p) - 3m(p - 2m)$ **30** $6x(2x + 3y) - 3x(x - 4y)$

31 $5a(a + 2b) + 4b(3a - c)$ **32** $7x(2x + 3y + z) - 3y(3x - 2z)$

M Multiplying out 2 brackets

Key Facts

Each term in one bracket must be multiplied by each term in the other bracket.

Consider $(a + b)(c + d)$.

F $(a + b)(c + d)$ multiply the First terms in each bracket → ac

O $(a + b)(c + d)$ multiply the Outer terms in each bracket → $+ ad$

I $(a + b)(c + d)$ multiply the Inner terms in each bracket → $+ bc$

L $(a + b)(c + d)$ multiply the Last terms in each bracket → $+ bd$

First
Outer
Inner
Last

Follow this order each time to make sure you do not miss any terms → $(a + b)(c + d) = ac + ad + bc + bd$

(a) Expand $(x + 5)(x - 2)$

$(x + 5)(x - 2)$

F O I L

$= x^2 - 2x + 5x - 10$

these middle 2 terms can be collected together

$= x^2 + 3x - 10$

(b) Expand $(2x + 3)(5x - 1)$

$(2x + 3)(5x - 1)$

$= 10x^2 - 2x + 15x - 3$

$= 10x^2 + 13x - 3$

(c) Expand $(x - 5)^2$

$(x - 5)(x - 5)$

$= x^2 - 5x - 5x + 25$

$= x^2 - 10x + 25$

WARNING!

$(x - 5)^2$ is **not** $x^2 - 25$ or $x^2 + 25$

Similarly

$(x + 4)^2$ is **not** $x^2 + 16$

M4.5

1 Copy and complete the following.

(a) $(x + 3)(x + 4)$
$= x^2 + 4x + \square + 12$
$= x^2 + \square + 12$

(b) $(a - 5)(a + 3)$
$= \square + 3a - 5a - \square$
$= \square - 2a - \square$

(c) $(m - 7)^2$ $(m - 7)(m - 7)$
$= m^2 - \square - \square + \square$
$= m^2 - \square + \square$

Expand the following:

2 $(x + 2)(x + 6)$ **3** $(p + 1)(p + 5)$ **4** $(a + 3)(a + 7)$

5 $(m + 3)(m - 1)$ **6** $(y + 2)(y - 6)$ **7** $(n - 5)(n + 2)$

8 $(b - 8)(b + 3)$ **9** $(x - 6)(x + 8)$ **10** $(c - 8)(c - 3)$

11 $(q - 2)(q - 7)$ **12** $(f - 2)(f - 10)$ **13** $(a + 9)(a - 4)$

Multiply out the following:

14 $(2x + 1)(3x + 4)$ **15** $(5y + 2)(y + 3)$ **16** $(4p + 2)(2p + 7)$

17 $(3a - 4)(5a + 2)$ **18** $(6f - 1)(2f + 3)$ **19** $(9y - 4)(4y - 2)$

20 $(3x - 4)(7x + 2)$ **21** $(3q - 4)(7q - 1)$ **22** $(4b - 3)(5b - 3)$

23 $(4z - 6)(2z - 3)$ **24** $(x + 7)(4x - 9)$ **25** $(6a - 5)(5a + 4)$

Expand the following:

26 $(x + 6)(x + 6)$ **27** $(x + 5)^2$ **28** $(a + 10)^2$

29 $(y - 1)^2$ **30** $(p - 3)^2$ **31** $(b - 9)^2$

32 $(2a - 1)^2$ **33** $(5x + 4)^2$ **34** $(3y - 5)^2$

13 Copy and complete

$3(3x + 4) = 4(2x - 2)$

$9x + 12 = \square - 8$

$9x - \square = -8 - 12$

$x = \square$

14 Copy and complete

$5(2n - 1) - 6(n + 1) = 1$

$10n - \square - 6n - \square = 1$

$10n - 6n = 1 + \square + \square$

$\square = \square$

$n = \square$

Solve the following equations:

15 $7(x - 1) = 2(2x + 4)$

16 $8(w - 3) = 4(3 - w)$

17 $3(a + 2) = 4(1 - a)$

18 $3(2n + 1) = 4(7 - n)$

19 $5(2 - p) = 2(4 + 2p)$

20 $2(3 - 2m) = 5(2 - m)$

21 $4(a - 2) = 3(a + 3) - 4$

22 $3(2q + 3) + 4(q - 2) = 8$

23 $6(2x + 5) + 3(2 - 3x) = x$

24 $5(c - 2) + 1 = 3(c - 1)$

25 $7(2h + 1) - 1 = 5(3h + 2)$

26 $2(4w - 3) - 7(2w - 7) = 1$

27 $4(2y + 1) - 9(y - 1) = 3$

28 $3(x + 1) + 1 = 2(2x + 1) - 3$

29 $2(b + 1) + 1 = 3(3b - 5) - 10$

30 $\frac{1}{6}(x - 14) = 2(x - 3)$

31 $\frac{1}{2}(4y + 1) - \frac{3}{4}(2y + 3) = \frac{3}{4}$

32 $\frac{1}{3}(2w - 5) + \frac{1}{6}(w - 4) = 1$

Mixed linear equations

Solve the following equations:

(a) $\frac{2x - 1}{3} = 5$

$2x - 1 = 5 \times 3$ [multiply both sides by 3]

$2x - 1 = 15$

$2x = 16$

$x = 8$

(b) $\frac{5}{x} = -2$

$5 = -2x$ [multiply both sides by x]

$x = \frac{5}{-2}$ [divide both sides by -2]

$x = -2{\cdot}5$

(c) $\frac{x - 3}{x + 2} = 7$ [multiply both sides by $(x + 2)$]

$x - 3 = 7(x + 2)$ [multiply out brackets]

$x - 3 = 7x + 14$

$-3 - 14 = 7x - x$

$-17 = 6x$

$x = -2\frac{5}{6}$

M6.3

Solve the following equations:

1 $\frac{x + 5}{4} = 5$

2 $\frac{n + 9}{3} = 7$

3 $\frac{1}{3}a + 2 = 7$

4 $\frac{x - 8}{2} = 5$

5 $\frac{1}{6}w - 8 = 1$

6 $2 = \frac{m - 10}{3}$

7 $5 - \frac{1}{4}z = 2$

8 $\frac{3m - 1}{5} = 4$

9 $8 = \frac{1}{7}(6b + 2)$

Copy and complete:

10 $\frac{16}{x} = 3$

$16 = \square$

$x = \frac{\square}{\square}$

$x = \square\frac{\square}{\square}$

11 $\frac{12}{x - 2} = 4$

$12 = \square(x - 2)$

$12 = \square - \square$

$12 + \square = \square$

$\square = \square$

$x = \square$

12 $\frac{3x + 2}{x + 4} = 5$

$3x + 2 = \square(x + 4)$

$3x + 2 = \square + \square$

$2 - \square = \square - 3x$

$-\square = \square$

$x = \square$

Solve the following equations:

13 $\frac{15}{a} = 3$

14 $\frac{24}{x + 1} = 6$

15 $\frac{36}{x - 2} = 4$

16 $\frac{18}{m - 8} = 3$

17 $4 = \frac{5}{a}$

18 $\frac{13}{m} = 6$

19 $-5 = \frac{9}{n}$

20 $\frac{3c + 1}{5} = 2$

21 $\frac{1}{3}(4x - 3) = 7$

22 $\frac{x + 1}{x - 3} = 3$

23 $\frac{2a + 1}{a - 4} = 5$

24 $\frac{3m - 2}{m - 6} = 7$

25 $\frac{5w - 3}{w - 2} = 6$

26 $\frac{4b + 1}{b + 3} = 3$

27 $\frac{5}{n} - 4 = 4$

28 $\frac{3}{f} + 7 = 9$

29 $6(a - 2) = 4(2a + 1)$

30 $\frac{1}{9}x + 7 = 10$

31 $5(2p + 3) + 2(3p + 5) = 33$

32 $\frac{7}{3m} = 1$

33 $8(a - 2) = 5(2a + 3) + 3(a - 4)$

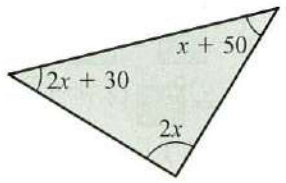
M Setting up linear equations

Many problems can be solved by writing them as linear equations first.
The unknown quantity is often chosen to be x.

> The sum of four consecutive numbers is 42. Let the first number be x and write down the other three numbers in terms of x. Find the four numbers.
> Other three numbers are $(x + 1)$, $(x + 2)$ and $(x + 3)$.
>
> Sum is 42 so $x + (x + 1) + (x + 2) + (x + 3) = 42$
>
> $$4x + 6 = 42$$
> $$4x = 36$$
> $$x = 9$$
>
> The four numbers are 9, 10, 11 and 12.

M6.4

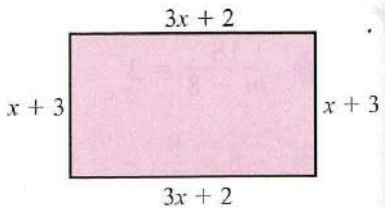
1



(a) Write down an equation using the angles.
(b) Find x.
(c) Write down the actual value of each angle in this triangle.

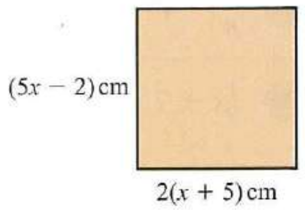
2 The sum of four consecutive numbers is 78. Let the first number be x. Set up an equation to find x then find the four numbers.

3 The perimeter of this rectangle is 58 cm.
(a) Write down an equation using the perimeter.
(b) Find x.
(c) Write down the actual length and width of the rectangle.



4 A rectangle has its length twice its width. If its perimeter is 42 cm, find the width of the rectangle.

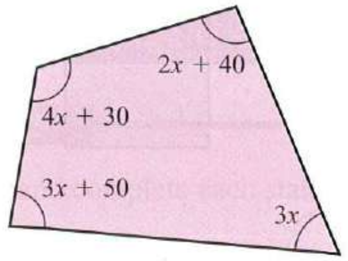
5



Work out the actual perimeter of this square.

6 £190 is divided between Jack and Halle so that Jack receives £72 more than Halle. How much does each person get? (Hint: Let x = Halle's money.)

7



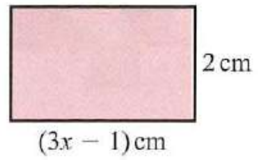
(a) Write down an equation using the angles.
(b) Find x.
(c) Write down the actual value of each angle in this quadrilateral.

8 The length of a rectangle is 3 times its width. If the perimeter of the rectangle is 32 cm, find its length and width.

9 A triangle has 2 angles which are each 4 times the size of the third angle. Find the size of each angle.

10 The sum of four consecutive odd numbers is 216.
(a) If x is the smallest number, write down the other numbers in terms of x.
(b) Find the actual numbers.

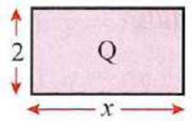
11



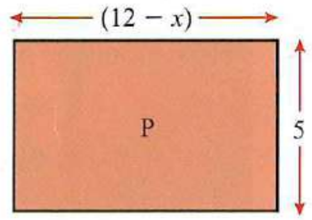
The area of the rectangle is 46 cm². Find the perimeter of the rectangle.

12 You have three consecutive *even* numbers so that the sum of twice the smallest number plus three times the middle number is four times the largest number. Find the three numbers.

13



The area of rectangle P is five times the area of rectangle Q. Find x.



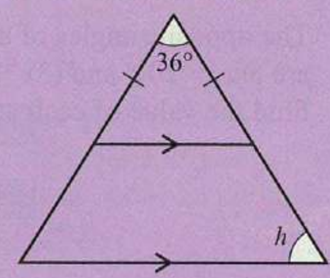
Can you still?

Mixed

1 Evaluate
(a) 2^{-1} (b) 3^{-2} (c) $\left(\frac{1}{9}\right)^{-\frac{1}{2}}$

2 Factorise
(a) $ac - bc - ad + bd$
(b) $12x^2 - x - 6$

3 Find the value of angle h.

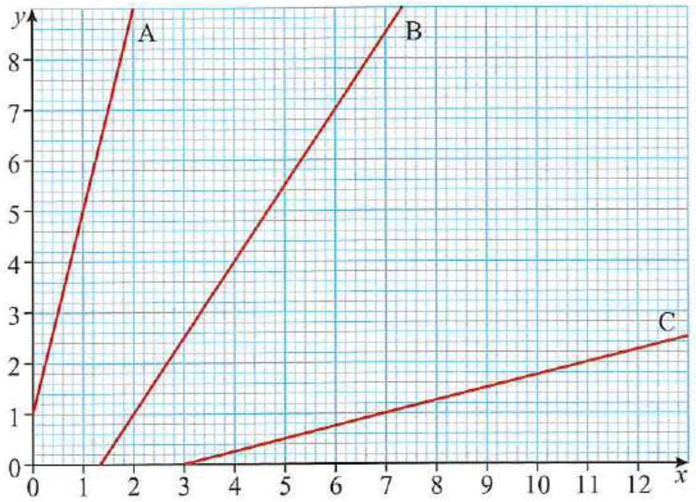


4 AB $= \frac{1}{4}$ cm and CD $= \frac{2}{3}$ cm.
Write down the ratio AB:CD in the form $m:n$ where m and n are integers.

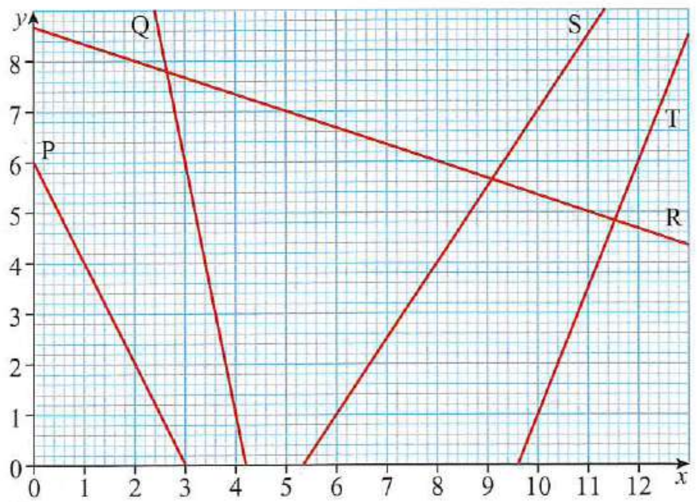
5 Solve $8^{\frac{x}{2}} = 32$

M6.12

1 Find the gradient of each line below:



2 For each line below, find the rate of change of y as x varies.



3 Find the gradient of the line joining each pair of points below:

(a) (1, 1) and (3, 5) (b) (2, 4) and (3, 7) (c) (3, 6) and (5, 2)

(d) (3, 1) and (5, 4) (e) (1, 4) and (3, 2) (f) (0, 5) and (2, 4)

(g) (5, 2) and (7, 3) (h) (−1, 2) and (2, 7) (i) (5, −2) and (9, −2)

(j) (−2, −3) and (1, −5) (k) (−4, 6) and (2, 5) (l) (1, 2) and (1, −5)

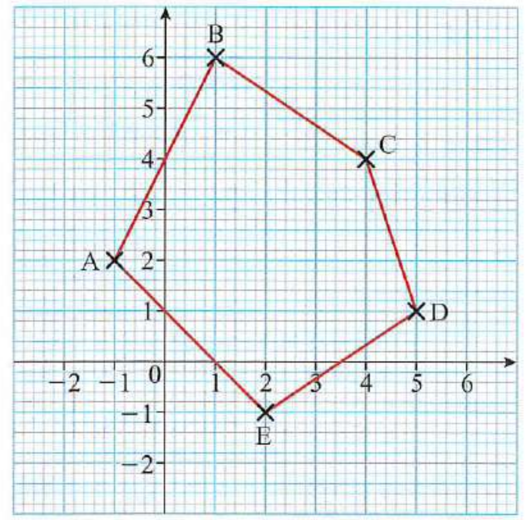
(m) $\left(\frac{1}{4}, 2\right)$ and $\left(\frac{2}{3}, 4\right)$ (n) $\left(-\frac{1}{3}, \frac{1}{2}\right)$ and $\left(\frac{1}{2}, -\frac{1}{4}\right)$ (o) $\left(\frac{2}{5}, -\frac{1}{3}\right)$ and $\left(-\frac{1}{4}, \frac{1}{5}\right)$.

4 Find the gradient of the line joining:

(a) B and C

(b) C and D

(c) A and E.



5 A line has a gradient of 6. One point on the line is (−2, 5). A point P on the line has an x-value of 1. What is the y-value at P?

6 A line shows that the rate of change of y as x varies is −4. One point on the line is (3, 7). A point Q on the line has a y-value of −5. What is the x-value at Q?

M $y = mx + c$

M6.13

Use a graphical calculator or computer if possible.

1 (a) Complete the table opposite then draw the straight line $y = 2x + 3$.

x	1	2	3
y			

(b) Use another table to draw $y = 2x$ on the same grid.

(c) Draw $y = 2x + 1$ on the same grid.

(d) Draw $y = 2x - 1$ on the same grid.

(e) Find the gradient of each line.

(f) What do you notice about the gradient of each line and its equation?

(g) Look at where each line cuts the y-axis. For each line what do you notice about this value and its equation?

2 Draw the following lines using the same set of axes and repeat parts (e), (f) and (g) from question **1**:

$y = -3x + 1$ $y = -3x + 4$ $y = -3x$

$y = -3x - 2$ $y = -3x - 5$

Key Facts

The equation of a straight line may be written in the form

$$y = mx + c$$

m is the gradient of the line

c is the *y*-value at the point where the line cuts the *y*-axis. This is known as the '*y-intercept*'

$y = mx + c$ is sometimes known as the 'gradient–intercept' form of the straight line.

(a) Write down the gradient and *y*-intercept of $y = \frac{1}{2}x - 3$

Gradient $= \frac{1}{2}$ *y*-intercept $= -3$

(b) Write down the gradient of $2x + 3y = 1$ and write down the co-ordinates of the point where the line cuts the *y*-axis.

rearrange into form $y = mx + c$

$$2x + 3y = 1$$

$$3y = -2x + 1$$

write the *x*'s first

$$y = -\frac{2}{3}x + \frac{1}{3}$$

Gradient $= -\frac{2}{3}$ and the line cuts the *y*-axis at $\left(0, \frac{1}{3}\right)$.

(c) Find the equation of the line which passes through (3, 1) and (6, 13).

Find gradient *m* first $m = \frac{13 - 1}{6 - 3} = \frac{12}{3} = 4$

We know $y = mx + c$ so $y = 4x + c$

$x = 3$ when $y = 1$

To find *c*, substitute one pair of *x* and *y* values into the equation of the line

so $1 = 4 \times 3 + c$

$1 = 12 + c$

$c = -11$

Equation of line is $y = 4x - 11$.

M6.14

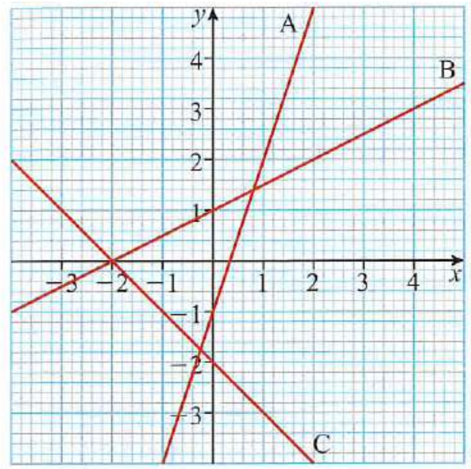
Write down the gradient and *y*-intercept of each of the following lines:

1 $y = 3x + 4$	**2** $y = 2x - 5$	**3** $y = 8x - 1$	**4** $y = x + 6$
5 $y = -4x - 2$	**6** $y = -4x + 3$	**7** $y = -x - 2$	**8** $y = -5x + 2$
9 $y = 3 - x$	**10** $y = 4 - 2x$	**11** $y = \frac{1}{3}x - 7$	**12** $y - 5x = 1$
13 $y + 4x = 5$	**14** $6x - y = 3$	**15** $2x + 5y = 3$	**16** $3x - 4y = 6$
17 $5x - 3y = 3$	**18** $4y - 2 = 5x$	**19** $4x + y - 6 = 0$	**20** $5x - 7y - 2 = 0$

Use your knowledge of $y = mx + c$ to *sketch* each of the following lines:

21 $y = 2x + 2$	**22** $y = 5 - x$	**23** $y - 3x = 1$	**24** $2x + 4y = 3$

25 Write down the equation of each of the 3 lines below:



26 Which of the following lines are parallel?

(a) $y = 4x + 1$	(b) $y = 2 - 4x$	(c) $y = 2x + 4$
(d) $y - 4x = 2$	(e) $4x - y = 2$	(f) $y = 4 - 3x$

Find the equation of each line in questions **27** to **36**.

27 The line passes through (0, 4) with gradient = 5.

28 The line passes through (0, 2) with gradient = −4.

29 The line passes through (3, 5) with gradient = 3.

30 The line passes through (5, −1) with gradient = 1.

Find the equation of the line passing through each pair of points below, giving the answer in the form $y = mx + c$.

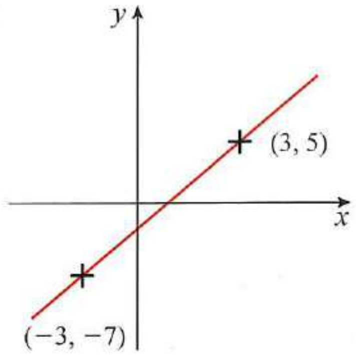
31 (3, 2) and (5, 8)	**32** (6, 1) and (8, 9)	**33** (−3, 4) and (−1, 10)
34 (5, −3) and (8, −9)	**35** (−2, −4) and (−5, −25)	**36** (1, −7) and (−3, 5)

37 Find the equation of the line that is parallel to the line $y = 4x - 3$ and passes through (3, 2).

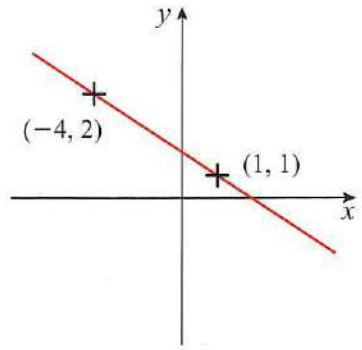
38 Find the equation of the line that is parallel to the line $2x + y = 1$ and passes through (1, −4).

39 Find the equation of each line below:

(a)



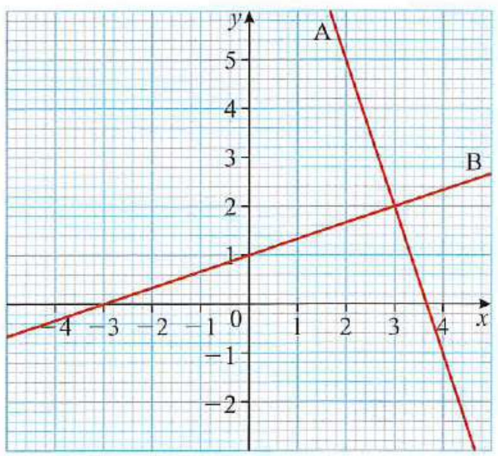
(b)



E Gradients of perpendicular lines

E6.7

1



Line A and Line B above are perpendicular (at right angles).

(a) Find the gradient of line A.

(b) Find the gradient of line B.

(c) *Multiply* together the gradient of line A and the gradient of line B.

Can you still?

Mixed

1 Carl and Dan earn the same amount each week. Carl gets a 5% pay rise and now earns £477·75.
Dan only gets a 3% pay increase. How much does Dan earn now?

2 Simplify $\frac{4}{\sqrt{2}} + \sqrt{18}$

3 P is directly proportional to the square root of Q.
$P = 12$ when $Q = 9$.
Find the value of P when $Q = 36$.

4 Expand $(x + 4)^2$

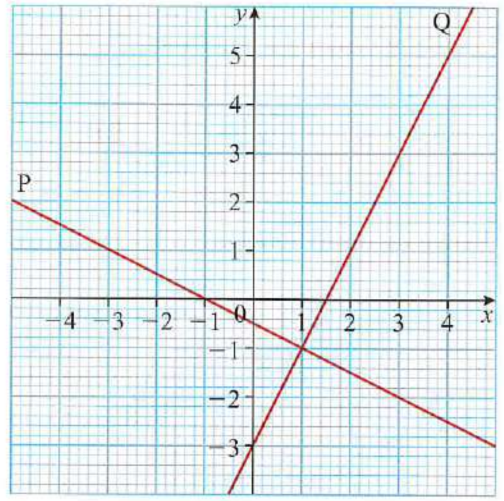
5 Truncate 7·81932 to two decimal places.

2 Line P and line Q are perpendicular (at right angles).

(a) Find the gradient of line P.

(b) Find the gradient of line Q.

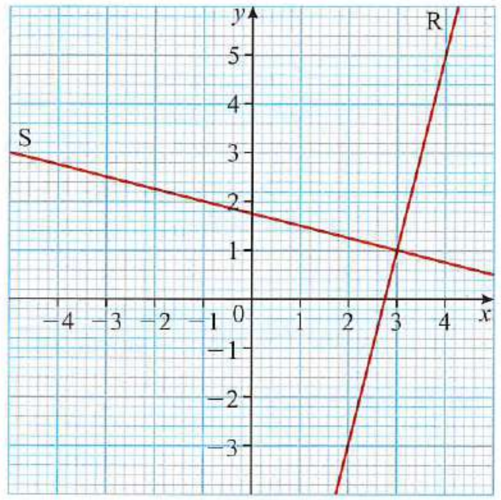
(c) Find the *product* of the gradient of line P and the gradient of line Q.



3 What do you notice about your answers to part (c) in both questions 1 and 2?

4 If a line has a gradient of 4, what is the gradient of a line perpendicular to this one?

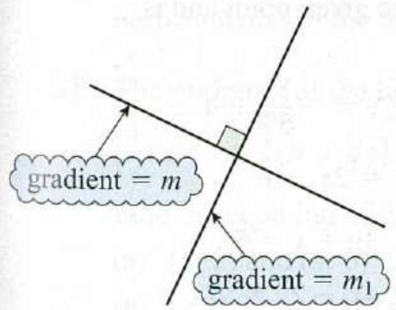
5



Line R has a gradient of 4.
Line S is perpendicular to line R.

Find the gradient of line S to check if your answer to question 4 was correct.

Key Facts



The product of the gradients of two perpendicular lines is −1

$$m\,m_1 = -1 \quad \text{so} \quad m = -\frac{1}{m_1}$$

Given a line with gradient $= m_1$, to find the gradient of a perpendicular line, find the reciprocal of m_1 $\left(\text{i.e. } \frac{1}{m_1}\right)$ then change its sign $\left(\text{i.e. } -\frac{1}{m_1}\right)$.

Write down the gradient of a line which is perpendicular to a line of gradient (a) -5, (b) $\frac{2}{3}$

(a) $-\frac{1}{m_1} = \frac{-1}{-5} = \frac{1}{5}$ (b) $-\frac{1}{m_1} = \frac{-1}{2/3}\,\frac{(\times 3)}{(\times 3)} = -\frac{3}{2}$ (the simplest way is to turn the fraction upside down and change the sign)

E6.8

1 Find the gradient of the line which is perpendicular to a line with each gradient given below:

(a) 7   (b) 1   (c) -4 (d) -8 (e) $\frac{1}{3}$ (f) $\frac{2}{5}$

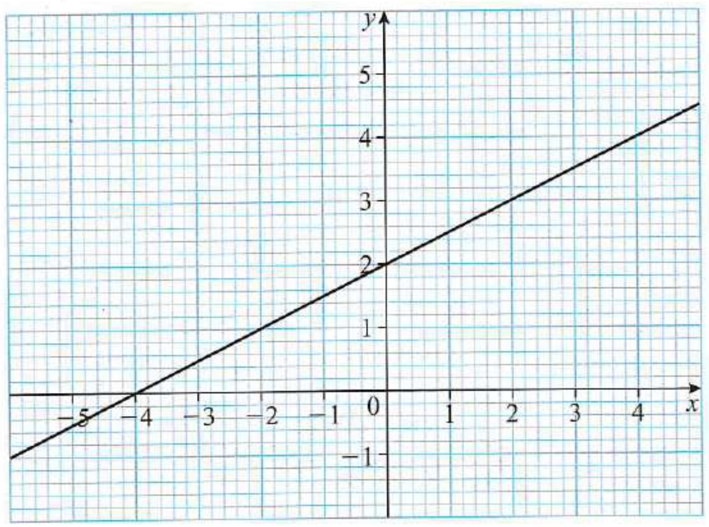
(g) $-\frac{1}{6}$ (h) $-\frac{3}{4}$ (i) $-\frac{9}{2}$ (j) $-0{\cdot}5$ (k) $0{\cdot}2$ (l) 0

2 Write down the gradient of any line which is perpendicular to:

(a) $y = 3x - 2$ (b) $y = -\frac{2}{3}x + 7$ (c) $5x + 8y = 3$

(d) $4y = x + 7$ (e) $6x - 2y = 3$ (f) $3x + 5y - 1 = 0$

3



Find the equation of the line which passes through (2, 1) and is perpendicular to the line shown.

4 Find the equation of the line which passes through the given point and is perpendicular to the given line.

(a) (0, 3) $y = \frac{1}{3}x + 6$ (b) (0, -2) $y = -\frac{1}{5}x + 4$

(c) (1, 1) $y = 8 - \frac{1}{4}x$ (d) (2, 5) $y = 2x - 1$

(e) (1, 4) $2y - x = 3$ (f) (-6, 2) $3y + x = 5$

(g) (-3, -3) $3x + y = 7$ (h) (4, -1) $4x - 2y = 9$

(i) (-1, 6) $x + y - 6 = 0$ (j) (-4, -3) $6x + 3y - 5 = 0$

5 A line passes through (3, 0) and is parallel to the line $y = 5x - 3$. Find the equation of the line.

6 Line P has equation $5y - 2x = 13$.
Line Q has equation $2y + 5x = 7$.
Show that line P is perpendicular to line Q.

7 Without drawing any of these lines, put them into pairs of lines which are perpendicular to one another.

(a) $3y - 2x = 7$ (b) $y = -\frac{1}{3}x + 5$

(c) $2y + x = 9$ (d) $5y + x = 9$

(e) $3x + 2y = 11$ (f) $y = 2x + 1$

(g) $y = x + 3$ (h) $y - 3x = 10$

(i) $y = 5x - 1$ (j) $y = -x + 5$

8 A line passes through (2, 5) and is *parallel* to the line $x + 2y = 1$. Find the equation of the line.

9 Line A has equation $7y = 3x - 4$.
Line B has equation $3y = 5 - 7x$.
Show that line A is perpendicular to line B.

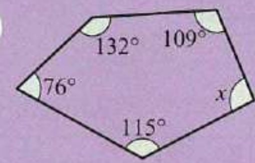
Can you still?

Mixed
Do not use a calculator

1 Draw a Venn diagram to show the prime factors of 42 and 112. Use the Venn diagram to find the HCF and LCM of 42 and 112.

2 Work out $(4 \times 10^{-19}) \times (8 \times 10^{7})$ leaving the answer in standard form.

3



Find the value of angle x.

4 Solve $x^2 - 6x + 8 = 0$

5 Solve $\frac{1}{3}(x - 1) = \frac{1}{6}x + 2$

6 Expand $(x + 2)^3$

10 Find the equation of the line which passes through (3, 2) and is perpendicular to the line which joins (-1, 0) to (3, 2).

11 The midpoint of the line joining (a, b) to (c, d) has co-ordinates given by $\left(\frac{1}{2}(a + c), \frac{1}{2}(b + d)\right)$.

Find the equation of the perpendicular bisector of the line joining:

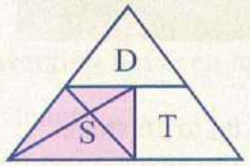
(a) (6, 2) and (4, 6)

(b) (-1, 3) and (4, 2)

(c) (2, 5) and (-4, 3)

(a) A car travels 100 miles in 2 hours 30 minutes. Find the speed in m.p.h.

Time must be in hours only: 2 hours 30 minutes = 2·5 hours.

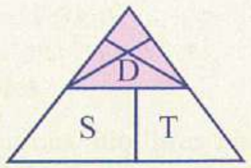


$$S = \frac{D}{T} = \frac{100}{2{\cdot}5} = 40 \text{ m.p.h.}$$

(b) Hazel runs at a steady speed of 8 m/s.

(i) How far does she travel in 4·3 s? (ii) What is her speed in km/h?

(i)



$D = S \times T$
$= 8 \times 4{\cdot}3$
$= 34{\cdot}4$ m

(ii) Speed = 8 m/s = $8 \times 60 \times 60$ metres per hour
$= \frac{8 \times 60 \times 60}{1000}$ km/h
$= 28{\cdot}8$ km/h

M10.3

1 A plane flies 480 km at 320 km/h. How long does the journey take?

2 A hiker walks 28·5 miles at 3 mph. How long does the hiker walk for?

3 Find the speed in mph for each of the following:

Distance	Time	Speed (mph)
30 miles	30 minutes	
9 miles	15 minutes	
15 miles	20 minutes	
6 miles	5 minutes	
30 miles	45 minutes	

4 Terry cycles at 16 mph for 30 minutes then slows down to 12 mph for 15 minutes. How far does he travel in total?

5 John walks at 6 km/h for 1 hour 30 minutes then 4 km/h for 2 hours 15 minutes. How far does he walk in total?

6 Sima drives 50 miles from Leeds to Manchester at an average speed of 40 mph. If she left Leeds at 10:20, when did she arrive at Manchester?

7 The speed of light is 300 000 000 m/s. How long will it take light to travel 6 000 000 km?

8 Convert the following speeds into km/h:

(a) 3 m/s (b) 20 m/s (c) 35 km/min (d) 78 cm/s

9 Convert the following speeds into m/s:

(a) 18 km/h (b) 115·2 km/h (c) 61 200 m/h (d) 0·408 km/min

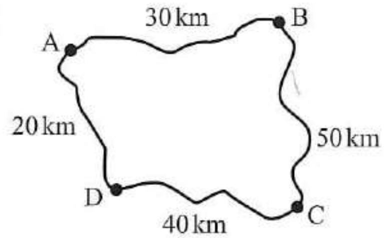
10 Two cyclists, Nerys and Ben, complete a race. Nerys has an average speed of 14·5 km/h and Ben has an average speed of 4 m/s. Who wins the race?

11 A car travels 80 km at an average speed of 50 km/h then travels 64 km at an average speed of 80 km/h. Find the average speed for the whole journey.

12 A plane travels 920 km at an average speed of 800 km/h. It then increases its speed by 50% and travels another 1020 km. Find the average speed for the whole journey.

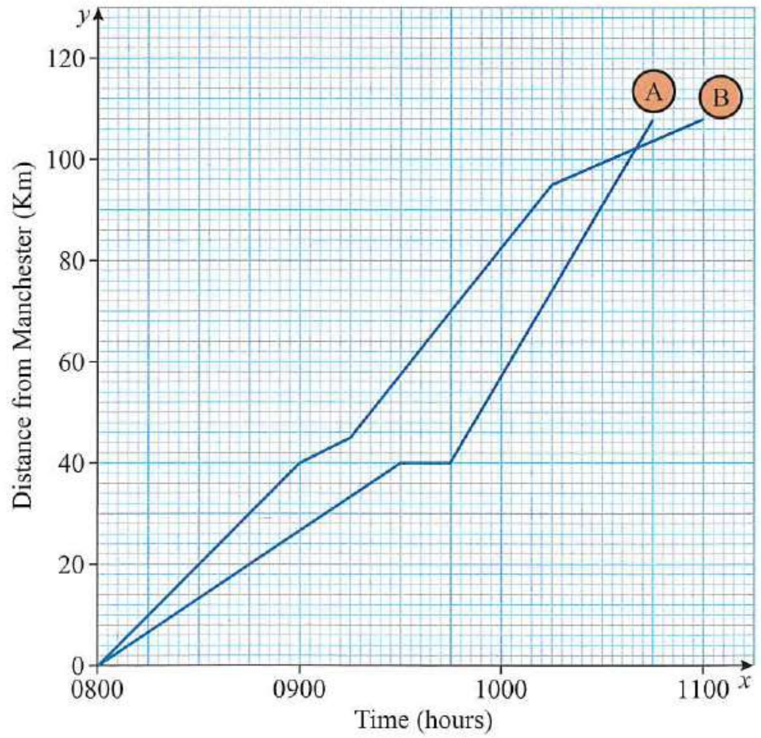
13 In a marathon race, Candice is 40 m behind Jess. Candice is running at 0·7 m/s but Jess is only running at 0.5 m/s. How long will it take Candice to catch up Jess?

14



Brooke travels from A to B at a steady speed of 45 km/h, from B to C at 60 km/h, from C to D at 36 km/h and from D to A at 60 km/h. Find Brooke's average speed for the whole journey.

15 The graph opposite shows the journeys of 2 cars from Manchester.



(a) How far from Manchester is car B at 10:30?

(b) At what time is car B 30 km from Manchester?

(c) Find the speed of car B in km/h between 09:00 and 09:15.

(d) Find the speed of car A in km/h between 09:45 and 10:45.

(e) Find the average speed of car B in m/s for the entire journey.

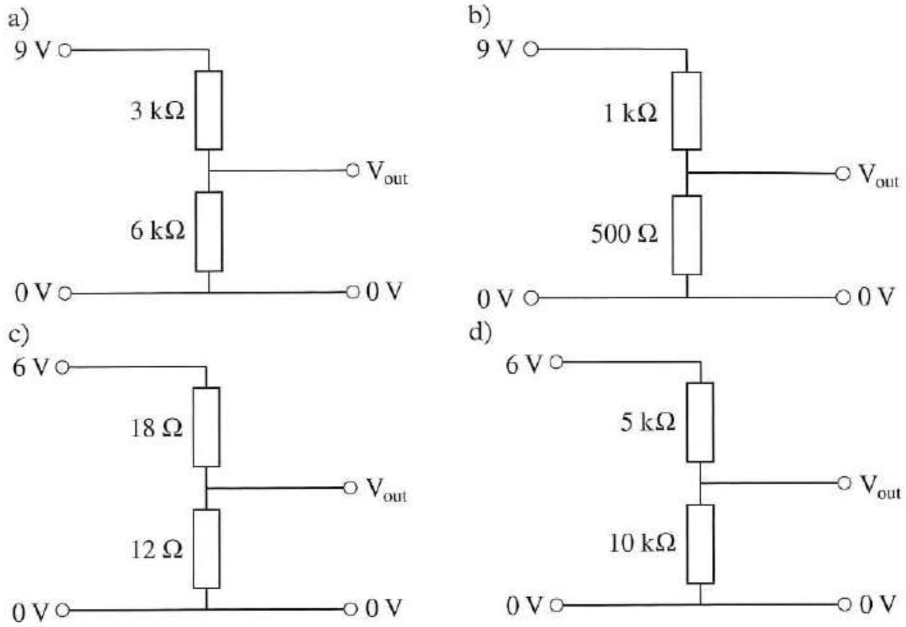
(f) Both cars travelled 108 km. Which car was the faster overall?

(g) Describe the journey of both cars.

KEY IDEA YOUTUBE VIDEO LINKS
Force and Motion Newtons laws: https://www.youtube.com/watch?v=NYVMlmL0BPQ **Newtons first law:** **https://www.youtube.com/watch?v=LEHR8YQNm_Q** **Newton's second law:** **https://www.youtube.com/watch?v=ZvPrn3aBQG8** **Newton's third law:** https://www.youtube.com/watch?v=MUgFT1hRTE4 Simulations of motion: http://phet.colorado.edu/sims/html/forces-and-motion-basics/latest/forces-and-motion-basics_en.html Distance-time graphs: https://www.youtube.com/watch?v=9LQdLDDEJ1g Calculating speed from d-t graphs: https://www.youtube.com/watch?v=JZD3WlqtRyo speed-time graphs and acceleration https://www.youtube.com/watch?v=3x22CpSB7zM worked examples of calculating acceleration https://www.youtube.com/watch?v=e6IOZb-03Zw
Momentum and energy Momentum **https://www.youtube.com/watch?v=wsVLU9A2TJM** **Gravitational potential energy and Kinetic Energy** **https://www.youtube.com/watch?v=MYwqb8m0jkM** Energy transfer diagrams/Sankey diagrams https://www.youtube.com/watch?v=NC8ltrcR2Ak Generating Electricity https://www.youtube.com/watch?v=hx_917HJiAI The National Grid https://www.youtube.com/watch?v=-1SLFzqLU5k Energy Resources **https://www.youtube.com/watch?v=SeXG8K5_UvU coal power 2min 12** https://www.youtube.com/watch?v=yGsPc3fptoY oil 4min18 **https://www.youtube.com/watch?v=f3S5UyBpymU gas 2min 03** **https://www.youtube.com/watch?v=_UwexvaCMWA nuclear 4min47** **https://www.youtube.com/watch?v=C1SDAgLn-tk biofuel 4min 56** https://www.youtube.com/watch?v=McByJeX2evM **electric mountain, wales,, 7min51 HEP** **https://www.youtube.com/watch?v=D67NnRjgJa0 solar power 6min32** **https://www.youtube.com/watch?v=D-OVU2RGNDo tidal power 6min03**
Waves https://www.youtube.com/watch?v=uWVS2aWy7KU
Light and em spectrum The E-M spectrum song https://www.youtube.com/watch?v=kOkv8ynpppk Tour of the E-M Spectrum https://www.youtube.com/watch?v=HPcAWNlVl-8 Refraction https://www.youtube.com/watch?v=7aU8sX8cFNs

Radioactivity https://www.youtube.com/watch?v=KYDil96NR5Q Uses of radioactivity https://www.youtube.com/watch?v=w0_VZuC4nfc Biological effects of radiation https://www.youtube.com/watch?v=EuKzI3g5ra4
Astronomy The Solar System https://www.youtube.com/watch?v=libKVRa01L8 Gravity and orbits https://www.youtube.com/watch?v=WUYWDjcFDro Life cycle of stars https://www.youtube.com/watch?v=NdmaprNK8yc Big Bang and red shift https://www.youtube.com/watch?v=KANnNIAIGAQ Evidence for the Big Bang https://www.youtube.com/watch?v=9f_i87aHKoo
Energy – forces doing work Work done and power https://www.youtube.com/watch?v=OyGG1Lm6L2Y Hooke’s Law https://www.youtube.com/watch?v=zJs27xNdKOM
Electricity https://www.youtube.com/watch?v=3YSH-RRoNWI Series and parallel circuits https://www.youtube.com/watch?v=zx2yqSQ-sWs Electrical Power https://www.youtube.com/watch?v=3UY2SFelMaI Plugs and Fuses https://www.youtube.com/watch?v=0OKTejgaWTY
Static electricity https://www.youtube.com/watch?v=V1c61Q7qU-s Dangers https://www.youtube.com/watch?v=FzsTamPPnHc
Magnetism and the motor effect, electromagnetism https://www.youtube.com/watch?v=dSNB-PsC2Vw
Particle model, forces and matter Specific heat capacity https://www.youtube.com/watch?v=6PXTHsD24Tw Specific latent heat https://www.youtube.com/watch?v=SzNAoyIGUeA Pressure https://www.youtube.com/watch?v=zlLpKzPz84Q Gas pressure https://www.youtube.com/watch?v=zvh9uv2Hxx4 Density https://www.youtube.com/watch?v=SimFy9wOMXY

3 For each of the following circuits, calculate the value of V_{out}.



4 A capacitor is discharged through a resistor. How can the discharge time be increased?

5 Outline the reasons why some people feel that privacy is no longer possible.

6 What types of job can a robot do well and what types of job does a human worker do better?

7 Some people think that mobile phones are dangerous. Why is this?

Examination questions

1 A student did an experiment with two strips of polythene. She held the strips together at one end. She rubbed down one strip with a dry cloth. Then she rubbed down the other strip with the dry cloth. Still holding the top ends together, she held up the strips.

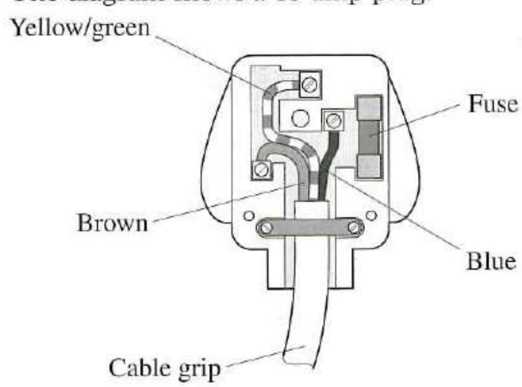
a) i) What movement would you expect to see? *(1 mark)*

ii) Why do the strips move in this way? *(2 marks)*

b) Copy and complete the **four** spaces in the passage.

Each strip has a negative charge. The cloth is left with a __________ charge. This is because particles called __________ have been transferred from the __________ to the __________ . *(4 marks)*

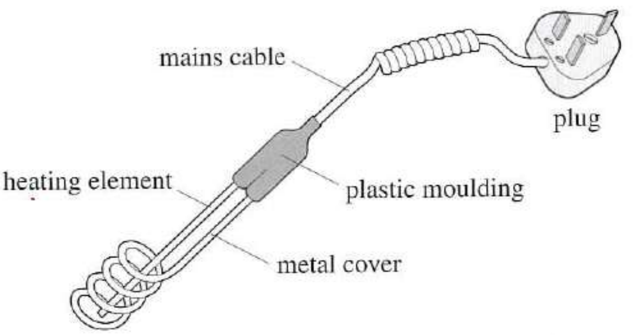
2 a) The diagram shows a 13 amp plug.



i) What is wrong with the way this plug has been wired? *(1 mark)*

ii) Why do plugs have a fuse? *(1 mark)*

b) The diagram shows an immersion heater which can be used to boil water in a mug.



i) Which part of the immersion heater should be connected to the earth pin of the plug? *(1 mark)*

ii) Complete the sentence by choosing the correct words from the box. Each word may be used once or not at all.

chemical	electrical	heat	light

When the immersion heater is switched on ________ energy is transferred to ________ energy. *(2 marks)*

3 a) Look at this table of results.

VOLTAGE (V)	0.0	3.0	5.0	7.0	9.0	11.0
CURRENT (A)	0.0	1.0	1.4	1.7	1.9	2.1

i) Plot a graph of current agains voltage. Place current, in amps, on the vertical axis and voltage, in volts, on the horizontal axis. *(3 marks)*

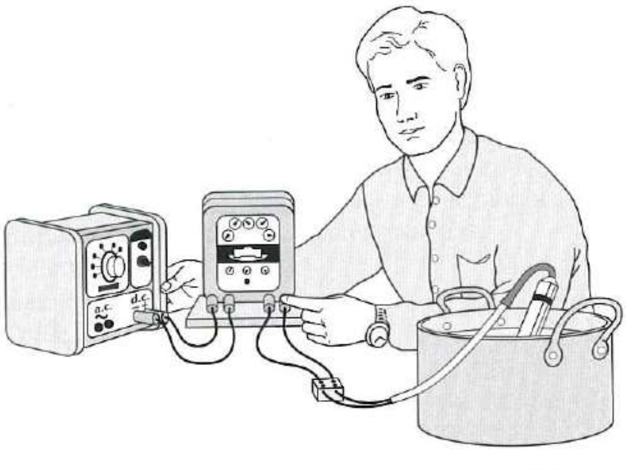
ii) Use your graph to find the current when the voltage is 10 V. *(1 mark)*

iii) Use your answer to (ii) to calculate the resistance of the lamp when the voltage is 10 V. *(2 marks)*

b) i) What happens to the resistance of the lamp as the current through it increases?

ii) Explain you answer. *(2 marks)*

4 The drawing shows an experiment using a low voltage supply, a joulemeter, a small immersion heater and a container filled with water.



The potential difference was set at 6 V d.c. The reading on the joulemeter at the start of the experiment was 78 882 and 5 minutes later it was 80 142.

a) Use the equation:

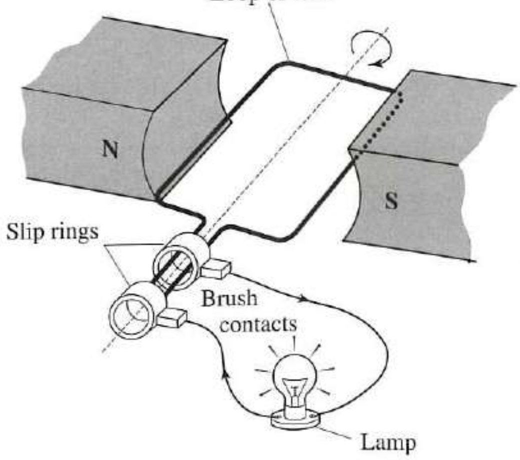
$$\text{potential difference} = \frac{\text{energy transferred}}{\text{charge}}$$

to work out the total charge which flowed through the immersion heater in five minutes. Clearly show how you get to your answer and give the unit. *(3 marks)*

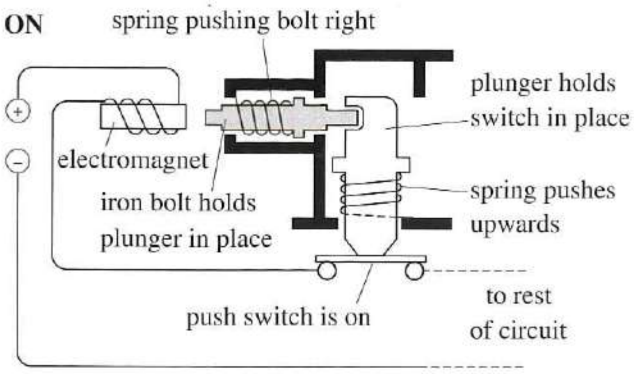
b) Calculate the current through the immersion heater during the 5 minutes. Write the equation you are going to use, show clearly how you get to your answer and give the unit. *(3 marks)*

5 The diagram shows a simple electricity generator. Rotating the loop of wire causes a current which lights the lamp.

State **three** ways to increase the current produced by the generator. *(3 marks)*



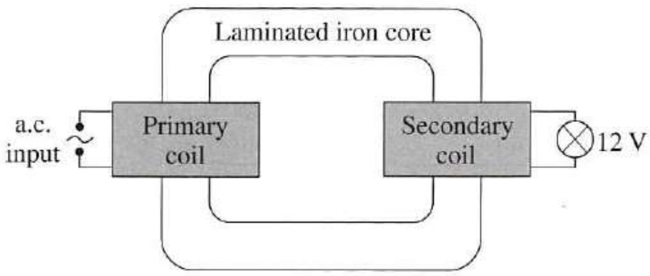
6 A fault in an electrical circuit can cause too great a current to flow. Some circuits are switched off by a circuit breaker.



One type of circuit breaker is shown above. A normal current is flowing.
Explain, in full detail, what happens when a current which is bigger than normal flows.

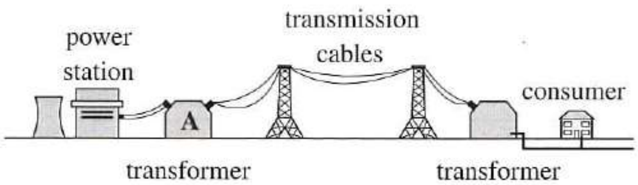
(4 marks)

7 a) The diagram represents a simple transformer used to light a 12 V lamp. When the power supply is switched on the lamp is very dim.



Give **one** way to increase the voltage at the lamp with without changing the power supply.

(1 mark)



b) Electrical energy is distributed around the country by a network of high voltage cables.

i) For the system to work the power is generated and distributed using alternating current rather than direct current. Why? *(1 mark)*

ii) Transformers are an essential part of the distribution system. Explain why. *(2 marks)*

iii) The transmission cables are suspended high above the ground. Why? *(1 mark)*

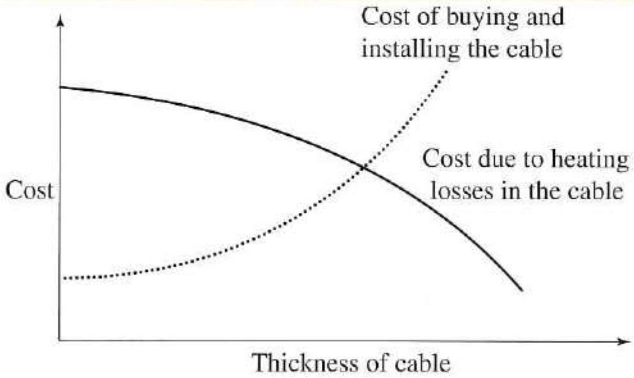
c) The power station generates 100 MW of power at a voltage of 25 kV. Transformer **A**, which links the power station to the transmission cables, has 44 000 turns in its 275 kV secondary coil.

i) Write down the equation which links the number of turns in each transformer coil to the voltage across each transformer coil. *(1 mark)*

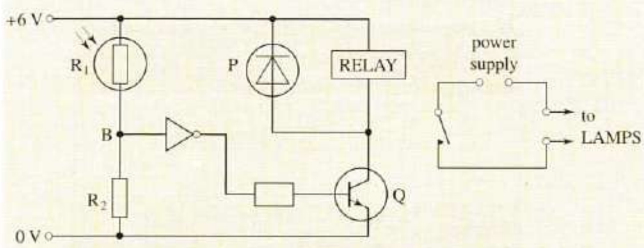
ii) Calculate the number of turns in the primary coil of transformer **A**. Show clearly how you work out your answer. *(2 marks)*

d) The diagram shows how the cost of transmitting the electricity along the cables depends upon the thickness of the cable.

Why does the cost due to the heating losses go down as the cable is made thicker? *(1 mark)*



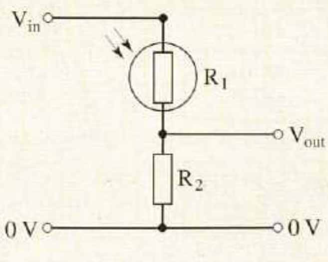
8 The diagram below shows a circuit which can be used as an automatic switch.



a) Name the following components: P, Q, R_1. *(3 marks)*

Use the following information for parts b) and c).

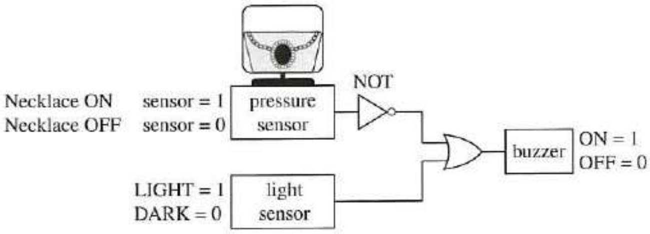
$$V_{out} = V_{in} \times \frac{(R_2)}{(R_1 + R_2)}$$



b) The resistance of $\mathbf{R_2}$ = 2000Ω.
V_{in} is 6V.
   i) In daylight the resistance of $\mathbf{R_1}$ = 500Ω. Calculate the voltage across $\mathbf{R_2}$.
   ii) In daylight the lamps will be OFF. Explain why. *(6 marks)*

c) In the dark the resistance of $\mathbf{R_1}$ is 198000Ω. Calculate the voltage across $\mathbf{R_2}$. *(2 marks)*

9 a) The diagram shows part of a simple alarm system used to protect a valuable necklace.



   i) Copy and complete the truth table for the NOT gate.

Input	Output
1	
0	

(1 mark)

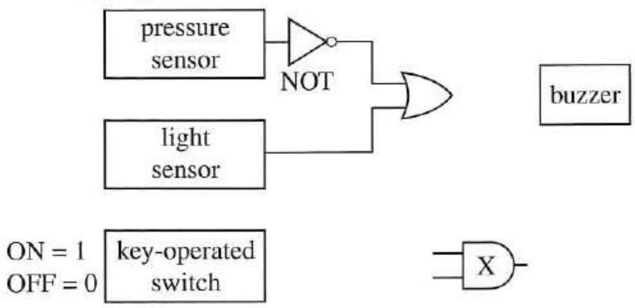
   ii) Copy and complete the truth table for the alarm system.

Pressure sensor	Light sensor	Buzzer
0	0	
0	1	
1	0	
1	1	

(2 marks)

   iii) Explain how this alarm system would work. *(2 marks)*

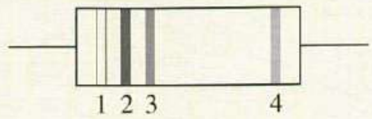
b) The alarm needs to be able to be switched on and off. To do this a key-operated switch and a logic gate **X** are added to the circuit.



   i) What type of logic gate is **X**? *(1 mark)*

   ii) Copy and complete the circuit above to show how the key-operated switch and logic gate **X** should be connected into the alarm system. *(2 ma*

10 a) The diagram shows the arrangement of th colour coded bands on a typical resistor.

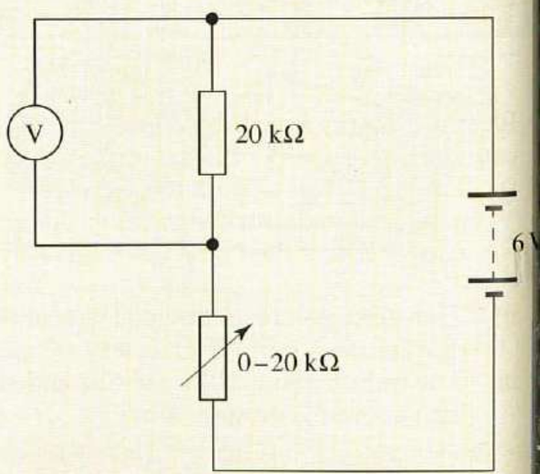


The colour code is given in the table belo

Figure	Colour
0	black
1	brown
2	red
3	orange
4	yellow
5	green
6	blue
7	violet
8	grey
9	white

   i) What are the colours of the first **thre** bands of a 20 kΩ resistor? *(2 ma*
   ii) What information is given by the **fourth** band? *(1 m*

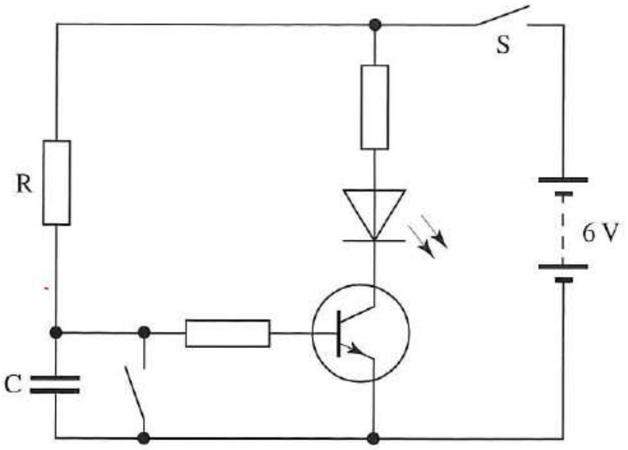
b) The diagram shows two resistors joined i series. The variable resistor can have any value between 0 and 20 kΩ.



   i) What is the smallest possible reading the voltmeter? *(1 m*

ii) What is the largest possible reading on the voltmeter? *(1 mark)*

c) The diagram shows one design for a time-delay circuit.



i) What is the function of a capacitor? *(1 mark)*

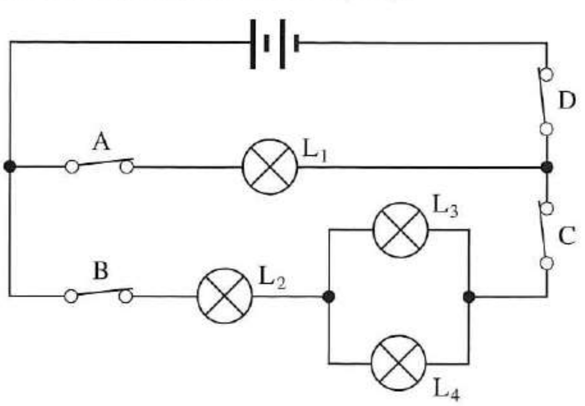
ii) When the switch **S** is closed, it is several minutes before the light emitting diode (LED) comes on. Explain why. The explanation has been started for you.

*When the switch **S** is closed, the voltage across the capacitor . . .* *(2 marks)*

iii) Give **one** practical use for this circuit. *(1 mark)*

iv) A pupil wires up the circuit. By mistake the positions of capactior **C** and the resistor **R** are swapped. Describe what will happen after the switch **S** is closed. *(2 marks)*

11 In the circuit shown below all four lamps are identical.
All four switches are closed (ON).



All four lamps are lit (ON).

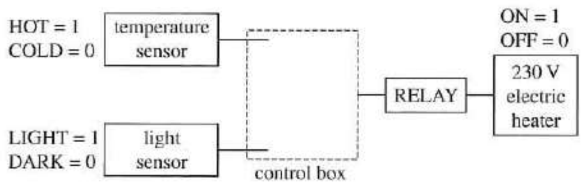
a) Which **single** switch, **A** to **D**, should be opened in order to
  i) turn OFF **all four** lamps?
  ii) turn OFF one lamp only? *(2 marks)*

b) When **all four** switches are closed (ON), state which lamp L_1 to L_4 will be the brightest. Give a reason for your answer. *(2 marks)*

c) Lamps are sometimes used in electronic systems as output devices. Other devices are used as input sensors.
Below there is a list of output devices and input sensors.
Identify the **three** input sensors.

buzzer **heater** **LDR** **motor**
switch **thermistor** *(3 marks)*

12 a) The diagram shows part of a heating system. It is designed to switch on automatically when it is both cold and dark. The control box contains two logic gates which are not shown.



i) What is the name and circuit symbol for an input sensor which responds to light? *(2 marks)*

ii) What is the name and circuit symbol for an input sensor which responds to temperature? *(2 marks)*

iii) Copy and complete the truth table for the control system.

Light sensor	Temperature sensor	Heater
1	1	
1	0	
0	1	
0	0	

(2 marks)

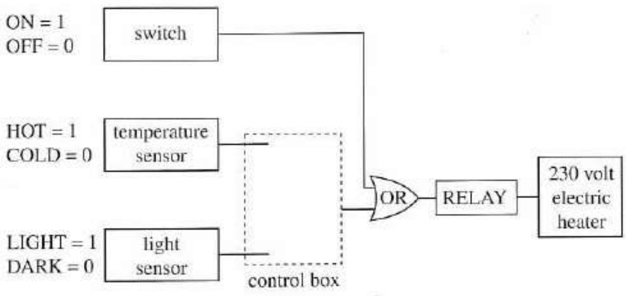
iv) Identify the names of the **two** logic gates that should be used inside the control box, from the list below.

AND NOT OR *(1 mark)*

v) Copy and complete the diagram in part a) to show how the two logic gates are used to connect the input sensors to the relay. Use the correct symbols for the logic gates. *(3 marks)*

vi) Why must a relay be used to operate the heater? *(1 mark)*

b) The diagram shows an additional logic gate and switch added to the system.



Explain how this change allows the heater to be switched on at any time. The explanation has been stared for you.

Closing the switch sends . . . *(2 marks)*

4 Under normal conditions the maximum speed that a lorry can go around a bend without skidding is 60 km/hr. Would the lorry be able to go around the bend faster, at the same speed, or would it need to slow down, if the road was muddy? Explain the reason for your answer.

Examination questions

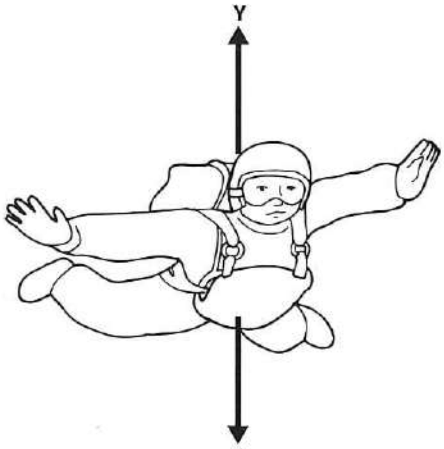
1 a) Two sky-divers jump from a plane. Each holds a different position in the air.

Copy and complete the following sentence.
Sky-diver __________ will fall faster because __________ *(2 marks)*

A

B

b) The diagram shows the direction of the forces acting on one of the sky-divers.



Copy the following sentences and complete them by choosing the correct endings from the boxes.

i) Force X is caused by [air resistance / friction / gravity].

(1 mark)

ii) Force Y is caused by [air resistance / gravity / weight].

(1 mark)

iii) When force X is bigger than force Y, the speed of the sky-diver will [go up / stay the same / go down].

(1 mark)

iv) After the parachute opens, force X [goes up / stays the same / go down].

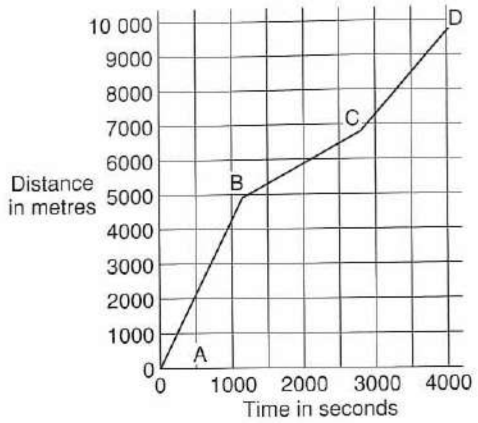
(1 mark)

c) How does the area of an opened parachute affect the size of force Y? *(1 mark)*

2 Two students Anna and Graham took part in a sponsored run. The distance–time graph for Graham's run is shown. Four points have been labelled A, B, C and D.

a) Between which pair of points was Graham running the slowest? *(1 mark)*

b) Anna did not start the run until 10 minutes after Graham. She completed the whole run at a constant speed of 4 m/s.



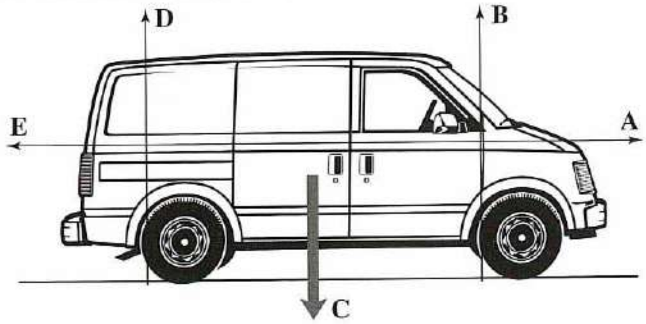
i) Write down the equation that links distance, speed and time. *(1 mark)*

ii) Calculate, in seconds, how long it took Anna to complete the run. Show clearly how you work out your answer. *(2 marks)*

iii) Copy the graph and draw a line to show Anna's run. *(2 marks)*

iv) How far had Graham run when he was overtaken by Anna? *(1 mark)*

3 Five forces, **A**, **B**, **C**, **D** and **E** act on the van.



a) Copy and complete the following sentences by choosing the correct forces from **A** to **E**.
Force __________ is the forward force from the engine.
Force __________ is the force resisting the van's motion. *(1 mark)*

b) The size of forces **A** and **E** can change.
Copy and complete the table to show how big force **A** is compared to force **E** for each motion of the van.
Do this by placing a tick in the correct box.
The first one has been done for you.

Motion of van	Force A smaller than force E	Force A equal to force E	Force A bigger than force E
Not moving		✓	
Speeding up			
Constant speed			
Slowing down			

(3 marks)

c) When is force **E** zero? *(1 mark)*

d) The van has a fault and leaks one drop of oil every second.
The diagram below shows the oil drops left on the road as the van moves from **W** to **Z**.

Describe the motion of the van as it moves from **W** to **X**, **X** to **Y** and **Y** to **Z**. *(3 marks)*

e) The driver and passengers wear seatbelts. Seatbelts reduce the risk of injury if the van stops suddenly.

backwards downwards force
forwards mass weight

Copy and complete the following sentences, using words from the list above, to explain why the risk of injury is reduced if the van stops suddenly.

A large __________ is needed to stop the van suddenly.
The driver and passengers would continue to move __________ .
The seatbelts supply a __________ force to keep the driver and passengers in their seats. *(3 marks)*

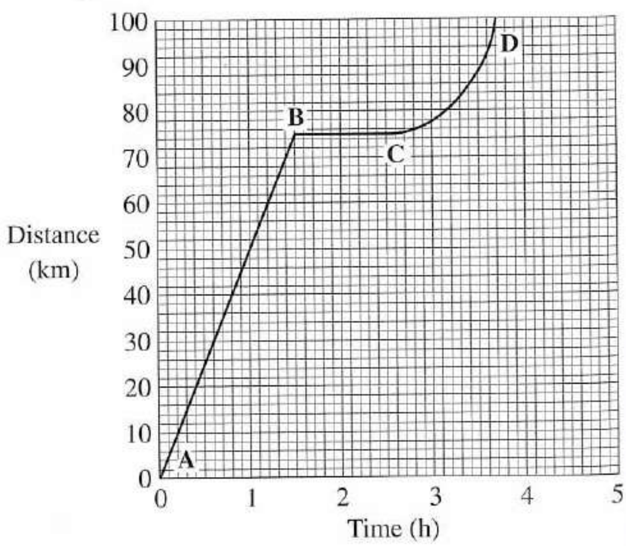
f) The van was travelling at 30 m/s. It slowed to a stop in 12 seconds. Calculate the van's acceleration. *(3 marks)*

4 The graph shows three stages of a van's journey.

a) During which stage of the journey **A–B**, **B–C** or **C–D**:

i) is the van stationary? *(1 mark)*

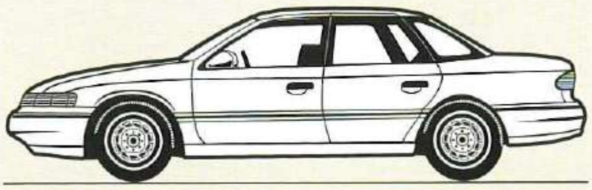
ii) is the van moving at a constant speed? *(1 mark)*



b) Calculate the gradient of the graph from **A** to **B**. *(2 marks)*

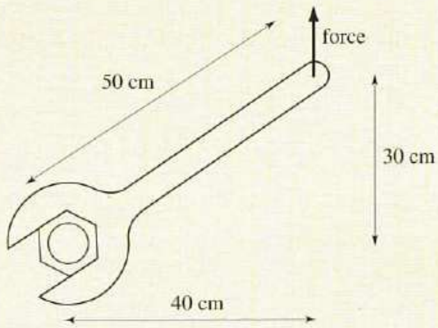
c) What does this gradient measure? *(1 mark)*

5 The diagram shows a parked car.



When the car is driven away, its engine gives a constant forward force.
The speed increases quickly at first, then more slowly. After a time the car reaches a constant speed.
Explain why the motion of the car changes in this way. *(3 marks)*

6 The diagram shows a spanner being used to undo a tight nut.



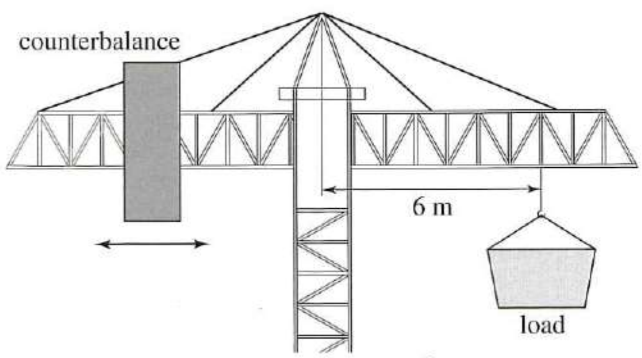
The nut was tightened using a moment of 120 newton metres.

Use the following equation to calculate the force needed to undo the nut. Show clearly how you work out your answer.

moment = force × perpendicular distance from pivot

(2 marks)

7 The diagram shows a tower crane.



a) Explain why the crane would be unstable without the counterbalance. *(2 marks)*

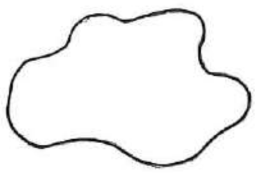
b) The counterbalance can be moved to the left or right, as shown by the arrows on the diagram. Explain the advantage of having a movable counterbalance. *(2 marks)*

c) The load shown in the diagram is 75 000N. The load is 6 m from the tower.
Calculate the turning effect (moment) of the load in newton metres. *(2 marks)*

d) The crane is balanced and horizontal. What is the turning effect (moment) of the counterbalance in newton metres? Explain your answer.

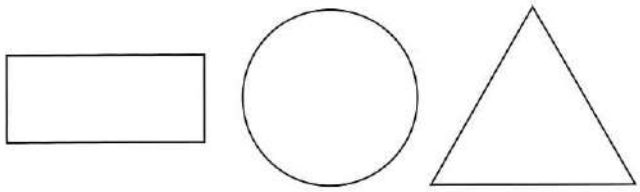
(3 marks)

8 a) A thin sheet of cardboard is cut to the shape below. Describe, with a diagram, an experiment to find its centre of mass.



(5 marks)

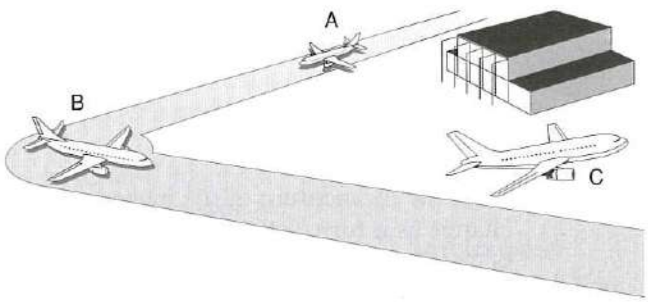
b) Copy and label with an **X** the centre of mass of each of the three objects below.



(3 marks)

c) Explain why a mechanic would choose a long spanner to undo a tight nut. *(2 marks)*

9 a) The diagram shows three aeroplanes at an airport.

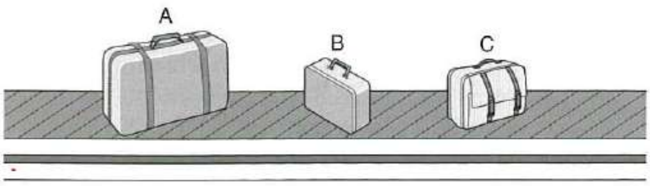


Aeroplane **A** is moving at constant velocity towards the main runway.
Aeroplane **B** is stationary, waiting to take off.
Aeroplane **C** has just taken off and is accelerating.

i) Which, if any, of the aeroplanes has zero momentum? *(1 mark)*

ii) The momentum of **one** of the aeroplanes is changing. Which one? Give a reason for your answer. *(2 marks)*

10 The picture shows luggage which has been loaded onto a converyor belt.



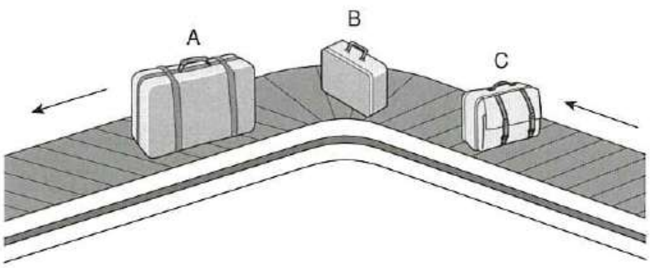
Each piece of luggage has a different mass.

mass of **A** = 22 kg
mass of **B** = 12 kg
mass of **C** = 15 kg

a) i) What is the momentum of the luggage before the conveyor belt starts to move? Give a reason for your answer. *(2 marks)*

ii) When the conveyor belt is switched on the luggage moves with a constant speed. Which piece of luggage **A**, **B** or **C** has the most momentum? Give a reason for your answer. *(2 marks)*

iii) At one point the conveyor belt turns left. The luggage on the belt continues to move at a constant speed.

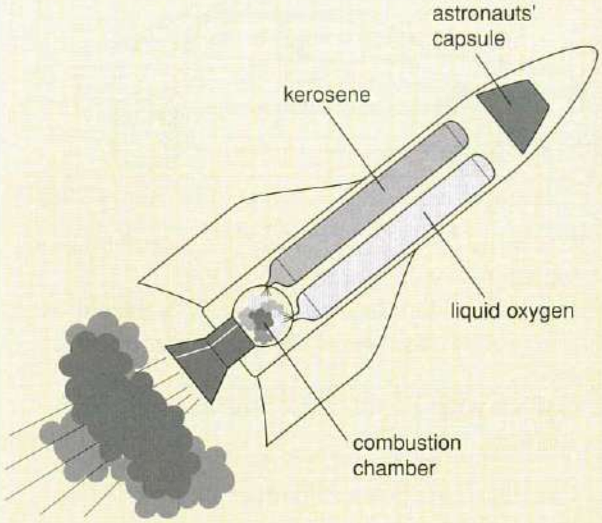


Does the momentum of the luggage change as it turns left with the conveyor belt? Give a reason for your answer. *(2 marks)*

b) Which of the following units can be used to measure momentum?

J/s   kg m/s   Nm   *(1 mark)*

11 a) The diagram shows a simple design for a space rocket.

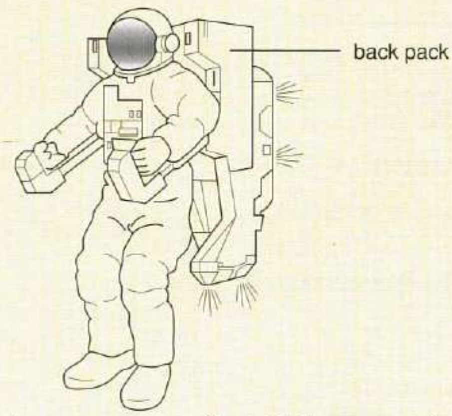


i) Explain, using the idea of momentum, how the initial propulsion of a rocket is produced. *(3 marks)*

ii) State and explain **one** way the acceleration of a rocket can be increased. *(2 marks)*

iii) In what unit is momentum measured? *(1 mark)*

b) The diagram shows an astronaut working in space. Releasing compressed gas from the back pack allows the astronaut to move around.

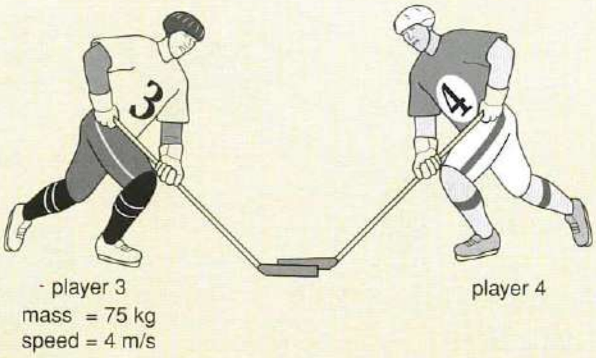


During one spacewalk, 0.5 kilograms of gas was released in 2 seconds. The gas had a speed of 60 metres per second. Use the following equation to calculate the force, in newtons, exerted on the astronaut by the gas. (Ignore the change in mass of the back pack).

$$\text{force} = \frac{\text{change in momentum}}{\text{time}}$$

(2 marks)

12 a) The picture shows two ice hockey players skating towards the puck. The players, travelling in opposite directions, collide, fall over and stop.



i) Use the following equation and the data given in the box to calculate the momentum of player number **3** before the collision. Show clearly how you work out your answer and give the unit.

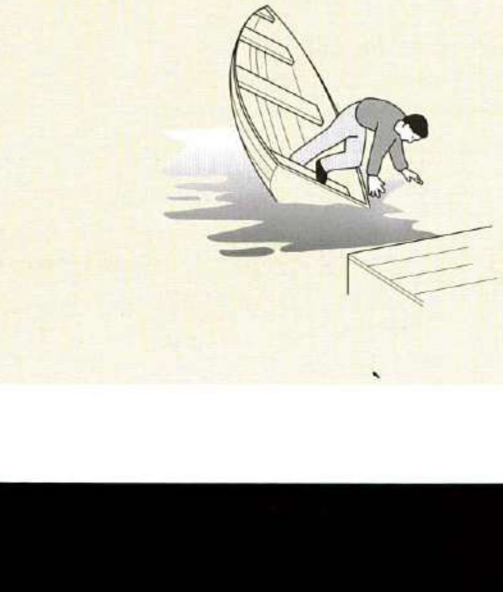
momentum = mass × velocity

(3 marks)

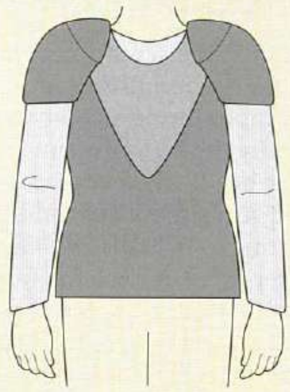
ii) What is the momentum of player **4** just before the collision? *(1 mark)*

iii) The collision between the two players is **not** *elastic*. What is meant by an *elastic* collision? *(1 mark)*

b) The pictures show what happened when someone tried to jump from a stationary rowing boat to a jetty. Use the idea of momentum to explain why this happened. *(2 marks)*

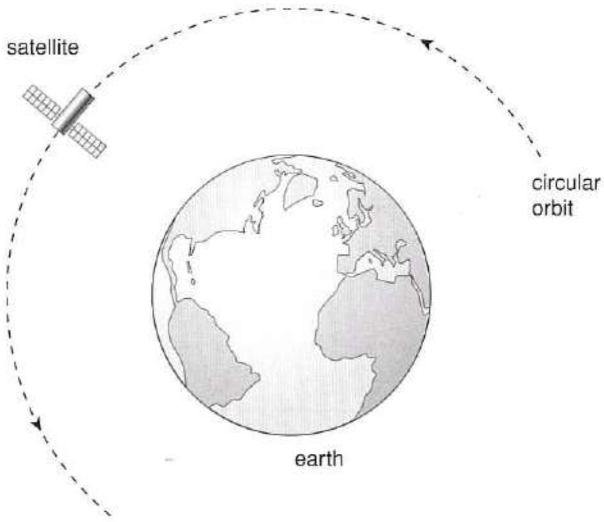


c) The diagram shows one type of padded body protector which may be worn by a horse rider.



If the rider falls off the horse, the body protector reduces the chance of the rider being injured. Use the idea of momentum to explain why. *(3 marks)*

13 The diagram shows a satellite in orbit around the Earth.



a) Copy and complete the diagram, drawing an arrow on the diagram to show the direction of the centripetal force which acts on the satellite. *(1 mark)*

b) Use words from the following list to complete the sentences.

greater **less** **unchanged**

i) If the mass of the satellite decreases then the centripetal force needed is ———— .

ii) If the speed of the satellite increases then the centripetal force needed is ———— .

iii) If the radius of the orbit increases then the centripetal force needed is ———— .

(3 marks)

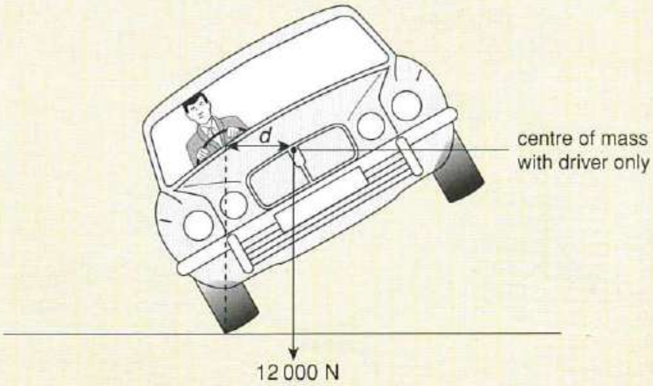
14 The following paragraphs appeared in a newspaper.

JEEP FAILS GOVERNMENT TEST

A car manufacturer confirmed yesterday that one of its four-wheel drive mini-jeeps rolled over at 38 mph during stability tests conducted by the Government.
Testing has been halted until safety cages can be fitted to seven makes of mini-jeeps which the Department of Transport has agreed to test after repeated complaints from the Consumer's Association. The Association claims its own tests show that the narrow track, short-wheelbase vehicles are prone to rolling over. The Government's tests highlight how passengers raise the centre of mass. All seven vehicles passed the test unladen, although one raised two wheels.

a) Write down **two** factors mentioned in the newspaper article which affect the stability of vehicles. *(2 marks)*

b) The diagram shows a tilted vehicle.



The distance ***d*** shown in the diagram is 50 cm. Calculate the moment of the force about the point of contact with the road. *(3 marks)*

c) Explain how passengers make the vehicles more likely to roll over (less stable). You may use diagrams if you wish. *(4 marks)*

Examination questions

1 The boxes on the left show some types of electomagnetic radiation. The boxes on the right show some uses of electromagnetic radiation.

Copy the diagram and draw a straight line from each type of radiation to its use. The first one has been done for you.

Gamma rays	In a remote control for a TV
X-rays	To communicate with satellites
Ultraviolet	To sterilise surgical instruments
Infrared	In sunbeds to give a sun tan
Microwaves	To obtain shadow pictures of bones

(3 marks)

2 a) The diagram represents the electromagnetic spectrum. Four of the waves have not been named. Copy the diagram and draw lines to join each of the waves to its correct position in the electromagnetic spectrum. One has been done for you.

	X-rays			Infrared	Microwaves	

Ultraviolet | Gamma rays | Radio | Light

(2 marks)

b) Copy and complete the following sentence by choosing the correct answer from the three lines in the box.

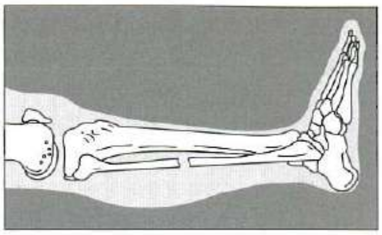
The speed of radio waves through a vacuum is

faster than / the same as / slower than the speed of light through a vacuum. *(1 mark)*

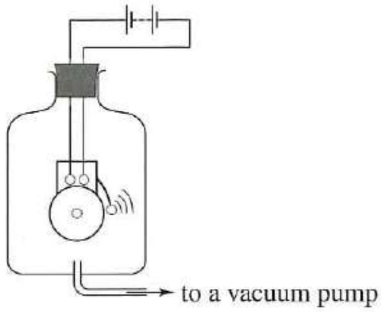
c) i) Before sunbathing it's a good idea to apply a sun cream to your exposed skin. Why? *(1 mark)*

ii) From which type of electromagnetic wave is sun cream designed to protect the skin? *(1 mark)*

d) The diagram shows an X-ray photograph of a broken leg.
Bones show up white on the photographic film. Explain why. *(2 marks)*



3 a) The diagram shows an electric bell inside a glass jar. The bell can be heard ringing.



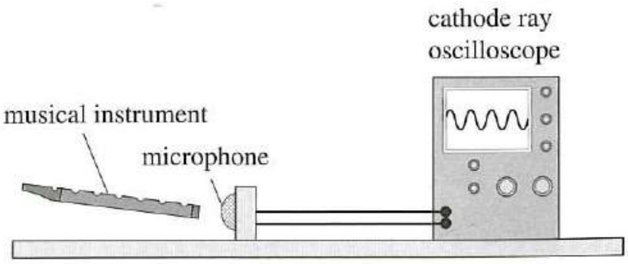
Copy and complete the following sentences, by choosing the correct line in each box.

When all the air has been taken out of the glass jar,

the ringing sound will stop. / get louder. / get quieter.

This is because sound travels faster / travels slower / cannot travel through a vacuum. *(2 marks)*

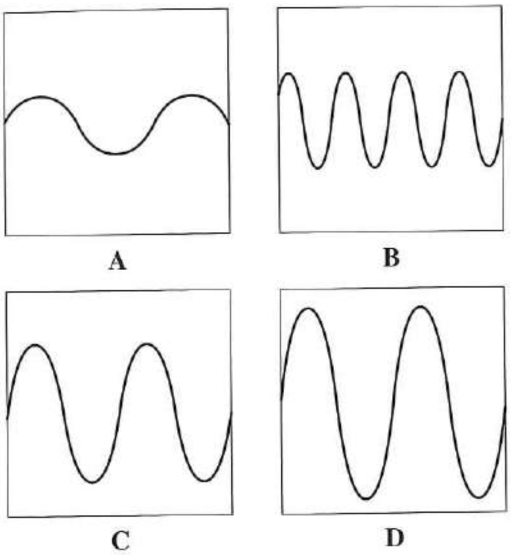
b) The microphone and cathode ray oscilloscope are used to show the sound wave pattern of a musical instrument.



One of the following statements describes what a microphone does. Identify the correct statement. *(1 mark)*

- A microphone transfers sound energy to light energy.
- A microphone transfers sound energy to electrical energy.
- A microphone transfers electrical energy to sound energy.

c) Four different sound wave patterns are shown. They are all drawn to the same scale.



i) Which sound wave pattern has the highest pitch? Give a reason for your answer. *(2 marks)*

ii) Which sound wave pattern is the loudest? Give a reason for your answer. *(2 marks)*

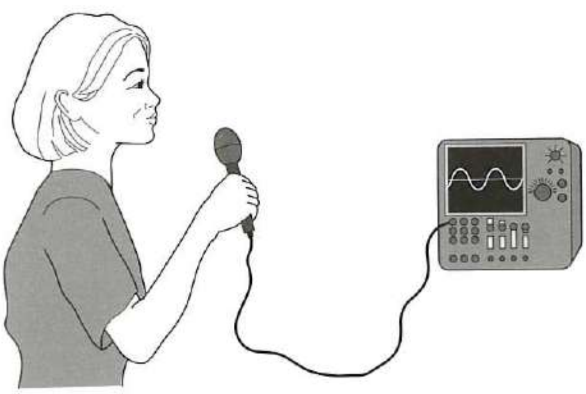
d) i) The frequency of some sounds is too high for humans to hear. Which of the following words describes this sound.

microwave **ultrasound** **ultraviolet**

(1 mark)

ii) Give **one** use for this type of sound wave. *(1 mark)*

4 a) The student is using a microphone connected to a cathode ray oscilloscope (CRO).



The CRO displays the sound waves as waves on its screen. What does the microphone do? *(2 marks)*

b) The amplitude, the frequency and the wavelength of a sound wave can each be either increased or decreased.

i) What change, or changes, would make the sound quieter? *(1 mark)*

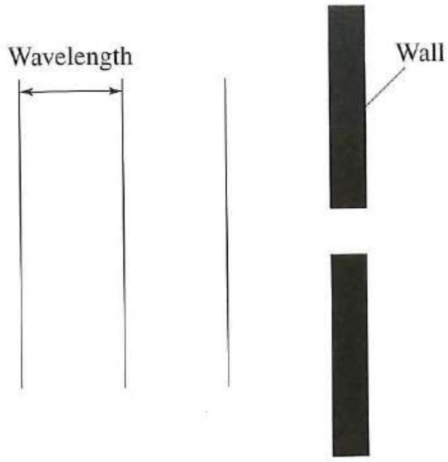
ii) What change, or changes, would make the sound higher in pitch? *(1 mark)*

c) People can generally hear sounds in the frequency range 20 Hz to 20 000 Hz.

i) What are very high frequency, and inaudible, sounds with frequencies **greater** than 20 000 Hz called? *(1 mark)*

ii) Give **two** uses for very high frequency sounds. *(2 marks)*

d) The diagram shows sound waves approaching a gap in a wall.

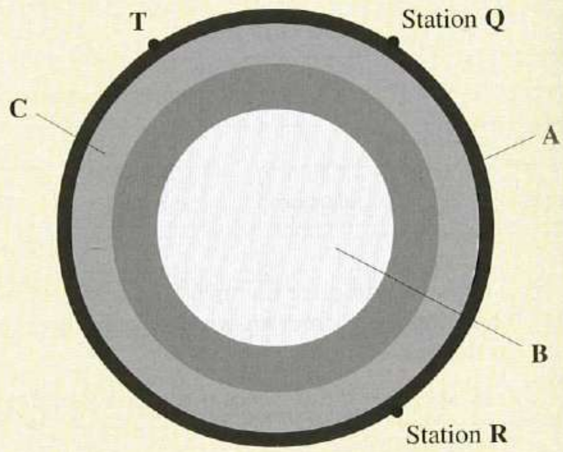


i) Copy and complete the diagram to show what will happen to the sound waves on the other side of the wall. *(2 marks)*

ii) What is the name of this effect? *(1 mark)*

iii) What would the width of the gap need to be for this effect to be most pronounced? *(1 mark)*

5 The diagram represents the structure of the Earth.



a) On the diagram, name the parts **A**, **B** and **C**.

b) An earthquake occurs at the point **T** on the Earth's surface. Two types of shock wave are produced by the earthquake, P waves and S waves.

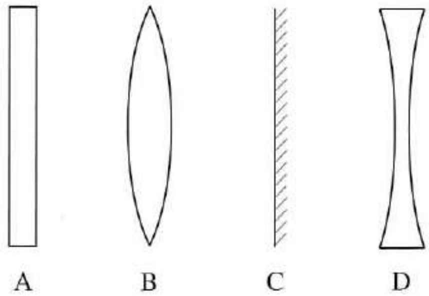
Describe **two** similarities and **two** differences between P waves and S waves as they travel through the Earth. *(4 marks)*

c) State whether P waves or S waves or both will reach:

i) Station Q *(1 mark)*

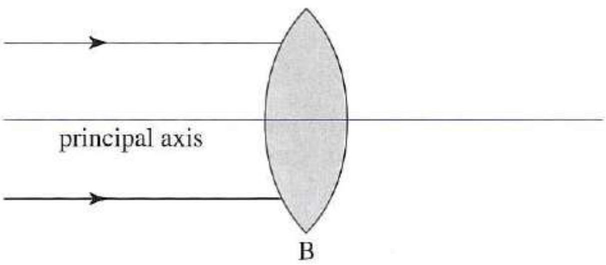
ii) Station R. *(1 mark)*

6 The diagrams below show some pieces of glass.



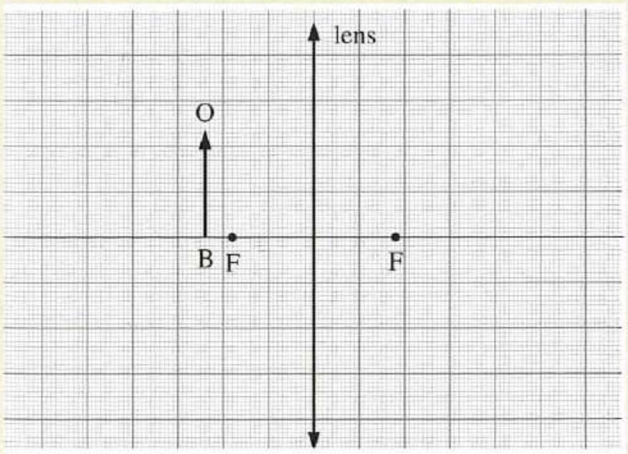
a) Which of **A**, **B**, **C** and **D** is
   i) a converging lens?
   ii) a diverging lens? *(2 marks)*

b) Copy and complete the diagram below to show what happens to the rays of light when they pass through **B**.



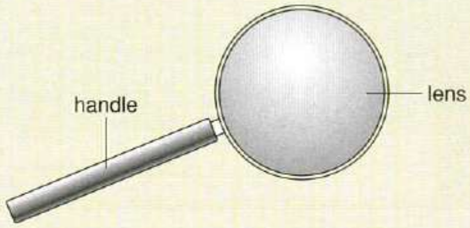
(4 marks)

7 a) An object OB is placed 12 cm in front of a converging lens of focal length 9 cm. The diagram below is drawn to scale.



i) Draw the ray diagram on graph paper to show the position and size of the image. Draw and label the image.
ii) Write down two ways in which the image is different from the object. *(6 marks)*

b) Cameras use converging lenses to produce an image of an object. Give two ways in which the image produced on the film is different from the object. *(2 marks)*



8

When some people are reading a book with very small print, they may use a lens like the one shown in the diagram.

a) State the type of lens used.
b) Explain, in as much detail as you can, how the lens makes it easier to read the print. *(4 marks)*

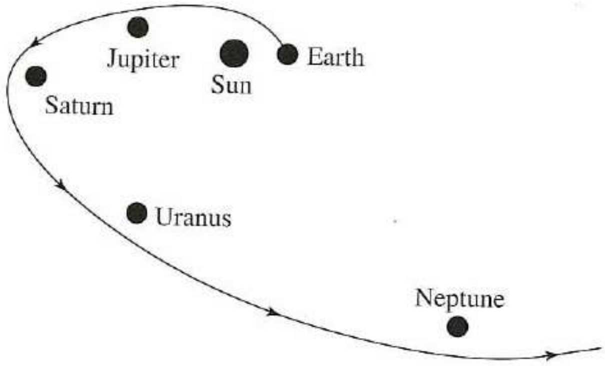
Examination questions

1 a) Copy and complete each sentence by choosing the correct word or phrase from the box. Each word or phrase should be used once or not at all.

milky way	moon	planet	solar system	star	universe

The Sun is the nearest ________ to the Earth.
The Sun is in the galaxy called the ________.
Within the ________ there are millions of galaxies.
Pluto is orbited by one ________. *(4 marks)*

b) The diagram shows the path taken by the Voyager 2 spacecraft.



Choosing from the forces in the box, which force caused the spacecraft to change direction each time it got close to a planet?

air resistance	friction	gravity

(1 mark)

2 a) The table gives some information about four planets.

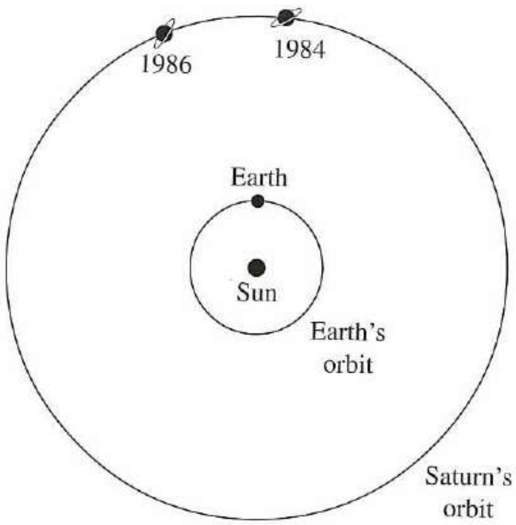
Planet	Average distance from the Sun in million km	Average time to complete one orbit in Earth years	Average orbital speed in km/sec
Jupiter	800	12	13.0
Saturn	1400	30	9.6
Neptune	4500	165	5.2
Pluto	5900	248	4.7

i) Draw a graph of each planet's average orbital speed against the distance the planet is from the Sun. Plot distance from the Sun on the horizontal axis and orbital speed on the vertical axis. *(3 marks)*

ii) How does the average orbital speed of a planet vary with its average distance from the Sun? *(1 mark)*

iii) The average distance between Uranus and the Sun is 2900 million kilometres. Use the graph to predict the average orbital speed of Uranus. *(1 mark)*

b) The diagram shows the position of Saturn in July 1984 and July 1986.



i) Saturn takes 30 Earth years to complete one orbit of the Sun. Copy the diagram and mark the position of Saturn in the year 2000. *(1 mark)*

ii) Suggest why it was difficult to see Saturn in July 2000. *(1 mark)*

3 A satellite in a stable Earth orbit moves at constant speed in a circle, because a single force acts on it.

a) i) Name the force acting on the satellite. *(1 mark)*

ii) State the direction of this force. *(1 mark)*

b) Communications satellites and satellites used to observe the Earth are placed in different orbits.

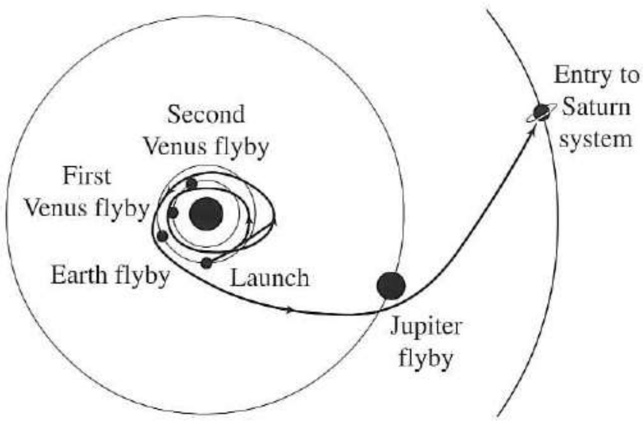
i) Describe the orbit of a communications satellite. *(3 marks)*

ii) Describe the orbit of a satellite used to observe the Earth. *(2 marks)*

iii) Explain why the satellites are placed in different types of orbit. *(3 marks)*

c) Explain, in terms of its orbit, why a comet is rarely seen from Earth. *(2 marks)*

4 a) The Cassini spacecraft launched in 1997 will take seven years to reach Saturn. The journey will take the spacecraft close to several other planets.



Each time the spacecraft approaches a planet it changes direction and gains kinetic energy. Explain why. *(2 marks)*

b) The Big Bang theory attempts to explain the origin of the Universe.
   i) What is the Big Bang theory? *(1 mark)*
   ii) What can be predicted from the Big Bang theory about the size of the Universe? *(1 mark)*

c) i) Explain how stars like the Sun were formed. *(2 marks)*
   ii) The sun is made mostly of hydrogen. Eventually the hydrogen will be used up and the Sun will 'die'.
   Describe what will happen to the Sun from the time the hydrogen is used up until the Sun 'dies'. *(3 marks)*

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Examination questions

1 a) Using words or phrases from the list copy and complete the sentences.

elastic **frictional** **gravitational**
less than **more than** **the same as**

When a child goes down a slide the __________ force makes him go faster.
On a damp day the child takes longer to go down the slide. This is because on a damp day the force of friction is __________ on a dry day. *(2 marks)*

b) Using words or phrases from the list copy and complete the sentence.

elastic **gravitational potential** **sound**
kinetic (movement) **light** **thermal (heat)**

When the child goes down the slide, the energy transfers are from __________ energy to __________ energy and __________ energy.
(3 marks)

2 a) The list gives energy resources which can be used to produce electricity.

coal **gas** **nuclear fuel** **oil**
sunlight **tides** **waves** **wind** **wood**

Write down the **four non-renewable** energy resources.

(4 marks)

b) Using words from the list copy and complete the sentences about generating electricity.

energy **gas** **generator** **smoke**
steam **transformer** **turbine** **water**

In a coal-fired power station, coal is burnt to release __________ . This is used to change __________ into __________ which drives a

b) To lift the weight, the weightlifter does 4500 joules of work in 3.0 seconds.
Use the following equation to calculate the power developed by the weightlifter. Show clearly how you work out your answer.

$$\text{power} = \frac{\text{work done}}{\text{time taken}}$$

(2 marks)

4 The diagram shows a high jumper.

In order to jump over the bar, the high jumper must raise his mass by 1.25m.
The high jumper has a mass of 65kg. The gravitational field strength is 10 N/kg.

a) The high jumper just clears the bar.
Calculate his gravitational potential energy.
(4 marks)

b) Calculate the minimum speed the high jumper must reach for take-off in order to jump over the bar. *(3 marks)*

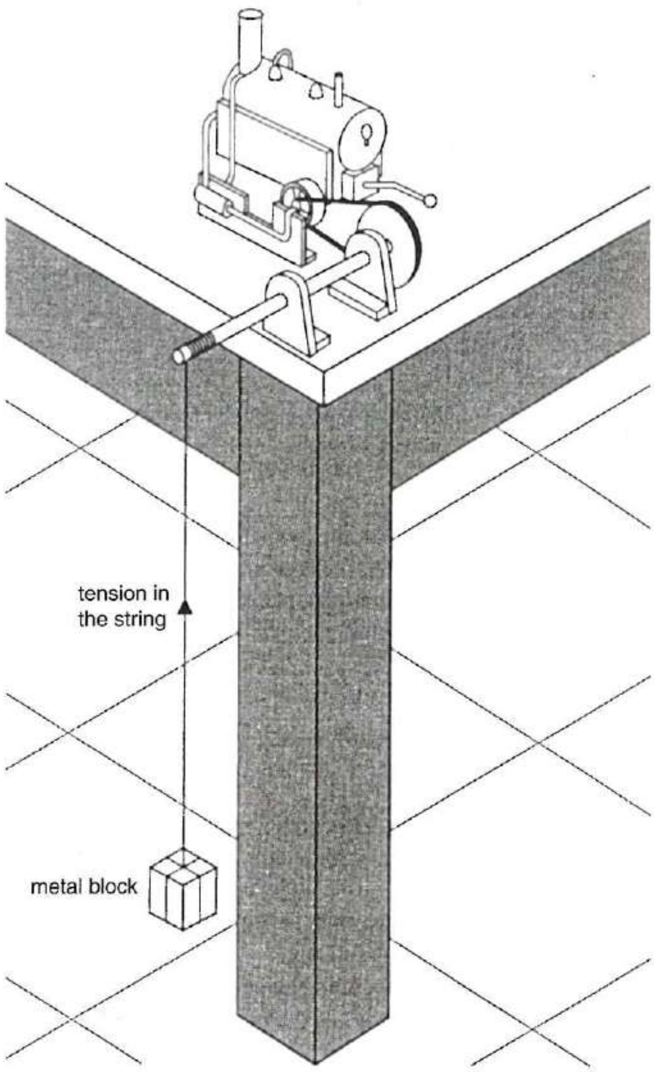
5 The drawing shows an investigation using a model steam engine to lift a load.
In part of the investigation, a metal block with a weight of 4.5 N was lifted from the floor to a height of 90 cm.

a) i) Calculate the work done in lifting this load. Write the equation you are going to use, show clearly how you get to your answer and give the unit. *(3 marks)*

ii) How much useful energy is transferred to do the work in part a) i)? *(1 mark)*

b) In another part of the investigation, 250 J of work is done in one minute.

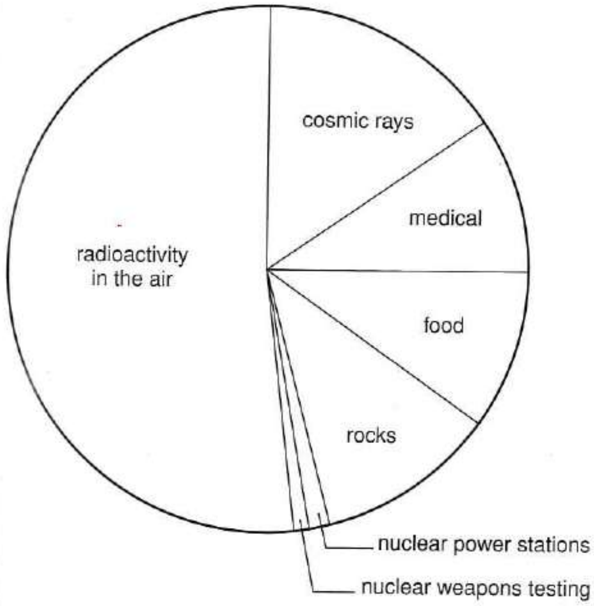
Calculate the useful power output. Give the unit. *(2 marks)*



6 State and explain the advantages and disadvantages of using nuclear power stations to produce electricity compared with coal-fired power stations. *(4 marks)*

Examination questions

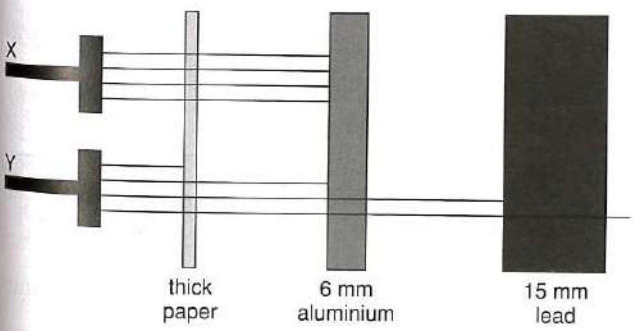
1 a) The different sources of radiation to which we are exposed are shown in the pie chart. Some sources are natural and some artificial.



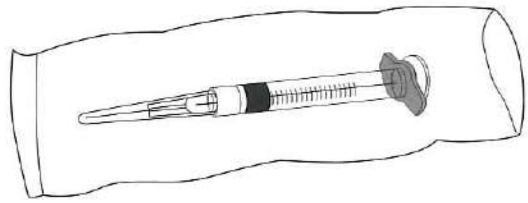
i) Name *one* natural source of radiation shown in the pie chart. *(1 mark)*

ii) Name *one* artificial source of radiation shown in the pie chart. *(1 mark)*

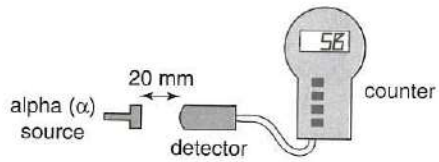
b) A radioactive source can give out three types of emission: alpha particles, beta particles, gamma radiation.
The diagram shows the paths taken by the radiation emitted by two sources, X and Y.
What types of radiation are emitted by each of the sources? *(2 marks)*



c) The diagram shows a disposable syringe sealed inside a plastic bag. After the bag has been sealed the syringe is sterilised using radiation. Explain why radiation can be used to sterilise the syringe. *(3 marks)*



2 a) The diagram shows the apparatus used by a teacher to investigate an alpha (α) source.



i) Which piece of apparatus could be used as a radiation dectector?

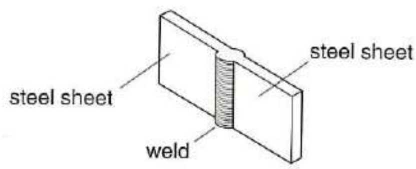
Geiger-Müller Tube	Oscilloscope	Voltmeter

(1 mark)

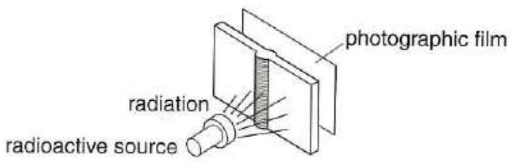
ii) Copy and complete the following sentence. When a piece of paper is placed between the detector and the alpha source the count rate will go __________ .

(1 mark)

b) Two sheets of steel were joined together by welding.

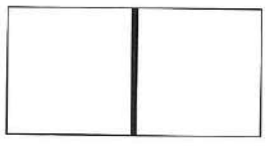


Radiation was used to check how well the welding had been done.



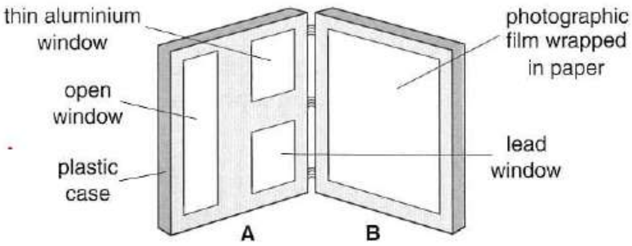
i) Which type of radiation should be used? Give a reason for your answer. *(2 marks)*

ii) The diagram shows the exposed photographic film.



Does the photographic film show that the weld was good or bad? Give a reason for your answer. *(2 marks)*

3 The diagram shows a film badge worn by people who work with radioactive materials. The badge has been opened. The badge is used to measure the amount of radiation to which the workers have been exposed.



The detector is a piece of photographic film wrapped in paper inside part **B** of the badge. Part **A** has "windows" as shown.

a) Use words from the list to complete the sentences.

alpha **beta** **gamma**

When the badge is closed

i) __________ radiation and __________ radiation can pass through the open window and affect the film. *(1 mark)*

ii) __________ radiation and __________ radiation will pass through the thin aluminium window and affect the film. *(1 mark)*

iii) Most of the __________ radiation will pass through the lead window and affect the film. *(1 mark)*

b) Other detectors of radiation use a gas which is ionised by the radiation.

i) Explain what is meant by *ionised.* *(1 mark)*

ii) Explain why ionising radiation is dangerous to people who work with radioactive materials. *(2 marks)*

4 a) The table gives information about five radioactive isotopes.

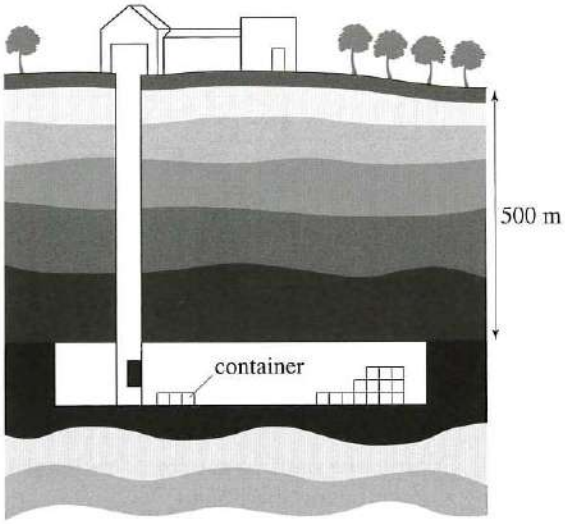
Isotope	Type of radiation emitted	Half-life
Californium-241	alpha (α)	4 minutes
Cobalt-60	gamma (γ)	5 years
Hydrogen-e	beta (β)	12 years
Strontium-90	beta (β)	28 years
Technetium-99	gamma (γ)	6 hours

i) What is an alpha (α) particle? *(1 mark)*

ii) What is meant by the term half-life? *(1 mark)*

iii) Which **one** of the isotopes could be used as a tracer in medicine? Explain the reason for your choice. *(3 marks)*

b) The increased use of radioactive isotopes is leading to an increase in the amount of radioactive waste. One method for storing the waste is to seal it in containers which are then placed deep underground.



Some people may be worried about having such a storage site close to the area in which they live. Explain why. *(3 marks)*

5 a) The graph shows how a sample of barium-143, a radioactive *isotope* with a short *half-life*, decays with time.

i) What is meant by the term *isotope*? *(1 mark)*

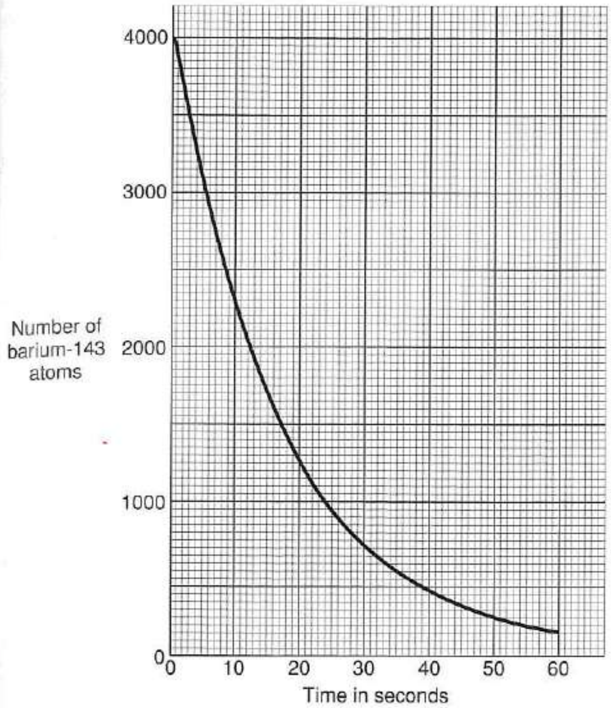
ii) What is meant by the term *half-life*? *(1 mark)*

iii) Use the graph to find the half-life of barium-143. *(1 mark)*

b) Humans take in the radioactive isotope carbon-14 from their food. After their death, the proportion of carbon-14 in their bones can be used to tell how long it is since they died. Carbon-14 has a half-life of 5700 years.

i) A bone in a living human contains 80 units of carbon-14. An identical bone taken from a skeleton found in an ancient burial ground contains 5 units of carbon-14. Calculate the age of the skeleton. Show clearly how you work out your answer. *(2 marks)*

ii) Why is carbon-14 unsuitable for dating a skeleton believed to be about 150 years old? *(1 mark)*



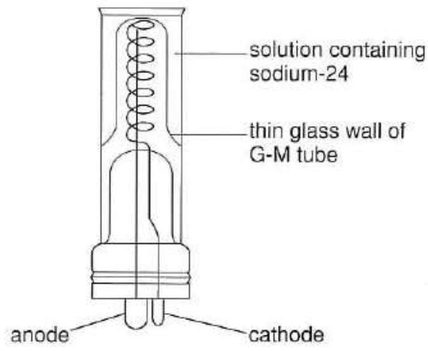
c) The increased industrial use of radioactive materials is leading to increased amounts of radioactive waste. Some people suggest that radioactive liquid waste can be mixed with water and then safely dumped at sea. Do you agree with this suggestion? Explain the reason for your answer. *(3 marks)*

6 The isotope of sodium with a mass number of 24 is radioactive. The following data were obtained in an experiment to find the half-life of sodium-24.

Time in hours	Count rate in counts per minute
0	1600
10	1000
20	600
30	400
40	300
50	150
60	100

a) Draw a graph of the results and find the half-life for the isotope. On the graph show how you obtain the half-life. *(4 marks)*

b) Sodium-24 decays by beta emission. The G-M tube used in the experiment is shown in the diagram. Each beta particle which gets through the glass causes a tiny electric current to pass in the circuit connected to the counter.



i) Why must the glass wall of the G-M tube be very thin?

ii) Why is this type of arrangement of no use if the radioactive decay is by alpha emission? *(1 mark)*

c) Sodium chloride solution is known as saline. It is the liquid used in 'drips' for seriously-ill patients. Radioactive sodium chloride, containing the isotope sodium-24, can be used as a tracer to follow the movement of sodium ions through living organisms. Give one advantage of using a sodium isotope with a half-life of a few hours compared to using an isotope with a half-life of:

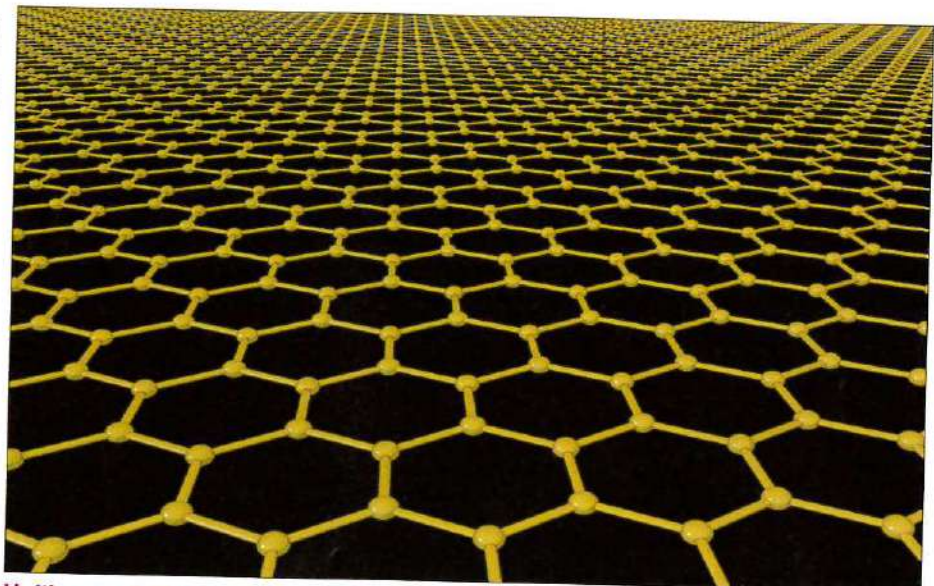
i) five years *(1 mark)*

ii) five seconds. *(1 mark)*

Graphene

Commercializing the 'wonder material'

Extracting graphene from the laboratory has proved challenging, but as **Ray Gibbs** explains, improvements in material processing are beginning to pay off, particularly in the aerospace sector



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Limitless possibilities Some forms of graphene are finding applications in hi-tech manufacturing.

Graphene has many amazing properties, including high strength and stiffness, high conductivity and impermeability to gases, to name but a few. These headline-grabbing properties have generated a considerable amount of hype, with potential new applications announced almost every day. However, as the graphene story has progressed, the task of translating properties measured in the laboratory into commercial applications has proved a greater challenge than many had anticipated. In particular, producing consistent single layers of graphene – the starting point for many potential electronics applications – is a technically difficult task, and doing so on a commercial scale is expensive.

Fortunately, other types of graphene are beginning to prove their worth in other industry sectors. At my firm, Haydale, our focus is on stacks of graphene with 5–100 layers. Materials at the lower end of this range are generally known as few-layered graphene (FLGs), while those at the higher end are termed graphene nanoplatelets (GNPs). When these materials are added to a resin or other thermoplastic material, the resulting mixture can become stronger, and may also become thermally conductive, electrically conductive or both. These enhancements could have applications in many areas, but they appeal particularly to the aerospace industry. Many key aircraft parts are made from carbon fibres bonded together with a thermoset resin. If this resin had better mechanical properties, it might be possible to reduce the number of carbon-fibre layers required – saving weight and thus cost.

Our experiments indicate that substantial improvements are possible: in one recent test, a carbon-fibre composite with FLGs added to the resin showed a 20% improvement in almost all mechanical properties. However, getting there involved much more than simply adding graphene to resin. The key to realizing the well-documented properties of graphene lies in starting with the right material and knowing how to process it for particular applications.

Producing graphene

Graphene can be produced in a number of ways, and individual manufacturers use slightly different processes. One common approach is the "top down" method, where mined organic graphite is exfoliated to produce flakes of fewer layers. Getting down to the desired number of layers may require multiple production stages, since the thickness of most organic materials varies. However, in bulk systems such as the composite inks, pastes and resins we work with, this is not a huge issue.

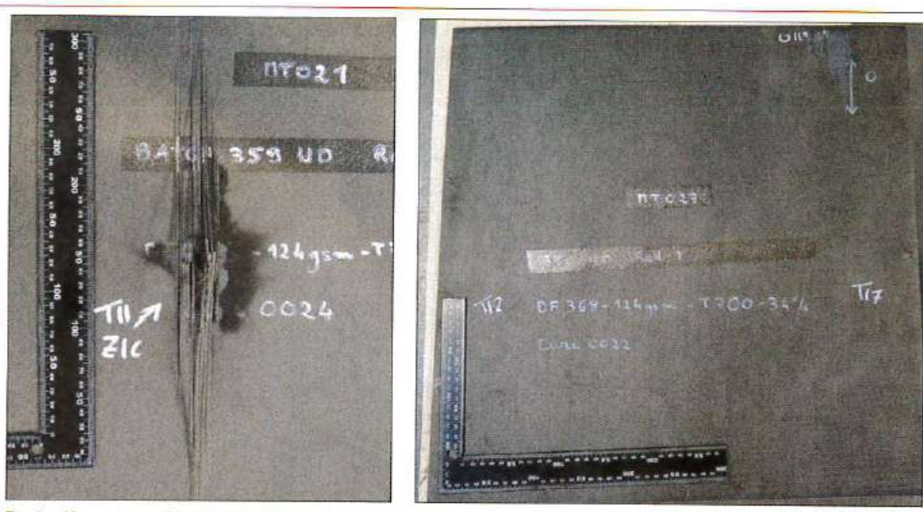
Alternatively, graphene can be produced layer-by-layer in a "bottom up" method such as chemical vapour deposition using methane gas or another carbon source. This process typically requires operating a reactor at energy-intensive temperatures (900 °C or more), and the reactors must also be cleaned after each batch is produced. Additionally, in many cases the graphene sheets produced by this method are not single layers but FLGs two or three layers thick. Expensive "release tapes" must then be used to peel off individual layers.

Clearly, graphene produced via the top-down method is very different from the bottom-up variety, both in its properties and in its manufacturing cost. However, due to a lack of industry standards, many different carbon nanomaterials can be described as "graphene". As a result, the prices of similarly labelled products can range from \$50 to more than \$2000 per kilogram. The temptation is to plump for the cheapest one available, but often this is not the best option. This is because every material produced at the nanoscale is different – in flake size, thickness and, crucially, the types and amounts of chemicals bonded to its surface and ends. These chemical groups are often involved in binding the graphene to other materials, and can thus affect the properties of the mixture. For example, a material with a lot of oxygen groups will act as an insulator, not a conductor. The size and shape of the flakes can also affect thermal conductivity, electrical conductivity and/or mechanical uplift.

> Mixing and dispersion know-how is crucial to functionalizing graphene

In our experience, whatever the desired application, mixing and dispersion know-how is crucial to "functionalizing" graphene (that is, getting other chemical groups to bond with it). Carbon as an additive is inert and does not mix well with other materials, so to get it to disperse in a homogeneous fashion, one needs both a good understanding of functionalization and a detailed knowledge of the particles' size and shape – which, when the particles are 2–5 μm across, requires special skills and equipment. It is also worth pointing out that adding nanomaterials to other substances does have some potential drawbacks; for example, it could change the viscosity of a resin, which can affect later steps in the production process. Often, there will be a trade-off between the desired performance of the final product and other properties that existed before the nanomaterials were added.

To develop our understanding of these issues, Haydale has conducted an 18-month programme of research in collaboration with Huntsman Advanced Materials using its high-end epoxy resin, Araldite. This work has given us considerable expertise of the mixing and processing techniques required to properly disperse graphene and other nanomaterials into a thermoset or thermoplastic resin. It has also become abundantly clear that adding a second nanomaterial (such as carbon nanotubes or silicon carbide) alongside graphene can have significant effects on performance, over and above the effects of purely adding graphene alone. We believe that this process, which we term "material hybridization", holds great promise for the future commercialization of composites and, indeed, other materials such as inks.



Haydale Composite Solutions

Protective properties The image at left shows the back face of a conventional, unprotected (that is, without copper mesh) composite panel after it was subjected to a severe lightning-strike event. "Punch-through" damage is clearly evident. The image at right shows a similar post-strike image, but in this case the panel had been modified with functionalized nanoparticles, and shows no visible back-face damage.

Taking flight

Since 2014 scientists at Haydale have been using functionalized graphene to improve the performance of carbon-fibre composites in the aerospace industry. This project was based on requirements specified by the Centro Italiano Ricerche Aerospaziali (CIRA), and was managed by an integrated team from CIRA, Haydale and the school of engineering at Cardiff University in the UK, with financial support from the Europe-wide Clean Sky Joint Technology Initiative.

Compared to resins, carbon fibres are immensely stiff and strong, so the structural properties of a component made from a fibre-reinforced composite is dominated by the properties of the fibre, not the resin. Hence, even though adding functionalized graphene to neat resin has been shown to double the resin's stiffness, one would expect the effect on the macrocomposite to be smaller. Our research investigated the effects of adding both GNPs and carbon nanotubes to resins, and we observed a 13% increase in compression strength and a 50% increase in compression after impact performance. These are both significant results, since damage resistance and compression properties are of paramount importance in high-performance structures such as composite aircraft wings.

In addition to stiffer, stronger materials, the aerospace industry is also looking for better ways of preventing lightning-induced damage to aircraft. Currently, copper mesh is built into the body of aircraft to dissipate electric charge from lightning strikes, but this mesh adds considerably to the aircraft's weight. If the actual fabric of the aircraft could be made to conduct electricity, this would render the mesh unnecessary and save substantial amounts of fuel.

Scientists in Haydale's composite division (Haydale Composite Solutions) are currently working with industrial partners such as Cobham Technical Services, Airbus and BAE Systems on two research projects that use functionalized nanoparticles to make aircraft components electrically conductive. The first project, Graphene Composites Evaluated in Lightning Strike (GraCELS), is investigating how functionalized nanoparticles affect the conductivity of carbon fibre-reinforced epoxy panels. The GraCELS experiments have shown that adding nanoparticles to the epoxy substantially improved the panels' electrical conductivity, and greatly enhanced their tolerance of lightning-strike damage. In particular, the modified panels showed no sign of "punch through" damage when subjected to a severe lightning-strike event (see images above).

The second project, known as Graphene-Enhanced Adhesive Technology through Functionalization (GrEAT Fun), is focused on the bonds between carbon-fibre panels in aircraft, rather than the panels themselves. Adhesive bonds made using conventional techniques are generally electrical insulators, which is a problem if we want the structure of the aircraft to conduct electricity. Previous studies have attempted to improve the electrical conductivity of structural adhesive bonds by adding metallic particulates or carbon nanotubes to the bonding material, but these efforts have had limited success in producing bonds that are strong and reliable as well as electrically conductive.

The GrEAT Fun project, in contrast, will use a patented technology for functionalizing GNPs to significantly improve the electrical conductivity of adhesive bonds as well as enhancing the strength of the bonded layer. This functionalized graphene can be incorporated into a thermosetting matrix resin. Inevitably, there will be a trade-off between mechanical and electrical performance and the ease of processing the modified resin; one of the project's goals is to establish the level of graphene loading that leads to the best overall performance of the adhesive.

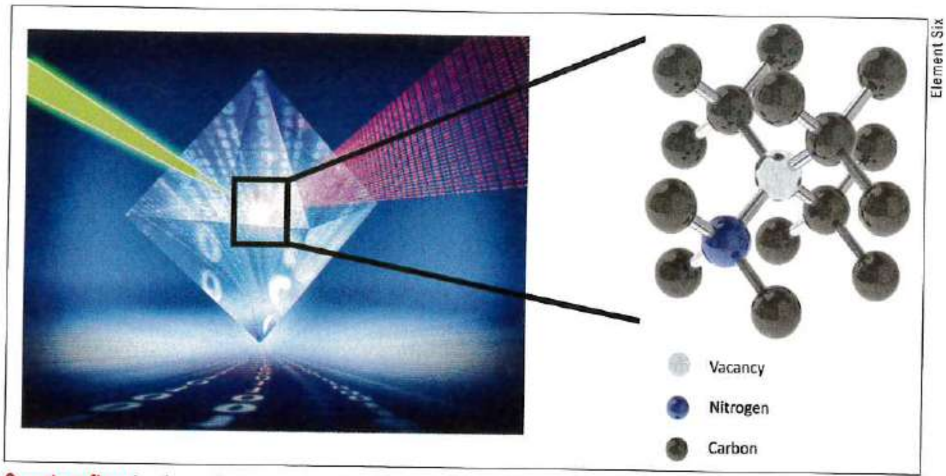
Future applications

The aerospace industry is likely to be an early adopter of the adhesives developed during the GrEAT Fun project, but other fields may also benefit. For example, improvements in the electrical conductivity of structural adhesive resin systems could enhance the performance of large off-shore wind turbines, while in the oil and gas industry, conducting resins could make it easier to dissipate static electricity and prevent it from causing damage to pipelines. As for the structural properties of functionalized graphene, there are myriad potential applications, from damage-resistant shower trays to tougher sporting equipment. The transport industry is likely to benefit, too, although here the time frame will be longer due to the regulated nature of the industry. Commercial applications for graphene may have taken longer to emerge than the hype suggested, but these recent developments could finally harness the wonder material's amazing properties.

Ray Gibbs is the chief executive officer of Haydale Graphene Industries, e-mail ray.gibbs@haydale.com

The cutting edge of quantum physics

Daniel Twitchen and **Matthew Markham** explain why carbon's most alluring allotrope could be a quantum physicist's best friend, and how the market for diamond-based quantum technologies is starting to take shape.



Quantum flaw A schematic representation of the nitrogen vacancy (NV) defect in diamond. The surrounding lattice of carbon atoms helps to shield the electronic spin state of the NV centre from noise.

In the 20th century many aspects of quantum physics were harnessed into world-changing technologies, including semiconductors, lasers and other now-ubiquitous devices. Throughout this first quantum revolution, however, one key aspect of quantum physics – superposition – has largely remained in the laboratory, a fundamental curiosity rather than a promising feature to be exploited.

However, this is about to change, thanks to several significant initiatives that aim to bring about a second quantum revolution. The key to this revolution's success will be the ability to "easily" engineer and control quantum bits. We use the word "easily" with caution, because initializing a quantum state and keeping it in a superposition for significant lengths of time is a difficult undertaking. Scientists are exploring many different approaches, using materials as varied as superconductors, synthetic diamonds, cold atoms and quantum dots, and the race is currently wide open. But diamond does have some intriguing advantages, both for quantum computation and for other applications such as magnetic-field sensing. The challenge for our organization, the industrial diamond firm Element Six, has been to support research in this area while also staying true to our core business interests in materials applications.

A useful flaw

The type of diamond that attracts would-be quantum revolutionaries has a defect in its otherwise uniform lattice of carbon atoms. This defect consists of a single nitrogen atom adjacent to a missing carbon atom, or vacancy. The nitrogen-vacancy (NV) centre has unique optical absorption and emission properties – among other effects, it gives diamond a red-to-pink colouration – and these properties have long been the focus of fundamental research on crystal structures.

In addition to its unusual optical properties, the negative charge state of the NV centre also has an electronic spin, $S = 1$, in its ground state. Remarkably, the state of this electronic spin can be controlled and read out at room temperature. The reason is that unlike most materials, the crystal lattice in diamond forms a low-noise environment, so fragile quantum properties are not lost and information can be stored and probed for longer time periods. The spin state can be read out by measuring the intensity of light given off by an NV centre as the system is excited by microwave radiation. At the NV centre's resonance frequency of 2.88 GHz, the spin state will flip from 0 to a +1 or –1, causing a dip in the intensity of red light emitted.

The robustness of this spin state, and the ease of reading it out, make NV diamond a very promising platform for a wide range of quantum technologies, with potential applications in secure communications, computing, imaging and sensing. A recent focus area for the diamond community is the use of NV defects to measure magnetic fields. Thanks to the Zeeman interaction, the gap between the frequencies of the $0 \rightarrow 1$ and $-1 \rightarrow 0$ microwave transitions in NV diamond increases as a function of magnetic field. Hence, in the simplest case, one can estimate the magnitude of the magnetic field by exposing the NV centre to a range of microwave frequencies and measuring the separation between the two dips in intensity. Remarkably, a basic measurement of this type can be performed using a single NV centre at room temperature. With multiple NV centres, the geometry of the diamond lattice means that one can make extremely sensitive measurements of the field's direction as well as its magnitude.

Advances in our diamond-making capabilities have opened up a wide range of potential applications

Raw materials

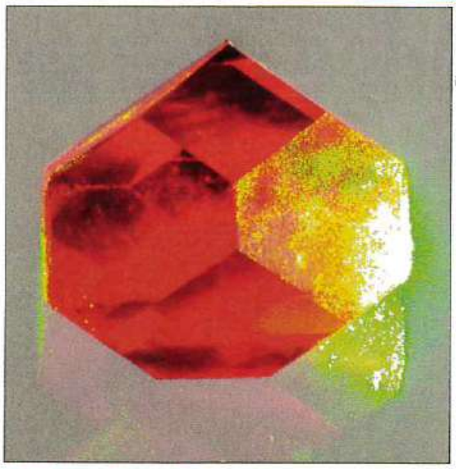
Of course, numerous technologies for estimating magnetic field already exist. These include superconducting quantum interference devices (SQUIDs), vapour cells, flux-gate sensors and the Hall-effect sensors that constitute the compass in modern smartphones. However, SQUID-based magnetometers must be cryogenically cooled, making them relatively bulky and costly to run, while other sensor technologies require frequent recalibration and offer limited frequency bandwidth for measuring changing magnetic fields. In contrast, NV diamond-based sensors do not need to be recalibrated, have a broad bandwidth and could be incorporated into a lightweight, low-powered device. Critically, NV centres can also be used to construct maps of magnetic field across a surface, thanks to the high spatial resolution provided by a microscopic probe. For these reasons, diamond-based magnetometers have strong potential both as replacements for existing technologies and as the enablers of applications where competing technologies do not yet exist.

For these applications to become a reality, though, we need a ready supply of high-quality NV diamonds. NV centres are rare in natural diamonds, and it is difficult to do much research if you are limited to working with a single sample. At Element Six we have developed methods for growing NV diamond synthetically using chemical vapour deposition (CVD). This process involves filling a microwave chamber with a mixture of hydrogen, methane and nitrogen gas, and heating it to 2500–3000 K to create a plasma. Diamond "seeds" placed in the chamber become the nuclei for new diamonds as carbon atoms from the plasma deposit onto their surfaces layer by layer. The hydrogen stabilizes the surface against forming graphite instead of diamond, while the nitrogen acts as a dopant, making it possible for NV centres to form.

This process is the result of more than 15 years of intensive R&D and it enables us to grow diamond in a controlled and scalable fashion, with a purity far exceeding that of natural diamonds. It also makes it possible to control the number of NV centres. Under high-purity conditions, small numbers of NV centres are produced via the chemistry of the growth process. These isolated vacancies can be probed individually in an experiment, so this type of NV diamond is well-suited for quantum-computation applications. Magnetic-sensing applications require higher numbers of NV centres, and we achieve this by increasing the nitrogen concentration during synthesis and then bombarding the crystal with high-energy electrons to create additional vacancies. Heating the diamond to 800 °C causes these vacancies to migrate through the crystal lattice until they encounter nitrogen atoms; at that point, the structure stabilizes, since the NV centre has a lower potential energy than a separate nitrogen and vacancy.

The value chain

Over the past decade advances in our diamond-making capabilities, coupled with a deepening understanding of the physics of quantum spins in NV diamond, have opened up a wide range of potential applications. Element Six has supported this nascent field by supplying state-of-the-art diamond samples and diamond engineering expertise to external partners, while focusing internally on making further improvements to the material. In recent years, however, we have also become more active in supporting commercial start-ups to allow them to incubate the technology and in helping larger companies assess the applicability of our diamonds to various market opportunities.


Element Six

Precision engineering Advances in synthetic diamond manufacturing have made it possible to create diamonds with the right number of NV centres for particular applications.

The breadth and depth of knowledge needed to appreciate these opportunities is significant. It requires one to consider an entire value chain: a material; a device made from that material; the package surrounding that device; the subsystems and systems the device fits into; and finally the user. As is often the case, the commercial value of this chain is concentrated at the subsystem and system level. But Element Six is a materials company, and we have grown by developing novel materials that address problems across multiple markets and industries. Making devices, let alone complete systems for end users, is not really our speciality. So how can we access the value at the other end of the chain?

Rather than changing our strategic focus, we have instead sought to exploit diamond quantum devices by communicating their "value proposition" to end users. A basic demonstration of the NV centre's ability to measure magnetic field is not difficult, and a prototype device can be made using remarkably simple components such as off-the shelf diode lasers and photodiodes, and coils of wire to deliver the microwaves to the sample. Packaging all of this together into a robust unit is less trivial, of course; ultimately, the performance of a diamond sensor will depend not only on the material itself and Element Six's expertise, but also on the stability of surrounding components and the data-processing algorithms used to transform raw measurements of light intensity into an accurate and highly sensitive map of the vector magnetic field. Nevertheless, it is always much easier to convince people of a device's potential with a demo than with PowerPoint slides.

Another component of our strategy has been to partner with university researchers who are developing diamond-quantum-device technology. This has enabled us to secure some intellectual property (IP) on the physics needed to make working devices – although, crucially, we actively avoided filing patents for the actual applications because we wanted to leave third parties free to develop their own. Our university partners have also been an important bridge between us and potential end users. Making a diamond-based quantum device (or indeed any quantum device) requires knowledge of quantum physics, and since this is an emerging industry most organizations do not yet have that expertise. Combining our IP and materials know-how with their quantum-physics expertise enabled us to start talking to organizations that were actually in a position to develop this technology. In addition, many of the academic groups we work with have produced spin-out companies. We have supported these companies with materials sales and knowledge-sharing, and we anticipate that the applications they develop will be a growth area for Element Six over the coming years.

Potential gems

Diamond quantum technologies are extremely promising, with many applications already at the proof-of-concept stage. These include applications in materials characterization such as nanoscale imaging of the write heads for next-generation magnetic hard drives, and biological imaging. New sensing methods for pressure and temperature, plus the alluring possibility of diamond-based quantum computing, makes this an exciting and productive area.

We foresee that diamond will continue to be used as a tool to aid our understanding of the quantum world. However, the real excitement concerns the possible technologies that this understanding will enable. In late 2016 a group of researchers led by Ron Walsworth at Harvard University, US used NV centres in diamond to study neuron activity in marine worms, measuring the tiny magnetic pulses from single neurons with high spatial resolution. No other existing technology can perform measurements at such high sensitivity and resolution; the maximum spatial resolution of standard MRI scans is about 1 mm^3, whereas diamond-based magnetic field sensing could, in theory, give us cellular-level images of chemical processes. We expect that this proof-of-principle experiment will be followed by breakthroughs in our understanding of how the brain works, as well as new diagnostic methods and treatments.

Daniel Twitchen is head of CVD business development (www.e6cvd.com) and **Matthew Markham** is a principal research scientist at Element Six, e-mail daniel.twitchen@e6.com

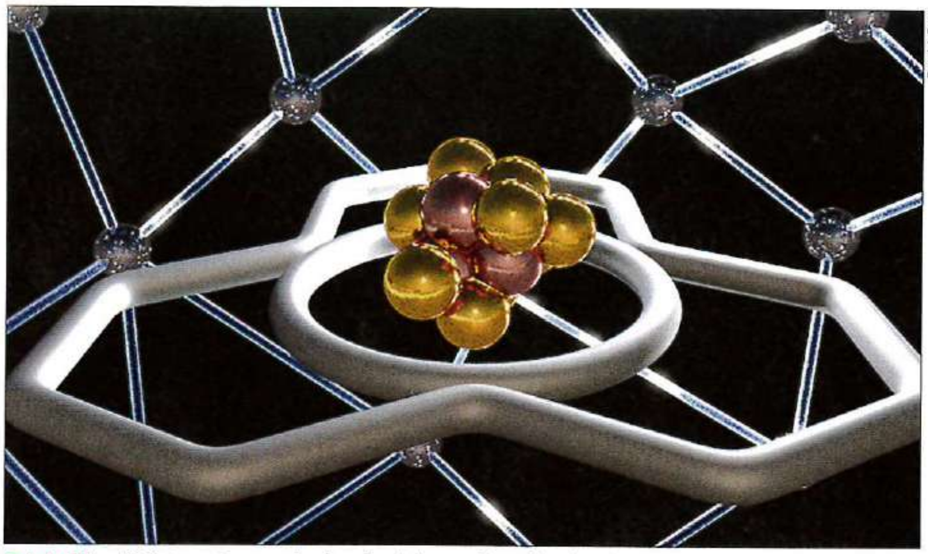
Computational nanoscience

Bridging the gap

Theoretical physicist and nanotech start-up founder **David Gao** tackles the challenges of working at the interface between academia and industry

When academics go looking for funding it is common (some might even say required) for their grant proposals to play up the industrial applications of their research. However, bridging the gap between fundamental research and industry is often difficult. One of the most important aspects of scientific research is the way it explores the unknown. This comes with a significant level of risk. The most interesting problems are often the most challenging ones and even seemingly straightforward questions are never as simple as they initially appear.

Academic research embraces the uncertainty that comes with this risk, celebrating the discovery of new questions and, in some cases, finding answers that are unrelated to the original line of enquiry. In contrast, within a commercial enterprise the most critical aspects of research projects are specific "deliverables" and the particular business needs they serve. Most companies do not have the resources to exploit new discoveries in unrelated fields or sectors, and instead focus on generating tangible returns within their own space.



Catalyst Combining quantum-mechanics simulations and machine-learning techniques to design the next generation of catalyst nanoparticles.

Best of both worlds

In an attempt to get the best out of both of these worlds, companies and academics sometimes form customer–provider relationships in which the industrial partner essentially pays for a research service. In this way, the company can retain all the desired intellectual property rights and clearly define the work plan and goals. The academic partner in turn receives much needed funding, as well as a valuable route towards applying their results. However, this relationship can become strained if the academic partner aims to develop new methods and build fundamental knowledge while their industry counterpart is expecting a specific deliverable or product. Unfortunately, in many sectors fundamental research is seen as an extremely long-term investment, making it one of the first budgets to be cut during a downturn. This can be problematic for academic partners.

I have personally experienced situations like this from both sides, having been both the industrial partner and the academic at various points of my research career. While working as an industrial materials scientist at Chevron I could see my research turn into tangible advances in technology. However, I was often frustrated by the fact that studying fundamental mechanisms and method development was given low priority. I then decided to return to academia, joining Alexander Shluger's group at University College London (UCL) to focus on the theoretical modelling of material properties. While I was now able to throw myself into studying fundamental mechanisms, it became difficult to see how my work developed into real-world products. So, when I took a step back and looked closely at what research and development means to me, and where I wanted to position myself, I decided to use my experience in both academia and industry to try to reconcile these two goals. My interest lies in pushing the boundaries of our knowledge, so becoming a contracted problem-solver was not an ideal arrangement. Instead, I decided to embark on an exciting journey: I started a new company, Nanolayers Research Computing, with a few like-minded colleagues.

People are often curious about this approach, and I am sometimes asked how I balance an academic life and an industrial one. In fact, this is quite demanding. I have given up a lot of nights, weekends and holidays, and even so, it would have been extremely difficult to stay motivated without the encouragement and support of close friends, family and my group at UCL. Another common question is "What does your company actually do?" The short answer is that we apply computational chemistry, physics and machine-learning techniques to design and develop new materials for a variety of industrial applications. However, what that statement actually means in practice is not transparent. How does a materials design firm – and a heavily theory-based one at that – fit in to a landscape of chemical, pharmaceutical and electronics companies?

Novel nanoparticles

For Nanolayers, part of the answer lies in the European Union's Horizon 2020 framework. This framework incorporates a role for companies that are designated as "translators" because they help research groups connect with people in industry who might want to use the group's software or methods. Our years spent in the theoretical physics community gave us an excellent network of potential university collaborators, while my past life as an industrial materials scientist provided several useful industry connections. Before long, we were invited to join a Horizon 2020 project that aims to replace certain critical, industrially-relevant catalyst materials with novel transition-metal nanoparticles.

Computational nanoscience

Within this project, known as CritCat (www.CritCat.eu), our role is to apply machine-learning techniques to results and data collected by our academic partners. We then use our findings to develop catalyst materials that do not incorporate elements such as platinum-group metals, which are of critical importance in Europe due to their cost and scarcity. Our strategy for catalyst design is to figure out what features are relevant in describing these materials and then train neural networks to learn how these features correlate to catalytic activity. This allows us to learn the mechanisms behind what makes a good material, and thus design and control the properties of our materials. We then design new nanoparticles that are subsequently produced by our manufacturing partners and then validated in real-world trials.

As a small-to-medium-sized enterprise (SME) capable of interfacing not only between academia and industry but also between theory and experiment, we hold a unique position within the CritCat project. We have taken a leading role in the dissemination and the exploitation of our technology, and have also leveraged our expertise in computational chemistry and theory techniques to provide additional support services and method development for our theory partners, who are based at Finland's Aalto and Tampere universities.

Beyond materials science

When I got the opportunity to network with other materials design-focused companies and projects such as NoMAD (novel materials discovery), one of my take away messages was the importance of developing a marketable product along with a diverse skillset. Since Nanolayers' core values involve performing exploratory research rather than commercializing something that has already been tested, we decided to take on more of a consulting or partner role and looked for an opportunity to apply our expertise and experience in other sectors. Our goal was to use our simulations and machine-learning techniques in an equal partnership with someone capable of producing marketable devices or software.

To this end we recently formed a partnership with two firms (GV Concepts in the US and eQuumSoft in Asia) to develop new technologies for monitoring vital signs and conducting medical pre-screenings remotely. By continuously monitoring patients' vital signs, clinicians may be able to spot qualitative early-warning signals for a variety of potential illnesses, and intervene if the risk is deemed high enough. The challenge is to do this outside a clinical setting, so that patients – particularly those who are elderly, high-risk or suffering from chronic diseases – can record these vital signs in the comfort of their own homes. This is a complex task, one that involves digital devices, diagnostic tools and complementary vital-signs data-collection software. Our solution will make it possible for patients to monitor their own health in a personalized way using a set of patented diagnostic tools including a digital stethoscope, otoscope, blood-pressure monitor, oximeter, thermometer, ophthalmoscope and camera. These devices are all integrated with a smartphone-based software suite that not only enables patients to connect remotely with healthcare professionals, but also allows doctors to remotely control diagnostic tools during the "virtual visit".

David Gao

Personalized care A suite of patented electronic medical attachments enhances a doctor's "virtual visit", reducing wait time, eliminating distance barriers and cutting overhead costs.

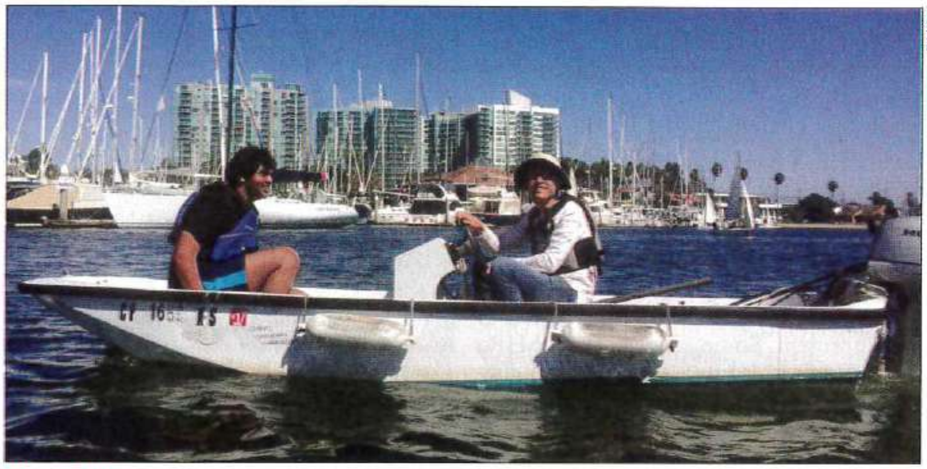
We use the data collected in this project in a way that is similar to the method we employ for designing novel materials. In this case, we are seeking symptom–disease relationships rather than structure–performance ones, but the strategy of using machine-learning techniques to identify relevant relationships is the same. For example, we use neural networks for image recognition and signal processing to help healthcare professionals interpret the collected data.

As we pick up more projects and partnerships that are structured in a similar way, Nanolayers continues to expand while focusing on the theme of bridging the gap between fundamental scientific knowledge and techniques and industrial applications. In this way, we can enjoy the best of both worlds by exploring new materials and techniques while making sure that the discoveries and advancements we make are applied in a meaningful way. Time spent on improving our own methods and gaining experience is not wasted. After all, one of our most important products will always be the research team itself.

David Gao is a research fellow at University College London, UK, and the founder and director of Nanolayers Research Computing, e-mail david@nanolayers.com

Smooth sailing

Superhydrophobic surfaces with the right microscopic structures could be the key to reducing friction on marine vessels, as **CJ Kim** explains



The call of the sea University of California, Los Angeles graduate students Shashank Gowda and Muchen Xu are testing superhydrophobic surfaces attached to the bottom of a motorboat in Marina del Rey, California.

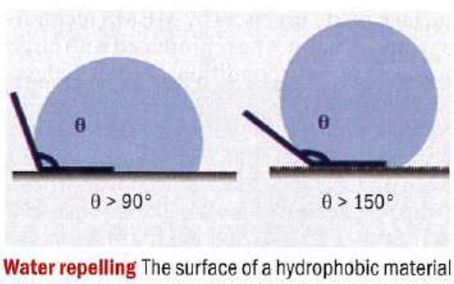
Ocean-going ships face a constant struggle. In order to maintain their motion, they must continuously overcome the drag of the water that surrounds them. When one considers that marine shipping accounts for 4% of all fossil-fuel use, a similar percentage of climate-change-causing emissions and more particulate pollution than all of the world's cars combined, it is clear that reducing this drag by even a small fraction would bring considerable benefits. Since the drag consists mostly of friction between the skin of the moving hull and the stationary water around it, lubricating this surface to reduce frictional motion would be a big help in reducing total drag.

We usually think of lubricants as being liquids, such as oil, but when friction occurs between a solid and a liquid, gas is the only real option for lubrication. For example, a torpedo can "fly" underwater, reaching otherwise unimaginable speeds, if a large pocket of water vapour engulfs its entire body via a method known as supercavitation. Also, blowing air bubbles onto the bottom side of a ship's hull would allow the ship to move faster at a given propelling power.

You might ask, then, why we do not have gas-lubricated boats around us already. The problem is that unlike a liquid lubricant on a solid surface, a gas lubricant on a solid surface in a liquid (such as air in water) will leave the surface rather than staying on it. And unfortunately, providing a continuous supply of a rapidly disappearing gas consumes a lot of energy, which tends to cancel out the energy saved through lubrication, limiting the overall benefit.

Superhydrophobicity to the rescue

This frustration helps to explain why superhydrophobic (SHPo) surfaces were so exciting when, in the early 2000s, researchers began considering their applications for drag reduction. A SHPo surface is one that repels water much more strongly than usual. For example, a Teflon surface will repel water, forming a contact angle of around 110° between the water droplet and the surface. However, when such a naturally water-repellent material is roughened, water will sit on top of the roughness as if levitated by the air in the rough surface, with contact angles increasing to more than 150°. As a result, the water will bead up and roll straight off when the surface is tilted. This "lotus leaf" effect has been a very popular topic in science and engineering for the past two decades, and thousands of images and online videos vividly demonstrate its intriguing properties.



Water repelling The surface of a hydrophobic material (left) becomes superhydrophobic when roughened, as water sits on the top of the roughnesses (right).

If SHPo surfaces repel water so well, they must reduce the drag of water – or so the thinking went. Returning to the gas lubrication process discussed above, it was speculated that gases would persist on the SHPo surface, and thus finally make it possible to lubricate water friction with a gas layer that would not dissipate. Yet despite this logical expectation, and a torrent of research activities worldwide over the last 15 years, so far no publication has reported a successful demonstration of superhydrophobicity reducing the drag on a boat in ocean water. This article discusses why this is so, and whether there is a light at the end of this tunnel.

To identify the problems, let's break down the issues. First, is it at least theoretically possible to obtain an appreciable drag reduction using a SHPo surface for real applications, such as a boat? Second, would a SHPo surface really save us from having to constantly supply a gaseous lubricant? Third, would it be economical to produce and implement such a SHPo surface for practical applications?

Enough drag reduction?

Scientifically, there is no doubt that a layer of air (known as a "plastron") on the SHPo surface in water will lubricate the motion and help reduce the drag. The real question is, just how much reduction are we talking about? If it is more than 10%, for example, that would be meaningful in practice. If the reduction is below 1%, however, we would not expect much impact in the real world even though it would still be scientifically interesting.

Despite the excitement generated by the idea's scientific merit, and some encouraging early experimental results, it took nearly 10 years for the research community to understand how much drag reduction would be possible, and on what kinds of SHPo surfaces. Looking back, a few reasons for the slow advance are apparent. First, hydrophobicity is related to drag reduction, but not directly. Since the dynamics of bulk water and droplets are fundamentally different, a surface more favourable for droplet rolling is not necessarily more slippery to water

Advanced nanomaterials

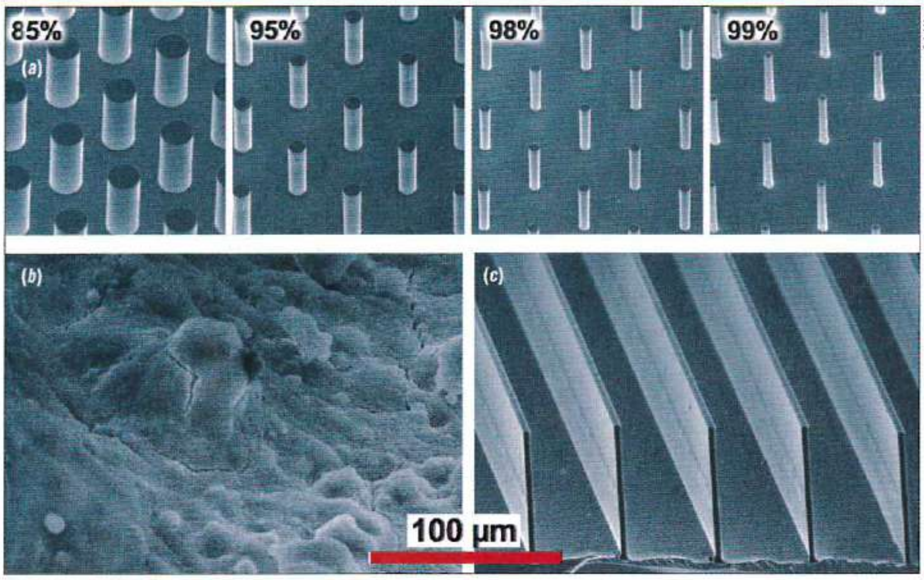
continuously flowing by. The underlying, and still widespread, notion – that if a SHPo is very repellent to water, then it must be also very slippery to water flowing on it – is now known to be flawed.

Second, there was some confusion between drag reduction and the "slipperiness" of the surface. These concepts are linked, but they are not the same thing: the amount of drag reduction is determined not only by how slippery a surface is, but also by the flow system where the surface is employed. This means that for a given drag-reducing surface, one may obtain 50% drag reduction in a microscopic channel but not even 0.1% reduction on a boat. This mix-up made it difficult to objectively compare one SHPo surface with another in terms of their ability to reduce drag.

A third source of delays was related to measurement. Some early work on SHPo surfaces reported fantastically large reductions in drag – reductions that we now know were impossible. In many cases, the errors seem to have come from the challenge of measuring drag reduction accurately. While the observed trends may have been correct, the actual amount of reduction was simply wrong. These early, incorrect experimental data probably slowed down the establishment of the knowledge base for SHPo drag reduction.

Today, the research community uses an objective measure called "slip length" to describe the slipperiness of a given SHPo surface. We also understand how much drag reduction a particular slip length will entail under a certain flow condition, at least for turbulence-free (laminar) flows. Micro and nanofabrication technologies using microelectromechanical systems (MEMS) have played a key role in advancing the field. By enabling researchers to construct SHPo surfaces with exact and deterministic micro and nano structures (figure *a*), rather than random roughness (figure *b*), these technologies have made it possible to confirm theoretical predictions about SHPo behaviour. In a nutshell, we have learned that a SHPo surface will be more slippery (that is, its slip length will be large) if its microstructures are slender (more void spaces and fewer solid portions) and dispersed (greater distances between the structure peaks).

These theoretical predictions have been confirmed for laminar flows. If we extrapolate this to turbulent flows, it seems that a highly slippery surface, consisting of slender microstructures dispersed far apart, is required before a boat will enjoy an appreciable reduction in drag. By fabricating SHPo surfaces full of parallel trenches tens of microns apart with a large void space between them (figure *c*), our lab has reported drag reductions as large as 75% in turbulent flows. This level of reduction



Exact construction vs random roughness These periodic microstructures were made precisely by microelectromechanical systems and helped to establish a quantitative relationship between a superhydrophobic surface's geometry and how slippery it is. The percentages are the proportion of void spaces on the superhydrophobic surface; surfaces with higher void percentages proved more slippery in tests.

was obtained under well-controlled flow experiments using a small (2×2 cm) SHPo surface made precisely by MEMS technology, and it may not be reproduced with large surfaces in field conditions. Nevertheless, it demonstrates the potential of SHPo drag reduction. The theory also suggests that more typical SHPo surfaces (figure *b*) with microscopic random roughness would have a slip length that is too small to induce any appreciable drag reduction for macroscale applications such as a boat in open water.

Maintaining an air layer

Recall that in the early days, SHPo surfaces were considered promising for drag reduction because of their presumed ability to retain an air layer (plastron) between the surface and water even when fully submerged. The assumption was that this plastron would persist for as long as it was needed to keep the surface lubricated. The reality is not so simple, and plastron behaviour is currently the most critical issue in the field of SHPo drag reduction.

Unlike in air, where microscopic voids between microstructures or roughness in a SHPo surface stay dry even after temporary wetting by water droplets, a SHPo surface fully submerged in water will become wetted once it loses the plastron. And unfortunately, the plastron is easily lost underwater because hydrostatic pressure forces the surrounding water into the spaces between microstructures. The smaller the spaces, the more persistent the plastron – but as we have already noted, narrowly packed SHPo structures are not very slippery. We cannot have it both ways: careful quantitative studies have shown that SHPo surfaces capable of providing an appreciable (>10%) drag reduction for a boat simply cannot retain the plastron if the SHPo surface is submerged to a depth of more than a few centimetres. For most applications the surface would need to be much deeper than that.

If the plastron will be lost for most applications, the principle of SHPo drag reduction won't apply to them either. Faced with this fundamental limitation, the only reasonable approach that is valid for all flow applications is to replenish the lost gas – ideally, using a method that is simple to implement and consumes a minimal amount of energy. Our lab is pioneering such an approach, but much still needs to be learned before it becomes practical for real-world applications.

Most drag-reduction research has been performed using SHPo surfaces with microstructures that are randomly rough. This is mainly because such surfaces are easy to fabricate: all you need to do is apply a commercially available SHPo spray coating. In contrast, SHPo surfaces with well-defined periodic microstructures, and thus a superior slip, would be simply too expensive to manufacture and implement on a ship hull – or so the discussion goes. The inconvenient fact, however, is that a surface with micro-

> We now understand the potential as well as the limitations of SHPo drag reduction much better than we once did.

scopic random roughness is simply not capable of providing enough slip to achieve meaningful drag reduction in most practical applications. A better approach would be to address this economic challenge by developing techniques to mass-manufacture SHPo surfaces that do have a chance of providing appreciable drag reduction.

Another reason why random SHPo surfaces continue to be studied, despite the well-established theory that indicates their severe limitations, is that one can also find many successful results reported in the literature. The reason for this apparent contradiction lies in the way drag reductions are tested. Most drag-reduction experiments have been performed in a water tunnel, in keeping with traditional flow experiments. But as my group confirmed recently, in flow tests using a water tunnel, the water quickly becomes supersaturated with air. In this supersaturated condition a very thick plastron forms on random SHPo surfaces, assisted by the few tallest rough protrusions. Naturally, one obtains a large drag reduction in these conditions: basically, you get the plastron you would expect from a SHPo surface with slender microstructures spaced far apart.

The problem, unfortunately, is that this thick plastron would disappear in open-water conditions, where the water is mostly undersaturated and tends to take the gas away. This dissimilarity between the water tunnel and open-water conditions is most likely why apparently successful lab studies have so far never been repeated in the real marine environment. In fact, the rare studies carried out in tow tanks actually reported an *increase* in drag, rather than a reduction, with random SHPo surfaces. The increase is understandable because high peaks of the random roughness will penetrate into the water once the plastron becomes thin, impeding the flow – rather like a coating of tiny barnacles.

On the other hand, a SHPo surface that is slippery enough to produce appreciable drag reduction in macroscale applications (such as a boat) is difficult to test in open-water conditions. These types of SHPo surface have large spaces between microstructures so they lose the plastron easily, and since they must be fabricated using MEMS technologies, it is difficult to manufacture the relatively large samples (more than $1\,m^2$) used for open-water tests. Actual boats are, of course, even bigger, and their hulls are curved. But these challenges are practical rather than fundamental. By developing ways to get around them, rather than confronting them head on (which will take much longer), my lab is currently performing experiments using a motor boat that replicates field conditions as closely as possible.

Clear water ahead?

After nearly two decades of research we now understand the potential as well as the limitations of SHPo drag reduction much better than we once did. We can predict how slippery a SHPo surface is and how much drag reduction is possible at a given flow condition. Although most of our understanding deals with laminar flows, we can extrapolate this to a certain extent for turbulent flows, including open-water conditions. My group has very recently obtained a 30% reduction with a boat in ocean water. This result is preliminary, but its unprecedented success is grounded in the extensive body of scientific knowledge summarized briefly in this article. It is, perhaps, a peek into the future of marine transport.

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News & Analysis

First black hole images unveiled

The Event Horizon Telescope has taken the first-ever images of a black hole, a breakthrough that lets astronomers study the event horizon of supermassive black holes. **Michael Banks** reports

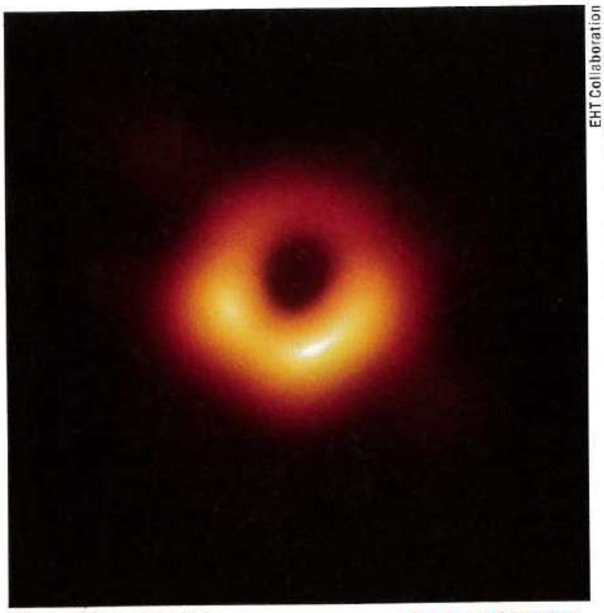
The first direct visual evidence of a black hole and its "shadow" has been revealed by astronomers working on the Event Horizon Telescope (EHT). The image is of the supermassive black hole that lies at the centre of the huge Messier 87 galaxy, in the Virgo galaxy cluster.

Located 55 million light-years from Earth, the black hole has been determined to have a mass 6.5 billion times that of the Sun, with an uncertainty of 0.7 billion solar masses. Although black holes are inherently invisible because of their extreme density and gravitational field, the researchers have managed to obtain images near the point where matter and energy can no longer escape – the event horizon.

"We are giving humanity its first view of a black hole – a one-way door out of our universe," says Sheperd Doeleman of the Haystack Observatory at the Massachusetts Institute of Technology (MIT) who is the EHT's lead astronomer. "This is a landmark in astronomy, an unprecedented scientific feat accomplished by a team of more than 200 researchers." Doeleman says that the result would have been "presumed to be impossible just a generation ago", adding that breakthroughs in technology and the completion of new radio telescopes over the past decade have allowed researchers to now "see the unseeable".

"General relativity has passed another crucial test," adds theorist Avery Broderick from the University of Waterloo, Canada, who was involved with interpreting the results from the EHT. "Seven complimentary windows have now opened on black holes. Science fiction has become science fact."

The EHT results have been published in six papers in a special issue of *Astrophysical Journal Letters,* which is published by the Institute of Physics on behalf of the American Astronomical Society. All the papers are free to read (ow.ly/Ajwa50pSHpO).



EHT Collaboration

Seeing is believing The first-ever image of a black hole is of the one that lies at the centre of the Messier 87 galaxy. Taken on 11 April 2017, the image shows a bright ring, which is the effect of photons being warped as they travel around the black hole. The central dark spot is the so-called "shadow" of the black hole, in which lies the event horizon.

Discs of glowing gas

Supermassive black holes are thought to lie at the centres of most galaxies in the universe, and astronomers are keen to decipher their key properties – such as how their extreme gravity affects the space–time around them, and how some of them fuel the massive jets of material that spew out from the galaxies that host them. A key feature of a black hole is its event horizon – the boundary at which even light cannot escape its gravitational pull, as the velocity required to do so would be greater than the speed of light, which is forbidden by Einstein's general theory of relativity. And while that theory has passed many tests, researchers want to see how well it holds up at the "ultimate proving ground" – a black hole's edge.

Despite their name, black holes are not, however, all dark. The gas and dust trapped around them in an accretion disc is so compact that it is often heated to billions of degrees even before the matter eventually succumbs to the black hole, making them glow brightly. Indeed, general relativity also predicts that a black hole will have a "shadow" around it, measuring around three times larger than the event horizon. The shadow is of great interest as its size and shape depend mainly on the mass and – to a lesser extent – on any possible spin of the black hole, thereby revealing its inherent properties.

"If immersed in a bright region, like a disc of glowing gas, we expect a black hole to create a dark region similar to a shadow – something predicted by Einstein's general relativity that we've never seen before," says Heino Falcke from Radboud University in the Netherlands, who chairs the EHT's science council. "This shadow, caused by the gravitational bending and capture of light by the event horizon, reveals a lot about the nature of these fascinating objects."

Experimental tour-de-force

To directly observe the black hole at the centre of Messier 87 – dubbed M87* – astronomers require a telescope with an angular resolution comparable to the event horizon, which is on the order of tens of microarcseconds across. But to achieve that resolution with an ordinary telescope – which is like spotting an orange on the surface of the Moon – would require a dish the size of our planet, which is clearly impractical.

EHT astronomers instead use the radio-astronomy technique of very-long-baseline interferometry (VLBI). It involves picking up radio signals from an astronomical source by a network of individual radio dishes and telescopic arrays scattered across the globe. The EHT, which first turned on in 2007, consists of eight radio telescope observatories in six different locations across the globe all operating at a wavelength of 1.3 mm. These telescopes include the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile, the South Pole Telescope (SPT) in Antarctica and the IRAM 30 m telescope in Spain. The distance between individual EHT telescopes – known as the "baseline" – ranges from 160 m to 10 700 km.

The signals received at each individual telescope dish in the network are precisely tagged with a very accurate time stamp, normally using an atomic clock at each location. Each telescope produces roughly 350 terabytes per day, which is stored on high-performance helium-filled hard drives. The data are later correlated and used to build up a complete image by supercomputers that are located at the Max Planck Institute for Radio Astronomy in Bonn, Germany, and the MIT Haystack Observatory in the US. The development of one of the algorithms used to crunch all the data and produce an image of the black hole was led by MIT graduate student Katie Bouman, whose efforts were widely reported last month.

This combination of multiple radio telescopes and computer algorithms makes the EHT the highest-resolution instrument on Earth – capable of taking images up to 2000 times better resolution than the Hubble Space Telescope and able to resolve features as small as 20 micro-arcseconds.

From theory to reality

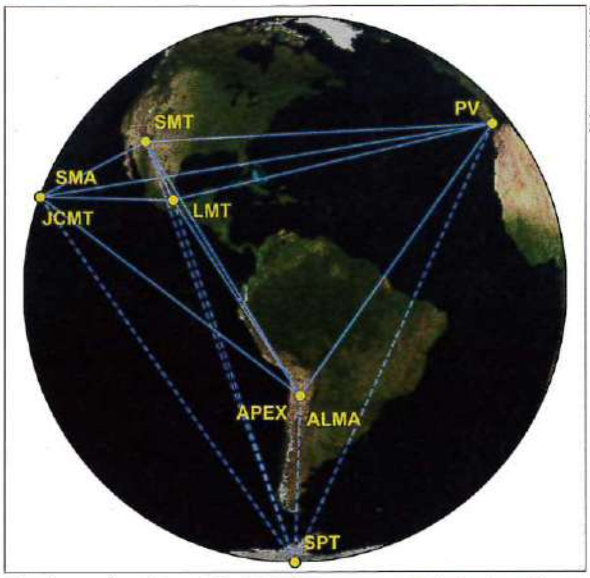
As a black hole's size is proportional to its mass, the more massive a black hole, the larger its shadow. Thanks to its enormous mass and relative proximity, M87* was predicted to be one of the largest viewable from Earth – making it a perfect target for the EHT. Astronomers observed M87* on 5, 6, 10 and 11 April 2017, with the telescope taking a series of scans of three to seven minutes in duration each day.

These multiple independent EHT observations have now resulted in the first image of a black hole including its shadow, revealing a ring-like structure with a dark central region. The diameter of the ring is 42 micro-arcseconds with a width less than 20 micro-arcseconds. EHT scientists also deduced the radius of the event horizon as 3.8 micro-arcseconds. The size of the black hole is around 40 billion kilometres across – slightly larger than our solar system.

By comparing the image with theoretical models such as general relativistic magnetohydrodynamic simulations, the observed image is consistent with expectations for the shadow of a Kerr black hole – one that is uncharged and rotates about a central axis – as predicted by general relativity. The EHT team also found that the rotation of the black hole is in a clockwise direction. The brightness in the lower part of the image is due to the relativistic movement of material in a clockwise direction as seen by us, so that it is moving towards us.

The researchers were able to deduce the mass of the M87* at 6.5 billion times that of the Sun. Previous estimates – based on models as well as spectroscopic observations of the galaxy by the Hubble Space Telescope – ranged between 3.5 and 7.7 billion solar masses. "Once we were sure we had imaged the shadow, we could compare our observations to extensive computer models that include the physics of warped space, superheated matter and strong magnetic fields. Many of the features of the observed image match our theoretical predictions surprisingly well," says Paul Ho, director of the East Asian Observatory and an EHT board member. "This makes us confident about the interpretation of our observations, including our estimation of the black hole's mass."

Sera Markoff from the Anton Pannekoek Institute for Astronomy at the University of Amsterdam says that the EHT results have now ended the "long controversy" over the mass of M87*. "Our determination of the mass lands right on top of the estimates, so this can now lead to better estimations of the mass of more distant black holes where we actually can't see the shadow."



Akiyama et al/ApJL

Global networking The Event Horizon Telescope combines the signals of eight radio telescope observatories including the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile and the South Pole Telescope (SPT) in Antarctica.

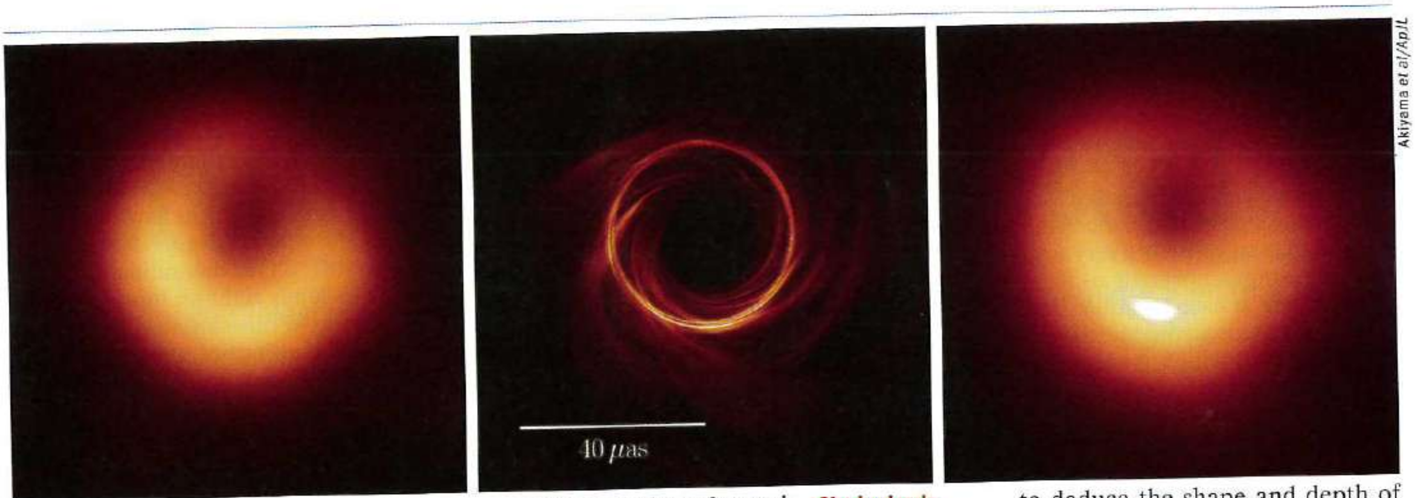
> This is a landmark in astronomy, an unprecedented scientific feat

As well as revealing the properties of M87*, the EHT has lifted a veil on the event horizon, showing that it is now possible to experimentally study the region via electromagnetic waves. This, the researchers write, has now transformed the event horizon from a purely "mathematical concept" to a "physical entity". Gopal Narayanan from the University of Massachusetts at Amherst, who built the spectroscopic imaging instruments and led the team that constructed two radio astronomy receivers at the Large Millimeter Telescope in Mexico, says that the finding is "a shot in the arm to theorists" who will now be able to test their theories with experimental data. "It's very gratifying and immensely exciting to see the results coming out after years of work," he adds. "At times it looked like an impossible task. But we showed that you can collaborate on this scale and get results. The camaraderie and team spirit was a wonderful thing to see."

Astrophysicist Rob Fender from the University of Oxford, who is not part of the EHT collaboration, says that the first production of radio images with a resolution comparable to the angular size of a black hole event horizon is a "major breakthrough" in high-energy astrophysics. He adds that the EHT observations are our best look yet at the region where the jet of the black hole is formed. "The region close to the black hole, just above the event horizon, is the site of much of the most extreme astrophysics in our universe since the Big Bang," he says. "These jets carry an enormous amount of energy away from the central black hole, via processes that are not well understood."

Building on success

While this latest result is the biggest yet from the EHT, it is not the first to come from the collaboration. In 2012 scientists working on the array managed to observe, for the first



Akiyama et al/ApJL

time, the base of the jet emanating from the M87 galaxy. The work established that the black hole at the heart of M87 is spinning and that the accretion disc follows the direction of spin. Three years later, researchers on the EHT measured the first direct evidence of magnetic fields near the event horizon of Sagittarius A* – the black hole at the centre of our Milky Way galaxy lying around 26000 light-years away but with a mass around three orders of magnitude smaller than M87*. By studying the right- and left-handed circular polarization of the incoming radio waves, they were able to infer the direction of linear polarization that traces the magnetic field, finding that it even changed on a daily basis and revealing the extreme dynamics at play at the heart of the black hole.

Astronomers now hope to carry out further observations of M87* to deduce the shape and depth of the shadow region more accurately. They are also hopeful to add more telescopes to the array that will allow for higher-resolution images. As well as M87*, the EHT team is attempting to take the first image of Sagittarius A*. But this is more difficult to resolve – despite being nearer – because it is more dynamic than M87*, changing on the scale of minutes rather than days.

Shadowlands From left to right, Event Horizon Telescope observations of M87* taken on 6 April 2017; a simulation of M87*; and a simulation convoluted to the resolution of the EHT.

Space

Israeli firm fails in private Moon landing

The first effort by a private organization to land a spacecraft on the Moon has ended in failure after contact with the Beresheet lander was lost just minutes before it was due to touch down. Had SpaceIL's craft landed successfully last month, it would have made Israel the fourth nation to reach the Moon, after the US, the Soviet Union and China.

"If at first you don't succeed, you try again," noted Israeli prime minister Benjamin Netanyahu from the control room, moments after the crash was announced. "Don't stop believing! We came close but unfortunately didn't succeed with the landing process," said the SpaceIL team via Twitter.

Beresheet was aiming to touch down within the *Mare Serenitatis* (Sea of Serenity), which lies in the northern hemisphere of the Moon. Designed to inspire an Israeli "Apollo Effect", the mission was closely followed across the world despite failing at the final hurdle.

"Beresheet offers inspiration to all those who are fascinated by space exploration but feel it is too hard or too expensive," said mission scientist Oded Aharonson from the Weizmann Institute, Israel, before the attempted landing. "In addition to learning something new about the Moon, it also offers a unique opportunity for educating young people in subjects of science and technology."

SpaceIL/IAI

Close encounters Beresheet takes a selfie during lunar landing before losing contact with mission control and crashing into the Moon.

Founded in 2011, SpaceIL is an Israeli not-for-profit organization that originally sought to win the Google Lunar XPRIZE – to build, launch and land an unmanned spacecraft on the Moon. Although Google's competition ended on 31 March 2018 with no winners, the team pushed on, making up the required $100m budget with support from philanthropists and the Israel Space Agency.

Beresheet, meaning "Genesis" in Hebrew, launched on 22 February this year on a Falcon 9 rocket. The Beresheet craft weighed 585 kg at launch and initially was put into a high-Earth orbit before being captured into the Moon's orbit on 4 April. On 11 April it began the landing process but shortly afterwards mission controllers lost contact with the mission's telemetry system before also experiencing an issue with its engine. The craft then crashed into the Moon's surface at high speed.

Not everything had been plain sailing for the SpaceIL team even before its fateful final minutes. During its journey to the Moon, Beresheet's onboard computer system crashed several times and its navigation system was blinded by the intensity of light from the Sun. "You run into the unexpected so you always have to have a plan B or some reserves because you will use that eventually," admitted Chris Russell, member of the SpaceIL Science team, ahead of the landing.

While the craft would have studied the Moon's magnetic field via a magnetometer, Beresheet's biggest legacy, however, would have been its status as the first private mission to land on our closest neighbour. In a statement after the crash, NASA nevertheless offered its congratulations for SpaceIL having sent the first privately funded mission into lunar orbit. "Every attempt to reach new milestones holds opportunities for us to learn, adjust and progress," wrote NASA head Jim Bridenstine. "I have no doubt that Israel and SpaceIL will continue to explore and I look forward to celebrating their future achievements."

James Dacey

Weighing water from space

By monitoring tiny changes to the Earth's gravitational field, the GRACE satellites have been pinpointing the distribution of fresh water on our planet for almost two decades. But as **Marric Stephens** explains, a new follow-on mission is also helping with plans for a space-based gravitational-wave detector

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Imagine the sea on a still day, calmer than you have ever seen it, with no wind to stir its surface, and no currents or tides to disturb its depths. Now imagine that the sea has risen to cover the whole face of the planet, submerging the continents and even the highest mountain peaks. What you are seeing approximates the "geoid" – a surface that joins all of the points on the Earth where the strength of gravity is the same. The geoid is the level that a hypothetical global ocean would attain in the absence of forces such as tides, winds and currents, influenced only by gravity and the rotation of the Earth.

You might expect the surface of such an ocean to be a nearly perfect sphere, albeit bulging a little at the equator due to centrifugal forces arising from its rotation. However, this hypothetical ocean is not uniform. Given that the gravitational field varies slightly across the Earth, this ocean would – in finding its natural level – flow towards areas where gravity is strongest. It would pile up over the heavy spots to produce a watery planet with a lumpy, undulating surface.

With only a few hundred vertical metres between the highest and lowest points of this ocean, it would still look remarkably featureless to the naked eye. Exaggerate the scale, however, and you would see a seascape that mirrors the geology and relief of the planet beneath. That's because the varying field strength is largely to do with the presence of topographic highs and lows, and with density differences in the crust and upper mantle. You would notice, for example, the ocean surface rising over the Andes and Himalayas – where gravity is enhanced by the huge thicknesses of continental crust – and sinking over the Indian Ocean, under which the material of the mantle appears to be unusually light.

But not all of the matter that matters is in rocks. The geoid is also shaped by more transient effects like the phase of the Moon, the motion of the oceans, and the state of the hydrosphere. Overlaid on the relatively static gravitational signature of mountain ranges, ocean trenches and deep geological features, there is therefore a constantly fluctuating signal that reveals how mass is redistributed about the Earth by dynamic processes. One of the most important contributors to this signal arises from the changing disposition of the Earth's water on a regional and global scale.

Overlaid on the relatively static gravitational signature of mountain ranges, ocean trenches and deep geological features is a fluctuating signal that reveals how mass is redistributed by dynamic processes

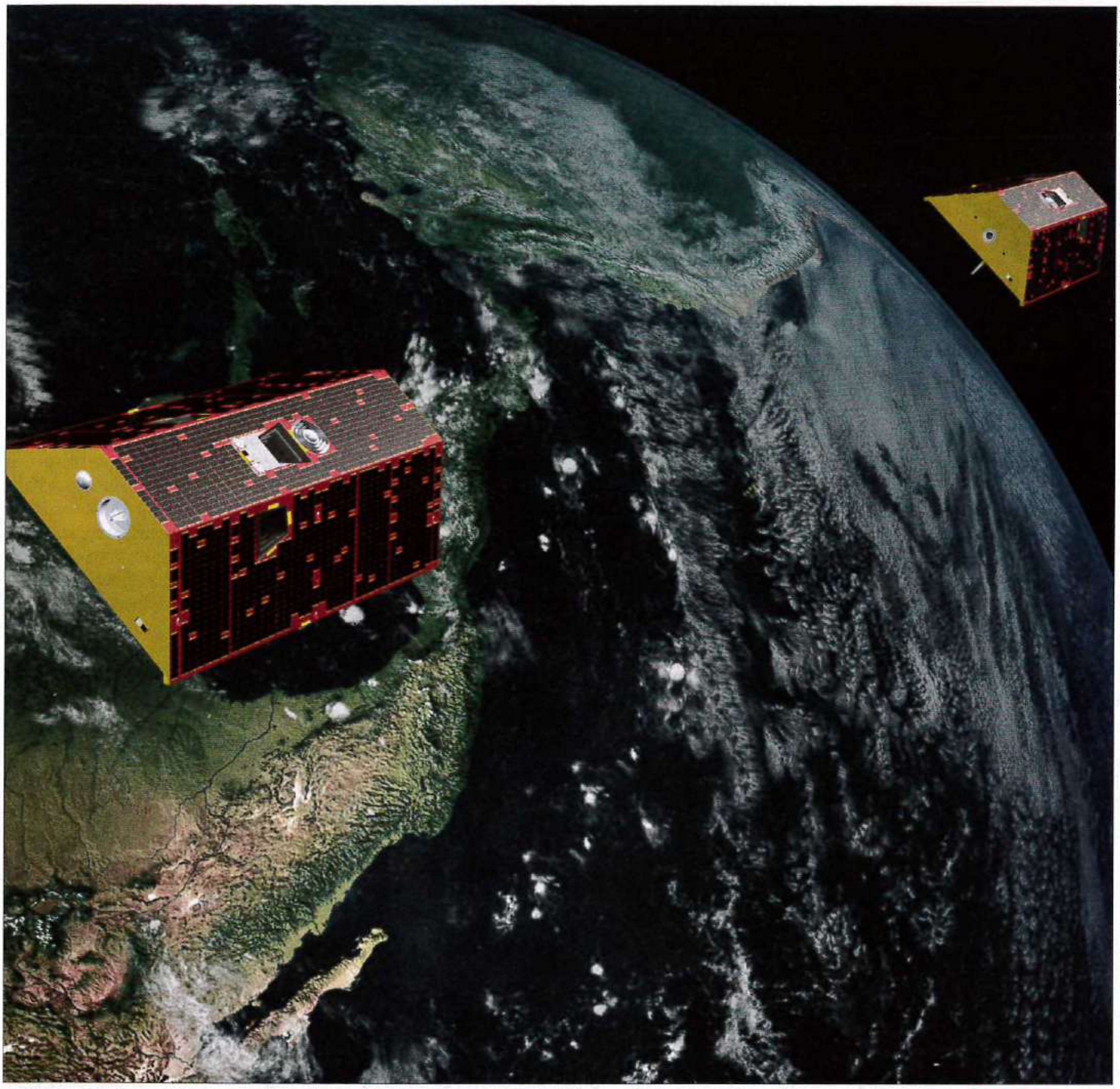
A state of GRACE

Detecting the impact of water on the geoid was one of the main aims of a space mission called the Gravity Recovery and Climate Experiment (GRACE), which was launched in 2002 by NASA and the German Aerospace Center (DLR). Its role was to map the geoid with enough sensitivity to observe tiny variations in mass distribution over months and years – the sort that allow scientists to monitor changes in sea level, ice caps and water stored on land.

Running for more than 15 years, the experiment consisted of two identical satellites, GRACE-A and GRACE-B, both orbiting the Earth's poles at an initial altitude of 490 km (although the height decayed gradually over the course of the mission). The two satellites did not fly together – instead, one orbited between 180 and 220 km ahead of its twin. The precise separation depended on various factors, including solar-radiation pressure, atmospheric drag, and any occasional forced adjustments to the crafts' trajectory to make them dodge any space debris.

However, all of these factors were just "noise" to be filtered out. The really important influence on the inter-satellite distance – the force that the experiment was designed to measure – was gravity, which increased or decreased as the spacecraft crossed contour lines on the Earth's geoid. If, say, the satellites' orbit carried them towards a mass concentration in the Earth below, the leading spacecraft would be the first to feel the greater tug of gravity, which would perturb its trajectory and extend the separation minutely but measurably. When the pair had moved on so that the mass concentration was between them, it would now be the trailing satellite's turn to feel the extra tug, while the leading satellite was pulled back in its orbit (figure 1).

Circling the Earth 16 times a day and achieving near-total global coverage every 30 days, the GRACE satellites – month by month and year by year – generated a map of where the two craft were pulled apart and where they bunched up. Mission sci-



entists were then able to translate these data into an increasingly detailed picture of the planet's gravitational field (figure 2).

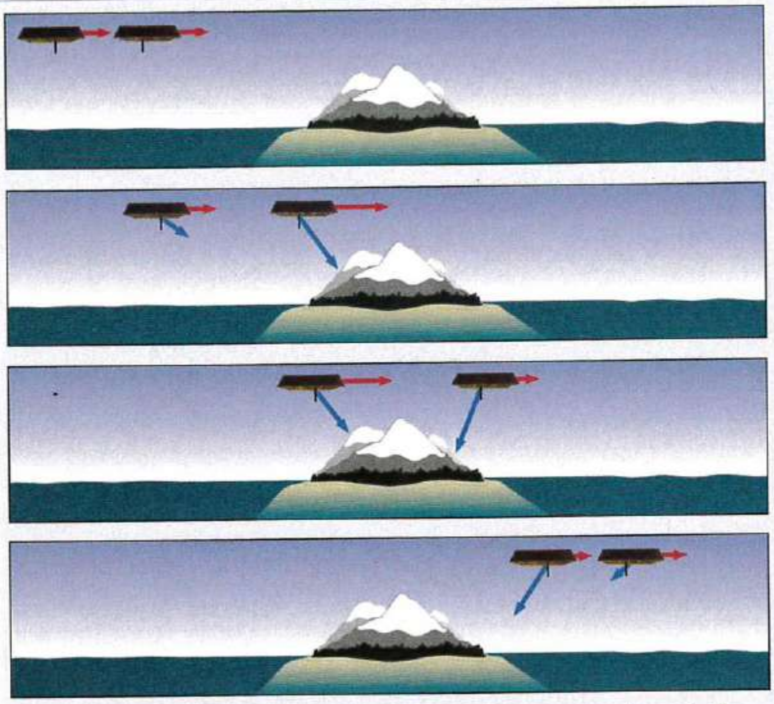
The initial sketch of the mean gravity field produced by the experiment depicted the Earth's large-scale geological structure: mountains, by definition, are big, and the gravitational signatures of such features were correspondingly easy to identify. Tracking the relatively small month-to-month changes in how water is distributed over oceans and continents, on the other hand, was a harder proposition.

The general locations of the satellites were measured using the Global Positioning System (GPS). But spotting the variation in satellite separation – and therefore gravity – associated with, for example, a depleted aquifer or a rising lake, required a sub-micron precision that GPS could not provide. Instead, the experiment sent a microwave beam from one satellite to the other, where it interfered with a reference beam on that craft. Changes in the inter-satellite distance would alter the relative phase of the two beams, revealing the shift as a change in the interference pattern.

Ascertaining the satellites' relative motion so precisely was only half the challenge, however. Also crucial was to carefully account for all the other, non-gravitational sources of perturbation, which would otherwise have overwhelmed the gravity signal. At the initial 490 km orbit height, the biggest of these effects was solar-radiation pressure, which fluctuated constantly as the satellites passed in and out of the Earth's shadow. This also created a cycle of warming and cooling, requiring sensors to measure each satellite's thermal expansion. Without this information, any change in the dimensions of one of the spacecraft could have been mistaken for a gravi-

Second step
Artist's rendering of the twin spacecraft of the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) mission, which launched in May 2018. Like its successful predecessor, GRACE-FO can monitor tiny changes in the distribution of mass on Earth.

1 A guide to the GRACEs



Adapted from an original by NASA/JPL-Caltech

Like the original GRACE project, the GRACE Follow-On mission measures changes in the gravitational pull (blue arrows) on the two craft resulting from changes in Earth's mass below the orbiting satellites, which can be due, for example, to variations in sea level, ice caps or the amount of water stored on land. As the satellites orbit the Earth, one following the other, these moving masses alter the gravitational pull, changing the distance between the craft very slightly. Separations have been exaggerated for effect.

tational effect on the distance between them.

Another significant non-gravitational force that had to be accounted for as the mission progressed was aerodynamic resistance on the GRACE satellites from the Earth's tenuous upper atmosphere. As with all orbiting bodies, there was a positive feedback effect: the drag made the craft lose height, which in turn made them travel through a denser atmosphere, which led to more drag and so on. Indeed, by the end of 2017 when the two craft finally stopped operating, the satellites were orbiting barely 300 km above the Earth's surface.

To compensate for all of these non-gravitational forces, each satellite had at its centre a 50 g "proof mass" suspended electrostatically within a cage. Electrodes in the walls of this container corralled the mass to within 30 μm of the satellite's centre of mass, and simultaneously measured any displacement. Non-gravitational forces applied to the satellite body deflected the proof mass relative to its cage, whereas gravitational perturbations affected the entire set-up equally. Any change in distance that could not be attributed to some non-gravitational force on one of the satellites was therefore taken to be an indicator of unevenness in the geoid.

Watery changes

With the confounding effects removed, the precision of the distance measurement meant that GRACE was sensitive to changes in strength of gravity on the order of a few microns per second squared, or less than a millionth of the value at the surface (roughly $9.81\,\mathrm{m\,s^{-2}}$). Members of the GRACE team could therefore spot changes in gravitational strength caused by the water level in a large lake or aquifer rising or falling by as little as one centimetre. Every month, they compiled such changes in the Earth's mass distribution and made the updated map available to researchers around the world.

One of those scientists is Matthew Rodell, head of the Hydrological Sciences Laboratory at NASA's Goddard Space Flight Center in Maryland, US, who has used these data to map the changing availability of fresh water across the planet, including regions that would otherwise be hard to access. "GRACE revealed and quantified groundwater depletion associated with irrigated agriculture in northern India, the North China Plain and parts of the Middle East, among others," says Rodell.

Writing in a recent paper in *Nature* (**557** 651), he and his team quantified dozens of global trends in freshwater distribution that are expected to affect food and water security in coming decades, and that could spark conflict if not managed carefully. The changes were a mix of natural, climate-change-related and directly human-caused effects, and the work simultaneously captured processes as diverse as ice-cap loss in Greenland and Antarctica, groundwater extraction in the Middle East, and the damming of rivers in China.

This ability to spot links between regional trends, which is a vital part of GRACE's observations, is illustrated by a discovery made by Rodell's colleagues at the Jet Propulsion Laboratory (JPL) in California (*Geophysical Research Letters* **39** L19602). They found that the global mean sea level, which had previously been steadily rising by about 3 mm a year, suddenly dropped between 2010 and 2011 by 5 mm. Carmen Boening from JPL, who began pondering the puzzle with collaborators at JPL, the National Center for Atmospheric Research and the University of Colorado at Boulder, wanted to know if the drop was related to ocean cooling or whether there was simply less water in the ocean.

Using GRACE data, Boening and her colleagues found that the sea-level fall really was due to missing mass, and that it was balanced by a corresponding increase in water stored on land. It turned out that the onset of La Niña conditions in the Pacific – a cyclical variation in ocean-surface temperature – had caused so much rain over Australia, south-east Asia and northern South America that the oceans were temporarily depleted, and the continents made measurably more massive. By 2012 the effect had ended and the rising trend, associated with global warming, had resumed. "So by using GRACE to weigh the ocean, we confirmed that there was less water there, which must have moved to the continents," Boening says.

Following the trend

The two satellites making up the original GRACE mission were designed to last for just five years, with operations scheduled to end in 2007. Sensitive electronics can only take so much radiation and thermal cycling before they start to break down, and the spacecraft had no means to maintain their orbits in the face of aerodynamic drag. However, in a fashion familiar to fans of NASA's Mars rover fleet, the GRACE scientists over-delivered, and the mission kept returning data until late 2017, shortly before the two satellites fell from orbit and burned up in the Earth's atmosphere.

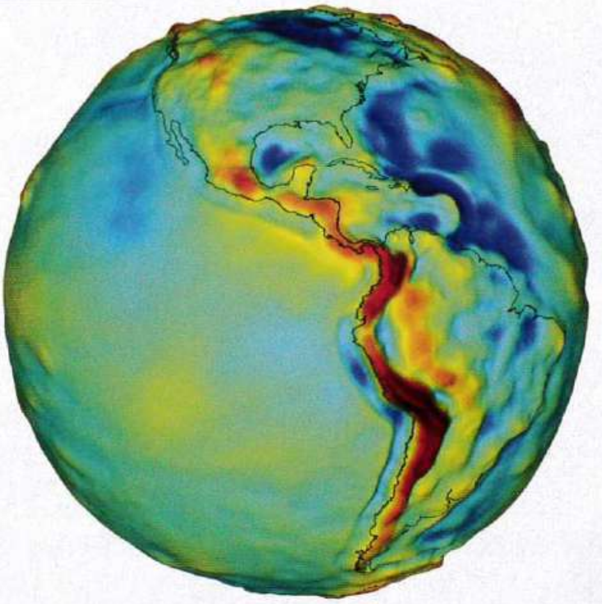
But the mission is not yet over. Recognizing the importance of obtaining further measurements, in 2011 NASA initiated a successor to GRACE, known as the GRACE Follow-On (GRACE-FO). With the US National Academy of Sciences also recognizing in its 2017–2027 Decadal Survey for Earth Science and Applications from Space that mass-change measurements are vital for tracking long-term trends in the hydrosphere, GRACE-FO was duly launched in May 2018 from the Vandenberg Air Force Base in California. To ensure continuity, GRACE-FO essentially duplicates the original experiment, but with a few minor improvements derived from lessons learned along the way.

The most novel aspect is the addition of a technology-demonstration instrument – a laser interferometer for measuring the inter-satellite separation. Developed by researchers from JPL as well as the Max Planck Institute for Gravitational Physics in Hannover and the Leibniz Universität Hannover, the device works on the same principle as the microwave-based method used by the original GRACE craft. It should, however, deliver a precision a hundred times greater because of the beam's shorter wavelength. "It's a really incredible piece of technology," says GRACE-FO project scientist Frank Webb from the JPL. "The sensitivity limit is at the hundreds-of-picometres level, which is about half the size of a water molecule – over a distance of 200 km."

In the current set-up, other sources of error are too large to do justice to the new instrument, so the increased precision cannot be fully utilized. Indeed, during routine operations, GRACE-FO will employ the same microwave-based method used by the original satellites. The laser interferometer is intended only as a validation of the technology for future missions, which will be able to make better use of the device to measure mass changes on the ground with greater accuracy and resolution. Even so, Webb will be surprised if scientists do not find some way to relate test data from the new device to mass change on the Earth. "The scientists are pretty clever, and they should be able to tease out a little more information from this new capability," he says.

GRACE-FO is slated to work for five years, but whether it can continue working for as long as its predecessor will depend in part on the strength of the next cycle of solar activity, which will start in late 2019. When the Sun is especially active, the increase in emitted ultraviolet radiation adds energy to the Earth's upper atmosphere. This makes the atmosphere "puff up", increasing the drag in low Earth orbit and accelerating orbital decay. The craft would then burn up, as its predecessors did, albeit much sooner. "A strong solar cycle will push the satellites lower, earlier," Webb says.

2 Gravitational highs and lows



NASA's Goddard Space Flight Center

A map from the GRACE mission of gravity across Earth. Red shows areas where gravity is stronger than the standard "idealized" value and blue where it is weaker. The mission was so sensitive that it could monitor month-by-month changes in the distribution of water across the planet.

Follow on following on

Not content with GRACE-FO as a successor to GRACE, there are already plans for a follow-on to the follow-on. These missions will not only continue the geoid observations, but will also incorporate design changes that minimize uncertainty from other quarters, such as the sensitivity of the accelerometer, letting scientists make full use of the increased resolution afforded by the laser interferometer. This will let researchers measure even smaller mass changes over finer spatial scales, potentially revealing additional trends not glimpsed by the satellites launched so far.

And while GRACE-FO – and its successors – will measure changes in the Earth' gravity field, a similar device could be used by another mission to observe gravitational signals from beyond. That's because the successful demonstration on GRACE-FO is a major milestone in the development of the European Space Agency's Laser Interferometer Space Antenna (LISA). Planned for launch in 2034, LISA will comprise three satellites arranged at the corners of a triangle 2.5 million kilometres on a side. Circling the Sun far from the noisy environment of low Earth orbit, the interferometer used on this mission will be able to detect a change in distance of just picometres – sufficient to spot the infinitesimal flexing of space due to the passage of gravitational waves from across the universe.

Results from the GRACE-FO demonstration will provide a practical lesson on how to operate, diagnose and, if necessary, debug the instrument after launch. Members of the LISA team – many of whom also work on GRACE-FO – will be watching keenly in preparation for when they turn their gravitational gaze outward from the Earth.

Supporting the professionals

Marc Delcroix says that amateur astronomers can play a key role when it comes to future planetary missions

Collaboration between professional and amateur astronomers has a long and successful history. Take Jupiter. In early 1994 scientists discovered that the Shoemaker–Levy 9 comet was fragmented and they observed parts of it hitting the giant planet in July that same year. It was an impressive series of collisions leaving traces visible for months. Many professional astronomers believed they had witnessed a once-in-a-lifetime event, something that would only be observed once in a century, or possibly longer.

In 2009, however, Anthony Wesley, an Australian amateur astronomer, saw an unusual small dark patch during his observations of Jupiter. He accurately identified it as the trace of an impact in the planet's atmosphere and alerted the professional and amateur communities, who later proved him right. A year later, he and other amateurs observed two flashes on Jupiter – a tell-tale sign of a smaller body hitting the planet's atmosphere – and found further impacts in 2012 and 2016.

All these discoveries were observed simultaneously by several amateurs, demonstrating the large observation coverage that they provide. The discovery has now led scientists to ponder the frequency of such impacts and to refine their model of small-body distributions, which could yield better estimates of the age of crater-hit bodies. This issue may well again be answered by amateur observations and analysis.

This remarkable progress has been due to the equipment that amateur astronomers use to observe planets in our solar system becoming ever more complex in recent years as technology has developed. In the 1990s amateurs used charged coupled devices but a decade later they were already using simple webcams to film planets. During this time, amateurs began to use techniques to image planets with a quality equal to that professionals had produced 20 years before. With imaging-sensor development driven by a huge consumer market and many industrial applications, the worldwide community of amateur astronomers now routinely uses top-quality yet affordable cameras to film planets. With their own advanced processing software, amateurs can reach the limit of their 20–40 cm telescopes and produce high-resolution images at visible wavelengths, detailing fine atmospheric phenomena.

Anthony Wesley

Impact zone It was once thought that objects hit Jupiter's atmosphere every 100 years, but in 2009 Australian amateur astronomer Anthony Wesley helped turn that view on its head.

Amateurs are estimating wind speeds, confirming cloud detections and presenting their results at professional meetings

Professional observations, on the other hand, are driven by ground-based 10 m telescopes that work in the infrared. These are mostly used to observe distant objects and are rarely used to study Earth's neighbouring planets. The best images of planets are produced by space-based instruments, such as the Hubble Space Telescope (when they are aimed at them, that is), while fly-by missions or orbiters usually focus on specific targets such as a planet's satellites, rings or magnetic field. This is where the two communities can come together: with plenty of time on their hands, amateurs can provide regular, high-quality images of planets, while professionals can call on them for support whenever they want to study a specific phenomenon.

This type of collaborative working has arisen over the last 10 years, which has seen the number of publications co-written by planetary science professionals and amateurs shoot up by a factor of 20. Every new atmospheric point of interest – be it the reddening of ovals in Jupiter's atmosphere, storm cloud sources on Saturn, or even Uranus and Neptune's cloud activity – has been studied not only from professional telescopes but amateur ones too. Amateur observations are also increasingly being used by researchers to justify bigger telescopes spending time on such sources to deliver more accurate observations.

Leading amateur astronomers are analysing their colleagues' images, estimating the wind speeds on the upper gaseous planet atmospheres, confirming cloud detections and presenting their results at professional meetings. Some are also developing advanced software for processing or analysing their own images to create equivalent tools to those professionals have used. Some lucky amateurs even have access to 1 m professional telescopes that they use for their own observations.

These and other endeavours by amateur astronomers have been recognized by planetary scientists, such as NASA's call for them to support the Juno mission to Jupiter when it arrives at the planet on 4 July. A workshop held in Nice in May – attended by 33 amateurs and senior professional astronomers – involved discussions about how to work best together on the mission and study Jupiter in general. The plans include high-resolution amateur observations of Jupiter's atmosphere during the mission to help determine what features the Juno camera will aim at. Another general target for amateurs is to continue looking for impacts on Jupiter to improve our knowledge of such events.

The contribution that amateurs play in astronomy is clear. An amateur astronomer observing planets can easily contribute by sharing observations on existing databases, user groups and on the Internet, or participating in specific observations or analyses. What a wonderful time it is now for amateurs to see their childhood passion turn into real science. For them it must feel like Christmas every day.

Marc Delcroix is director of the French Astronomical Society's planet section, e-mail delcroix.marc@free.fr

Critical Point See like a solar system

Robert P Crease discusses what the science of the solar system teaches us about perception

Many years ago I read a news item in which a scientist said that a sodium cloud issuing from a volcano on Jupiter's moon Io was "the largest permanently visible feature in the solar system" (*Science News* **137** 359).

That remark stopped me cold. What does it mean to "see" a sodium cloud? More generally, what do scientists mean when saying they see dark matter or black holes? Are they speaking precisely or metaphorically? What is perception?

Questions like these were a big factor in attracting me to the philosophy of science. Perception, I decided, isn't as easy as it looks. To be a scientist is to develop an extended ability to perceive – and the science of the planets in our solar system is replete with examples.

NASA/JPL

Eyeing up How do we use instruments like a NASA Mars rover to "see" other planets?

To be a scientist is to develop an extended ability to perceive

Seeing like a rover

When scientists say they see things like sodium clouds, they speak rigorously. To perceive is not just to grasp something somewhere from a single perspective. It is also to have a sense, however rudimentary, of how that thing looks from other perspectives. Whenever I see a cup, I see only one profile of it. But thanks to our earlier experiences with cups, to see something as a real cup – rather than as a cutout or hallucination – means to anticipate other profiles; how it'll appear if I walk around it, pick it up and so on. Sometimes these profiles surprise us, or we turn out to be deceived or wrong, but to perceive is always to grasp a profile of something and have a set of expectations about other anticipated profiles. Perception, in short, has a deep structure.

The same is true for a space scientist's perception, except that it is technologically mediated. In philosophical language, scientists sometimes "embody" their instruments, seeing the world through them relatively directly, just as a blind person sees the world through a cane. When we perceive a planet or comet through an optical telescope, for instance, our previous experiences make us expect the object to be visible at other times in other locations – and that when observed through stronger telescopes it will have profiles that we might not know but that we can guess. At other times, scientists don't embody but "interpret" their instruments. Just as we say "it's cold outside" by looking at a thermometer, so a space scientist "sees" a sodium cloud with filters and spectrometers if these belong to expected profiles.

Astronomical perception involves a complex combination of these two concepts of embodiment and interpretation. An interesting case study is found in the 2013 article "Mediating Mars: perceptual experience and scientific imaging technologies" (*Foundations Sci.* **18** 75) by the philosopher Robert Rosenberger from the Georgia Institute of Technology, US. In it, he describes a debate about a rock formation imaged by NASA's Mars Global Surveyor in a Martian crater known as Eberswalde. Some scientists argued they were looking at the remains of a river delta, others an alluvial fan, still others that they were seeing the product of mudslide-like events.

Rosenberger shows that the scientists went about resolving the controversy, not by evaluating competing theories or explanations about the rock formation itself, but by appraising the different strategies that they were using to produce the images. They asked themselves, Rosenberger writes, "How does the process of transforming this object of study (i.e. a rock formation on Mars) into a specific form we are able to perceive here on Earth (i.e. images) leave these images open to interpretation in particular ways?" Without being able to move freely around the formation as they would on Earth, the scientists had to sharpen their perception of the rock formation by understanding the profiles better, and by analysing other profiles provided by shadows, laser altimeter data and so on.

Another analysis of scientific perception is found in *Seeing Like a Rover: How Robots, Teams, and Images Craft Knowledge of Mars* (2014 Princeton University Press) by the Princeton University sociologist Janet Vertesi. She based her book on two years spent as an ethnographer studying scientists in NASA's Mars Exploration Rover mission. Vertesi found the researchers' workspaces, computer screens and Powerpoints were saturated with images: filtered, false-colour, 3D, fish-eye, panoramic and more.

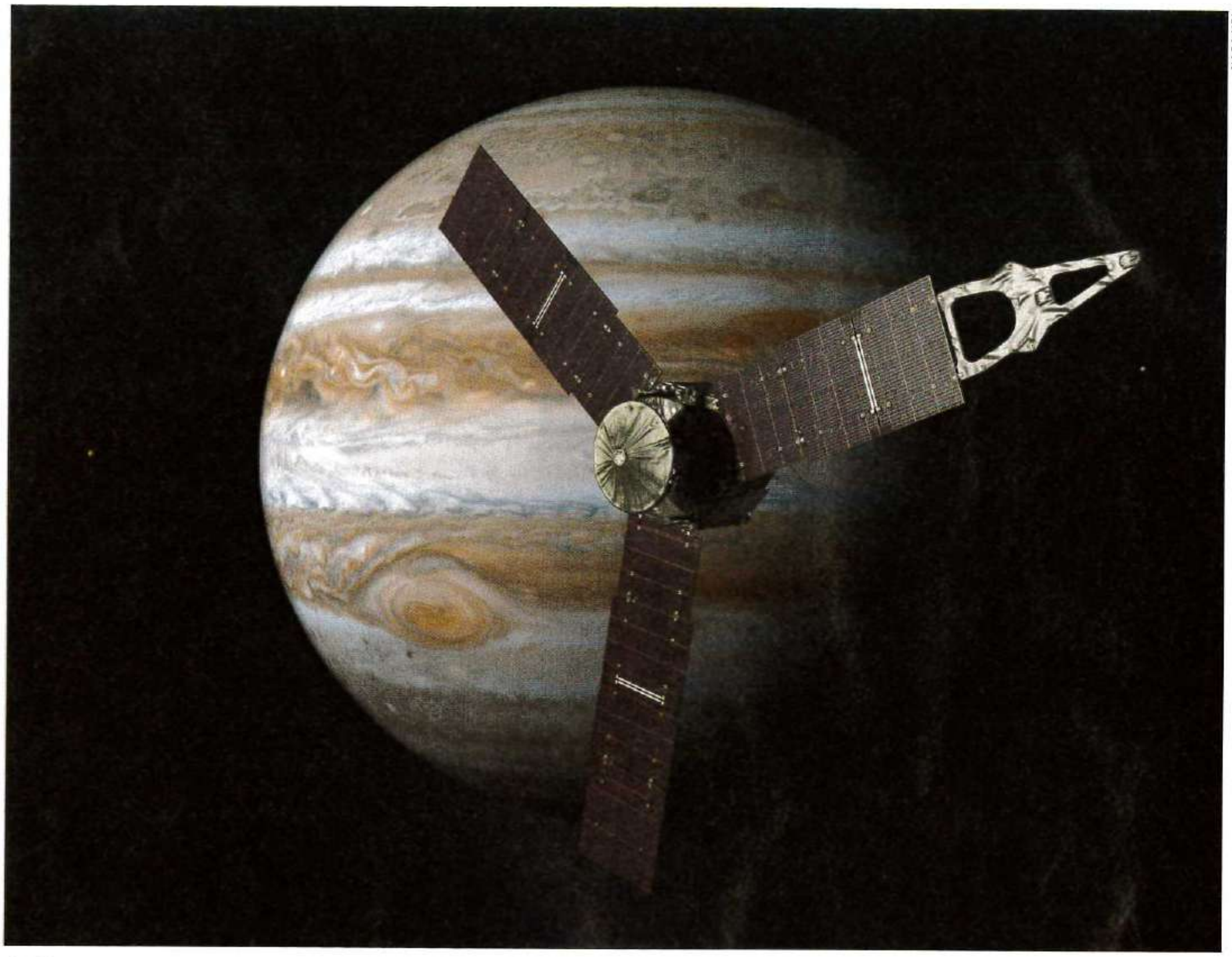
Taken by the two rovers Spirit and Opportunity, these images let the researchers "see" on Mars, but not with a human eye. One researcher told Vertesi that the two rovers' view of the world was like "trying to make your way through a dark cluttered room with nothing but a flashbulb". Yet the researchers became skilled at it, seeing and manipulating phenomena on the Martian surface. "When you work with the team for a while," another researcher told her, "you kind of learn to see like a rover."

Vertesi's book shows that seeing like a rover is not just a matter of grasping profiles and horizons, but also involves ways of speaking and gesturing, emotional connections, habits and even the research group's social and organizational structure. Seeing like a rover, she writes, "is…a question of seeing from *somewhere*, not adopting a view from nowhere" – with the "somewhere" referring not just to the rover's cameras but to the entire research team and its activity.

The critical point

The curse of current-day philosophy of science is the lingering but fraudulent idea among philosophers that science involves the quest to see phenomena from nowhere. Instead, it's done by people with inherited concepts using particular equipment to study topics that seem important. To perceive a scientific phenomenon involves grasping how all of the profiles you can see of it – and how others that you don't yet or never will see – hang together. Not only that, but mediated scientific perception deepens and extends our notion of what it is to perceive at all.

Robert P Crease is a professor in the Department of Philosophy, Stony Brook University, US. He is the co-author of *The Quantum Moment*, e-mail robert.crease@stonybrook.edu



Brave new Jupiter

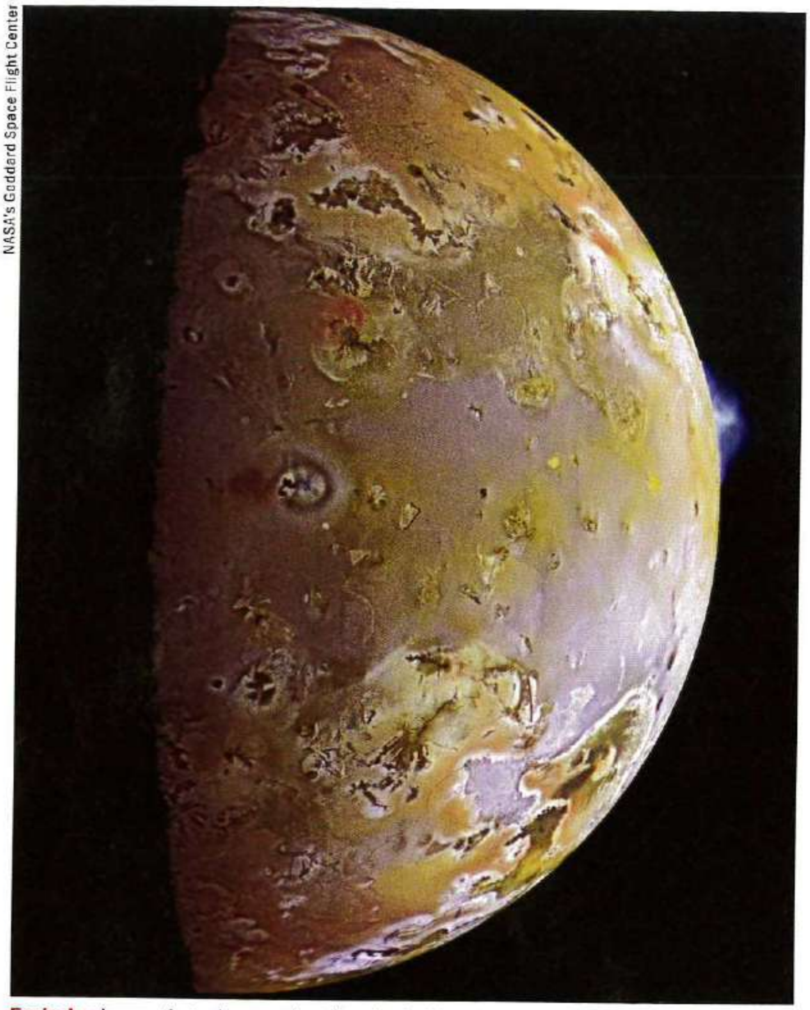
With NASA's Juno mission to Jupiter arriving this month, researchers look to our local, ancient behemoth to figure out how planets form – including our own – as **Stephen Ornes** reports

Stephen Ornes is a science writer based in Nashville, Tennessee, US, e-mail stephen@stephenornes.com

For the last five years, NASA's Juno spacecraft has been barrelling towards its final destination: Jupiter, king of the planets. On 4 July this year, the four-tonne, spinning craft – which looks like an oversized propeller that has abandoned its plane – will fire its thrusters and slow down enough to be captured by the gas giant's gravity. The burn should only last about 40 minutes, but they'll be a tense 40 minutes: during that time, as Juno shifts from orbiting the Sun to orbiting Jupiter, the rest of its devices will go quiet. (As will the physicists at NASA's Jet Propulsion Laboratory in Pasadena, California, tracking the mission from the ground and, one imagines, with fingers crossed.) Then the instruments should flicker back on, and over the course of more than 35 long, loping polar orbits throughout the following year, Juno will execute an intimate and unprecedented observation of our local colossus, beaming data back to Earth.

Scott Bolton, Juno's principal investigator, says the effort to study Jupiter is no less than a desire to understand the origin story of the solar system. Bolton is a space physicist at the Southwest Research Institute in San Antonio, Texas, and has led the \$1.1bn mission from idea to execution. "When you want to understand where we all came from and how the planets were made, you have to start with Jupiter," he says. Jupiter's composition seems more star than planet, as it is dominated by hydrogen, followed by helium. At the same time, its atmosphere is drizzled with the heavier elements – including carbon, nitrogen and oxygen – that make life on Earth possible. "Jupiter is enriched with the same stuff we're

NASA's Goddard Space Flight Center



Explosive An erupting volcano on Io, taken by the New Horizons mission.

made of," says Bolton. "We're trying to understand our own history."

Bolton's words echo a growing wisdom among astronomers: if you want to know details about how the solar system formed, or how giant, gassy worlds coalesce around far-flung stars, you have to ask Jupiter. It likely formed early and fast, sweeping up most material left behind after the Sun formed. Jupiter is more than twice as massive as all the other planets, moons, asteroids, comets and Kuiper-belt objects in our system combined. Because of its age and heft, the gas giant probably played a critical role in arranging the solar system, helping to jockey planets into their current positions. (With 67 known moons, it effectively hosts its own planetary system too.) Astronomers even credit Jupiter's gravitational oomph for diverting comets and asteroids that might otherwise have plummeted into Earth and brought a quick end to life as we know it.

Ancient civilizations watched the planet with awe and interest, and astronomers have been probing its mysteries since Galileo Galilei first studied it and its moons through a telescope more than 400 years ago – observations that showed that not everything in the heavens orbits Earth. The more scientists learn about Jupiter, the more unknowns they find. Even after centuries of inquiry, Jupiter is shrouded in mystery.

Scientists don't know the structure of its thick, hot atmosphere, or how much water that atmosphere contains. Even more mysterious is the structure of its centre, hidden far below. Brilliant light shows, called auroras, encircle the opposite poles like twin crowns – and even exist deeper in the atmosphere – though researchers disagree on how they form (see "Extraterrestrial light shows" on pp37–39). Ground-based observations of Jupiter and its moons offer tantalizing hints at answers to these mysteries, but the best way to ask how the king of planets ticks is to go there and see for ourselves.

Juno's goals are simple. How did the planet form and evolve? What hides beneath Jupiter's clouds? The answers to those puzzles may help answer even bigger questions about why planets form at all. "We're after the recipe for the solar system," Bolton says.

The story so far

In Roman mythology, Juno was the wife (and sister) of Jupiter, king of the gods, and she didn't take kindly to his extramarital interests. To conceal an affair with a mortal priestess named Io, Jupiter concealed himself with a dense cloud cover. Not to be fooled, Juno handily swept the clouds aside – an action that resonates with the modern Juno mission.

The planet Jupiter, long a source of fascination for stargazers, appears in one of the first *bona fide* science-fiction stories. In 1752 French philosopher Voltaire published *Micromégas*, a story that reads a bit like *Gulliver's Travels*, but in space. The tale follows the adventures of a 37 km-tall alien and his 2 km-tall friend as they compare experiences and explore the solar system. Their trajectory takes them to the moons of Jupiter and briefly to the planet itself: "They stopped at Jupiter and stayed for a week, during which time they learned some very wonderful secrets," which are not, unfortunately, revealed in the story. (The duo later visits Earth, but as its inhabitants are too small to be seen, they dismiss the possibility of finding intelligent life there.)

The Juno mission represents the ninth Jovian visit by a human-built ship. The most recent was New Horizons, en route to Pluto, in 2007. The first arrived in 1972, when the Pioneer 10 spacecraft snapped 300 images and took measurements as it zoomed by at 132 000 km/h, about 130 000 km above the tops of the clouds. Data from that mission helped scientists to make early hypotheses about the fluid-filled interior and to analyse plasma in the planet's giant magnetosphere – the region in which charged particles are affected by Jupiter's magnetic field. The mission wasn't entirely smooth sailing: some of the onboard instruments malfunctioned due to the intensity of the radiation surrounding Jupiter, but those problems helped guide the design of better protection for future missions. The next year, on its way to Saturn, Pioneer 11 flew by Jupiter, even lower and faster than its predecessor. The Voyager 1 and 2 missions followed in the late 1970s, sending back more data – and unanswered questions.

"The Voyager missions opened up a bunch of unknowns," says physicist Theodor Kostiuk of NASA's Goddard Space Flight Center in Maryland,

Picture this Jupiter's magnetosphere as it would appear from Earth if visible.

who uses ground-based telescopes to study Jupiter's atmosphere. Voyager, for example, identified active volcanoes on Io, a large inner moon, that affect the entire planetary system. (Prior to Voyager, astronomers didn't know that volcanic activity existed anywhere else in the universe.)

The Ulysses spacecraft measured Jupiter's magnetosphere during flybys in 1992 and 2000, when it used gravitational assists from the planet to slingshot itself towards the Sun, its primary research target. The Cassini–Huygens spacecraft, while en route to Saturn, took tens of thousands of pictures of Jupiter and made detailed measurements of its atmosphere during a six-month period in 2000 and 2001. The first orbiter to reach Jupiter was Galileo, which spent eight years circling the planet's equator and studying the Jovian moons, but it ran into problems and did not ultimately fulfil all of its scientific goals.

Planetary space physicist Fran Bagenal, of the University of Colorado at Boulder, worked on Galileo's science team and now leads the plasma research teams for both Juno and New Horizons, the mission that reached Pluto last year (see "Our new view of Pluto" on pp40–43). "Galileo's observations told us a lot about the moons, but it had this problem," she says. In 1991 Galileo's 4.8 m high-gain antenna, which was shaped like an umbrella and designed to radio data back to Earth, only partially opened. Scientists tried for five years to fix the problem from Earth, but to no avail. "It meant we couldn't do a lot at the planet itself," Bagenal recalls. The mission couldn't send back as much data as scientists had anticipated, and the spacecraft disintegrated during its intentional, final plunge into Jupiter's turbulent atmosphere.

Juno is the scientific heir to Galileo, but it differs in important ways. Galileo's price tag was about $1.4bn, whereas Juno's estimated cost is about $1.1bn. Where Galileo circumnavigated the equator, Juno will orbit the poles. Galileo, like most spacecraft, used nuclear fuel to travel through space. Juno relies on solar power. Its three radial arms are 9 m arrays that hold 19 000 solar cells, and in January of this year Juno set a record for the farthest distance travelled using solar power. (The record was previously held by the European Space Agency's Rosetta spacecraft, which travelled to the asteroid belt between Mars and Jupiter.)

In Earth's neighbourhood, Juno's solar cells receive enough sunlight to generate 14 kW – which could power 10 microwave ovens at once. Near Jupiter, where sunlight is weaker, the cells collect only enough light for about 400 W. That's not enough to power a hair dryer, but it's sufficient for Juno's suite of scientific instruments. "It demonstrates that solar power works in a new environment that we hadn't thought possible," says Bolton. The radiation belts around Jupiter, he says, are "one of the harshest regions in the solar system".

Preparing for the storm

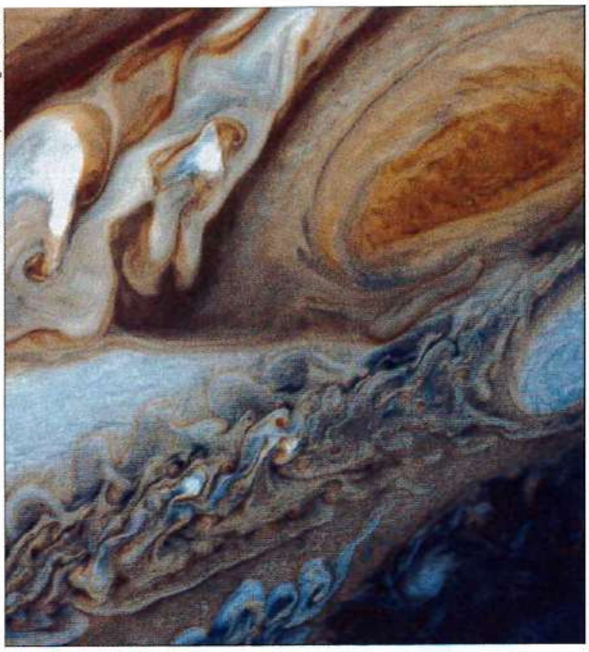
Jupiter is notoriously inhospitable. Winds blow at 650 km/h or more. Lightning strikes with 100 times the intensity of lightning on Earth. The Great Red Spot – the solar system's biggest storm, which has been raging for more than three centuries – is so big it could swallow Venus.

The planet's biggest threat to space travel, though, is radiation. Jupiter's magnetic field is 10 times stronger than Earth's. Indeed, its magnetosphere is the largest known structure in the entire solar system. If it glowed visibly, the magnetosphere would appear to observers on Earth more than twice as big as the full Moon. Such a sprawling magnetosphere traps a lot of high-energy particles, creating radiation belts that circle Jupiter, forming what must be the most hazardous doughnut in space. (The belts are similar in shape and structure to Earth's Van Allen belts.)

"You've got this stream of electrons and protons circling the planet, and they're lethal to spacecraft," says astronomer and Juno team member Tobias Owen of the University of Hawaii, whose goal is to measure oxygen in Jupiter's atmosphere. "Until now, spacecraft have been farther out. We're going to be inside it."

Instruments onboard Juno include a particle detector, magnetometer, ultraviolet and infrared spectrometers, and radio instruments for measuring fluctuations in the gravitational field. (The payload also includes three LEGO figurines, representing Juno, Jupiter and Galileo.) The electronic devices would ordinarily be crippled by the intense radiation, which is why they are safely housed in a protective vault with centimetre-thick titanium walls. Juno's flight plan, which takes it over the poles, will also reduce exposure to the powerful radiation.

The same magnetic field that makes the mission so treacherous embodies one of the planet's most pressing mysteries. Io's active volcanoes, as Voyager observed, spew sulphur-dioxide particles that


NASA's Goddard Space Flight Center

Swirling bands Jupiter's atmosphere as imaged by Voyager 1. Vibrant bands of clouds carried by winds that can exceed 650 km/h continuously circle the planet's atmosphere. Such winds sustain spinning anticyclones such as the Great Red Spot – a raging storm three and a half times the size of Earth.

become ionized and fill the magnetosphere, says Bagenal. As they accelerate to high energies, many of the particles end up bombarding the atmosphere of Jupiter – a process that's believed to contribute to the auroral light shows at the poles.

However, "we've never flown over the poles of Jupiter before, and we don't know what it's like up there" says Bagenal, whose research focuses on plasma in planetary magnetospheres. "We don't know what processes accelerate those particles into the atmosphere." Juno, she says, will be able to measure the magnetic field, charged particles and plasma waves as it looks down on the auroral emissions in the atmosphere. "We're trying to put together the bigger picture of what causes the auroras, and how they work."

Beneath the clouds

It's tempting to assume that Jupiter's auroras form like those on Earth, which arise after charged particles from the solar wind are accelerated along magnetic field lines into the upper atmosphere, where they collide with other particles and emit light. But such an explanation might be too simplistic for Jupiter. Ultraviolet images taken by the Hubble Space Telescope 20 years ago show that the auroras form round, oval-shaped structures near the poles. Though small-scale changes occasionally occur within and to each oval, "it really doesn't vary a whole lot" says Bagenal.

That might be in part because Jupiter's powerful magnetosphere protects its atmosphere from the solar wind. In that case, the auroras might be generated internally, from "an atmospheric region deep in the atmosphere" says Kostiuk. Using infrared imaging, Voyager identified a thermal aurora deeper in the atmosphere in the north hemisphere, which researchers have studied for three decades with ground-based measurements and, in 2001, data from the Cassini flyby. Kostiuk points out that recent ground-based measurements of the aurora in the infrared do show some variation with the solar cycle – suggesting a contribution from the solar wind.

From within or without? "That's the big debate," says Bagenal. She suspects the auroral emissions arise from how the plasma in the magnetosphere moves with respect to the planet, which completes a rotation in just under 10 hours. "At some point, the clutch begins to slip," she says. "We think electric currents associated with that process are partly driving the auroras." But scientists won't know for certain until Juno takes a look.

Another of Juno's scientific goals is to better understand the colourful, swirling bands of clouds. To date, it's been difficult for scientists to probe the depths because it's too hot, and the pressure is too great. Juno's multi-frequency microwave radiometer will receive thermal radiation from the depths of Jupiter's cloud cover, up to pressures about 1000 times Earth's normal atmospheric pressure at sea level. That penetration will help researchers better understand the rotation of the atmosphere relative to the core – if it exists – and what elements exist there.

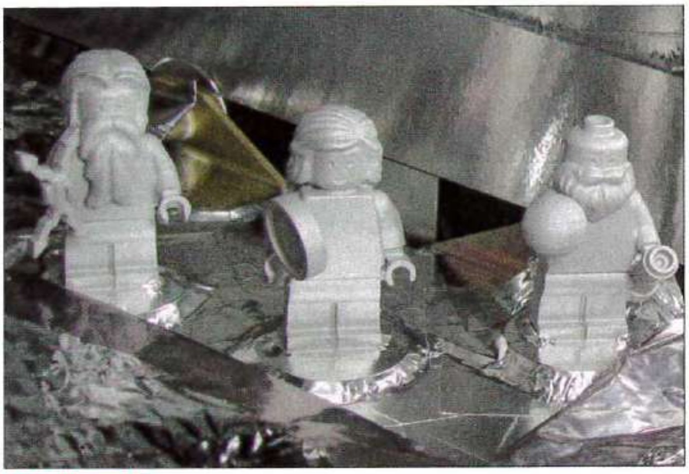
"The thing that's most exciting to me is the determination of water deep in the atmosphere," says Owen. "By measuring the water we'll get an idea of the way that Jupiter came together." Many astronomers have proposed models to explain Jupiter's formation, but different models predict different levels of water. Measuring that abundance, says Owen, will help models get closer to approximating the origins of the planet. "Water abundance is key if you're trying to understand how planets are formed in our solar system," says Bolton.

Juno will also be studying what lies beneath the clouds. The planet likely contains a vast and bizarre ocean unlike anything found on Earth – and unlike anything that can even be simulated on Earth. It's made of hydrogen under so much pressure that electrons separate from protons, and the fluid conducts electricity like a metal. As this strange sea rotates with the planet, it generates Jupiter's powerful magnetic field. "We think that's where the dynamo is produced," says Bagenal.

But scientists don't know how deep the liquid metallic hydrogen extends, or what's underneath it. They hypothesize that Jupiter's core is rocky and

To date, it's been difficult for scientists to probe the depths of Jupiter because it's too hot, and the pressure is too great

NASA/JPL-Caltech/KSC



Mission mascots Three LEGO minifigures aboard Juno represent the Roman god Jupiter, his wife Juno and Galileo Galilei.

made of heavier elements. Since no device could reach the hydrogen sea – much less any core that lies beneath – Juno will map the interior structure by tracking changes in the planet's gravitational field as it orbits.

The end of Juno

Juno will spend a full year measuring and sending data to astrophysicists on Earth, but Bolton warns that definite answers about Jupiter won't show up immediately. "We're limited on how we can interpret Juno's data," he says. Using gravity measurements to map the distribution of mass will be fairly straightforward. But to connect data on variables like temperature and pressure and forge one big, coherent picture will require physicists to agree on an equation of state to describe the conditions on Jupiter. That's a challenge in and of itself: no-one has any idea how metallic hydrogen is supposed to behave. They also suspect, but can't prove, that heavier elements likely dissolve in that strange soup.

Bagenal says the equation of state is a crucial and missing piece of the puzzle. "Every time we have a meeting of the interior working group of the Juno mission, these guys come up with a new equation of state," she says. "They're always improving, and always changing their minds. Since we launched, they've changed their minds a few times."

At the same time, Juno's data will immediately be put to use by theorists who come up with models of how Jupiter formed. "All theories on how Jupiter forms will have to be consistent with what Juno sees," says Bolton. "By making these measurements, we will constrain the models." Those limitations will, in turn, lead to more refined models that more accurately represent the reality of Jupiter.

Once Juno's year-long data-gathering feast is over, it will change direction one last time. The spacecraft won't be allowed to orbit indefinitely because of the unlikely chance it might collide with and contaminate Europa, a Jovian moon with a subsurface ocean where, one day, scientists would like to look for life. So instead of drifting off, Juno will end, like Galileo before it, by disintegrating during a final plunge into the heart of its host.

Pathway to Planet Nine

Konstantin Batygin explains what led him and astronomer Mike Brown to propose the existence of a ninth planet in our solar system

Konstantin Batygin is an assistant professor of planetary science at the California Institute of Technology, US, e-mail kbatygin@gps.caltech.edu

As one of the oldest forms of natural science, astronomy has enjoyed a long and dramatic history. However, it was not until the early 1600s that the entire discipline was kicked into high gear by Galileo's adoption of the telescope as a scientific instrument. No longer bound by the resolving power of the human eye, astronomers had finally attained the freedom to search the night skies for the wandering motion of the faintest stars. The door to the discovery of additional planets that orbit the Sun had been cracked open.

In terms of sheer numbers, efforts to expand the solar system's planetary album have yielded rather unimpressive results. Over the last four centuries, only two planets that were not known to ancient civilizations have been found. The discovery of the first of these planets, Georgium Sidus (now known as Uranus), was announced by William Herschel at the time of the American Revolutionary War, in 1781. This finding simultaneously marked the beginning and the end of purely astronomical detection of planets in the solar system. Indeed, the revelation of the next planet would rely more on celestial mechanics than on a telescope.

Soon after Herschel's announcement of Uranus, astronomers began to compute its orbital motion and flirt with the idea that an additional, more distant object could gravitationally perturb its trajectory. Among the first astronomers to lead this charge was Anders Johan Lexell. In a set of compiled astronomical tables published in 1821, which included accidental observations of Uranus that predated its formal discovery, Alexis Bouvard (then director of the Observatoire de Paris) noted that Uranus was indeed deviating from its predicted path. Without discounting the possibility of spurious data, Bouvard joined Lexell in speculating that the irregularities in Uranian motion could be caused by an additional planet.

It would take more than two decades before the promise of Bouvard's data came to fruition. In a parallel set of calculations completed in 1846, John Couch Adams and Urbain Le Verrier independently predicted the existence of Neptune. Although the computed orbital period and mass of the putative Neptune exceeded the real values by a significant margin, the calculations gave the correct location in the sky. Then, in a remarkable feat of observational confirmation of theoretical results, Neptune was spotted by Johann Galle on the first night of his observational campaign later that same year.

Once the ability to deduce the presence of an additional planet using orbital irregularities had been demonstrated, a number of contemporary mathematicians attempted to derive the existence of even more distant objects using existing data. As a result, by the early 1900s there was no shortage of hypothetical planets beyond Neptune. One particularly notable prediction was Percival Lowell's famed Planet X hypothesis, which led to the accidental discovery of Pluto in 1930 (see "Our new view of Pluto", pp40–43).

In the end, it was unmanned spaceflight that killed Planet X. Following Voyager 2's 1989 encounter with Neptune, the planet was recognized to be a fraction of a per cent less massive than previously thought. Like a Rubik's cube snapping into its orderly configuration, this small change cleansed the solar system's astronomical charts of any irregularities, and erased the theoretical need for Planet X. As history shows, the claims of additional planets following Neptune's dis-

A ninth planet? Artist's impression of Planet Nine. For the first time in 170 years, evidence for the existence of an additional massive planet in the solar system is mounting up.

covery had more to do with erroneous interpretation of the observational data than anything else. Every time the observations seemed to call for the introduction of another planet, further analysis revealed that the apparent anomalies could be fully reconciled within the framework of the known solar system.

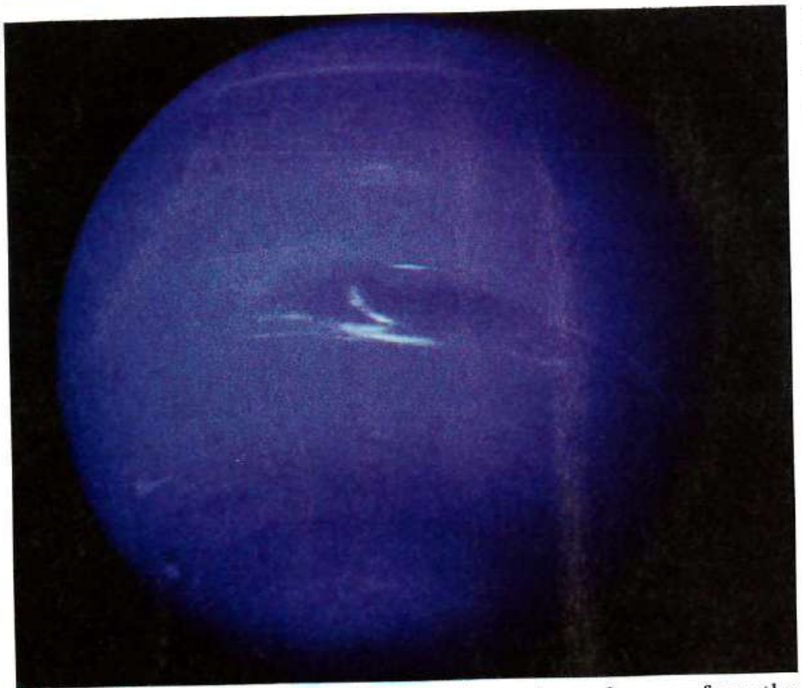
The first discoveries of icy debris beyond the orbit of Neptune, now collectively known as the Kuiper belt, conformed to this narrative well. As observational surveys began to expose the intricate dynamical structure of the Kuiper belt, it became increasingly clear that virtually every Kuiper belt object's orbital evolution could be explained through gravitational interactions with Neptune. While some objects are currently locked into orbital resonances with Neptune, others show signs of having been tethered by its gravitational pull in the past. Hence, at the turn of the 21st century, the large-scale architecture of the solar system showed no signs of abnormality whatsoever.

Kuiper belt clues

The solar system in 2016 tells a very different story. Over the course of the last 15 years, observational mapping of the Kuiper belt has revealed a simple, fundamental fact: the orbital arrangement of the most distant bodies in the Kuiper belt is incompatible with an eight-planet solar system.

The first real hint that the solar system still has some tricks up its sleeve came in 2003, when a team of astronomers led by Mike Brown discovered Sedna, a Kuiper belt object (KBO) unlike any other. Whereas most known KBOs have orbital periods not too different from the approximately 250-year period of Pluto, Sedna requires more than 11 000 years to complete its journey around the Sun. Another impressive feature of Sedna's orbit is its staggering ellipticity. At its furthest from the Sun, Sedna swings out to almost 1000 astronomical units (where one astronomical unit is the mean Earth–Sun distance, roughly 150 million kilometres).

The truly remarkable thing about Sedna, however, is that its orbit is not elliptical enough. Most KBO orbits appear to physically hug the orbit of Neptune. That is because – due to gravitational potential being conservative – any small object that has been sent on a highly elliptical trajectory by Neptune must come back to its point of origin, i.e. the orbit of Neptune. Sedna's orbit represented the first true exception to this rule: even at its closest approach to the Sun, NASA



Data-led discovery
To date, Neptune (pictured here by Voyager 2) is the only planet in our solar system to have been predicted by theory and later confirmed by direct observation.

Sedna remains more than twice as far away from the Sun as Neptune. As a result, Sedna's origin posed somewhat of a mystery. A body that never experienced direct interactions with Neptune could not have been placed on its orbit by Neptune alone.

In a paper detailing Sedna's discovery, Brown, Chad Trujillo and David Rabinowitz speculated on the various scenarios that could potentially account for the genesis of its strange orbit, including a scenario where an undiscovered Earth-mass planet lurks beyond the orbit of Neptune (2004 *Astrophys. J.* **617** 645). Around the same time, Brett Gladman and Collin Chan independently discussed the possibility of a rogue planet shaping some features of the Kuiper belt. A similar viewpoint was adopted by yet another researcher, Rodney Gomes, in Brazil. In some sense, the discussion mirrored the Lexell–Bouvard speculation of the early 1800s, in which close examination of Uranus had given clues to the existence of Neptune. Clear echoes of a distant perturbing body were beginning to emerge.

Sedna's loneliness as an outlier finally came to an end in 2014, when Trujillo and Scott Sheppard discovered a second Sedna-like object, 2012 VP113 (*Nature* **507** 471). With a perihelion distance (a body's closest distance to the Sun) even larger than that of Sedna, 2012 VP113 confirmed that these objects are not outliers: they are members of a separate, detached population of KBOs. It was with this very paper in hand, and a facial expression showing a combination of excitement and concern, that Mike Brown walked into my office two years ago.

Could it truly be that after 170 years of false alarms and non-detections, we had stumbled upon actual evidence that the solar system's planetary catalogue is incomplete?

Gravity of the situation

"Have you seen how weird this is?" Mike asked, pointing to figure 3 in Trujillo and Sheppard's paper. Here the authors note that all KBOs with orbits with perihelion distances beyond Neptune and with periods longer than 2000 years tend to cluster in their argument of perihelion. (The argument of perihelion is a bizarre parameter: it is the angle between the point at which an orbit intersects the ecliptic plane while travelling from south to north on the sky and the point of closest approach to the Sun. Taken at face value, a collection of similarly inclined orbits that cluster in the argument of perihelion would trace out a cone-like structure.) Not swaying from tradition, Trujillo and Sheppard had speculated that this clustering could be due to an unseen, few-Earth-mass planet, with a circular orbit and a period equal to that of 2012 VP113. However, the authors simultaneously acknowledged that such a planet could not, in fact, explain the data adequately.

Intrigued, Mike and I examined the data ourselves. The clustering pointed out by Trujillo and Sheppard emerged on the computer screen. However, to our surprise, this clustering was not alone – other orbital co-ordinates were grouped as well. Immediately, it was clear that the clustering of the argument of perihelion is only part of the full picture. A closer look at the data showed that six objects that occupy the most expansive orbits in the Kuiper belt (including Sedna and 2012 VP113) trace out elliptical paths that point into approximately the same direction in physical space, and lie in approximately the same plane.

Mike and I were genuinely perplexed. Could the confinement of the orbits be due to an observational bias, or perhaps to mere coincidence? Will any theory aimed at explaining these observations suffer the same fate as Lowell's Planet X hypothesis (i.e. the need for it disappears once more accurate observations are made)? Thankfully, the probability of the observed alignment being fortuitous can be assessed in a statistically rigorous manner, owing to the large size of the comparison sample (i.e. other KBOs that are found at a similar radial distance to our objects of interest). The probability that the alignment is a fluke clocked in at only 0.007%. Not a great gamble.

Could this orbital alignment be a relic of an encounter with a passing star during the solar system's infancy? An application of simple mean-field perturbation theory showed that if allowed to evolve under the gravitational influence of Jupiter, Saturn, Uranus and Neptune, these objects' orbits would become randomly oriented on timescales much shorter than the multi-billion-year lifetime of the solar system. So the dynamical origin of the peculiar structure of the Kuiper belt cannot be outsourced to the distant past – something is holding the orbits together *right now*.

Having quadruple-checked our results, we sat on my couch and stared silently at each other. The gravity of the situation began to sink in. Could it truly be that after 170 years of false alarms and non-detections, we had stumbled upon actual evidence that the solar system's planetary catalogue is incomplete? We got to work.

Glimpse of hope

Our progress was initially anything but rapid. Coming from observational and theoretical backgrounds respectively, Mike and I don't always speak the same language, and would spend hours arguing profusely, only to later realize that we are in fact, saying the exact same thing. Then there were all the calculations that did not pan out. Ideas crowding our outtakes reel range from models where the self-gravity of the Kuiper belt itself keeps the observed structure intact, to a scenario where the orbit of a distant planet cradles the orbits of KBOs from the outside, maintaining the same average orientation. Each hypothesis failed when confronted with the data.

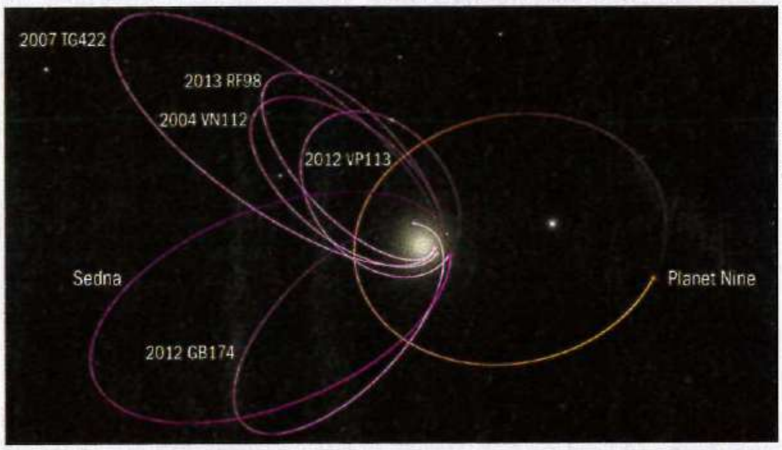
Last summer brought our first glimpse of hope. We were running a series of evolutionary numerical experiments, starting off each time with a randomized disc of planetary building blocks, or "planetesimals". We placed these objects in eccentric, Neptune-hugging orbits that were allowed to evolve under the gravitational influence of a distant perturber, which we dubbed "Planet Nine". We began to notice that groups of planetesimals emerged in orbits that were co-linear and spatially confined. Intriguingly, this would occur only if Planet Nine was chosen to be about 10 times more massive than the Earth, and to reside on a highly eccentric orbit. More unexpectedly, the confined orbits would cluster in a configuration where the long axes of their orbits are anti-aligned with respect to Planet Nine.

At first glance, this outcome was puzzling. If the trajectories of the KBOs intersect the orbit of the perturbing planet, wouldn't the objects have been scattered away at some point over the past few billion years? It turns out that the answer can be summarized in one word: resonance. Just as the overlapping orbits of Pluto and Neptune are protected from close encounters by a clockwork-like orbital period ratio of 3:2, the confined orbits of the distant Kuiper belt glean long-term stability from resonances with Planet Nine. However, the latter picture is somewhat more complex: the resonances at play are exotic and interconnected, yielding orbital evolution that is fundamentally chaotic. In other words, perturbed by Planet Nine, the distant orbits of the Kuiper belt remain approximately aligned, while changing their shape unpredictably on million-year timescales.

Surprising and unforeseen results continued to accrue. Upon a cursory examination of the simulation data, we noticed that gravitational torques exerted onto the Kuiper belt by Planet Nine would induce long-period oscillations in the perihelion distances of the confined KBOs. This naturally generated detached orbits, such as those of Sedna and 2012 VP113. Suddenly, the origins of these objects became abundantly clear: they are regular KBOs that have been pulled away from their original locations by Planet Nine. Moreover, the evolutionary calculations suggested that if we were to revisit the Kuiper belt in a hundred million years, objects like Sedna and VP would once again look like conventional, garden-variety KBOs, while some of the more typical objects would now be in detached orbits.

Finally, there was a weird, crazy twist. In every simulation that produced a synthetic Kuiper belt that resembled the real one, the model also consistently generated orbits that were nearly perpendicular to the plane of the solar system. Given that there is virtually no other way to produce such extreme inclinations in the solar system, we thought that this would be a strong prediction: if such objects were ever discovered, they would constitute tangible evidence for the existence of Planet Nine.

1 Peculiar arrangement



Robert Hurt, IPAC/Caltech

Kuiper belt objects that have periods in excess of 4000 years have highly elliptical orbits that cluster in physical space. This peculiar orbital arrangement can be explained by the existence of Planet Nine beyond Neptune.

Planet Nine falls into place

Caught up in our attempts to understand the dynamics of the simulations, we had forgotten to check the actual data. Then, on a sunny afternoon in October, we plotted the observed catalogue of objects on top of our model's predictions to see if, by any chance, highly inclined bodies of the type our simulations predicted had been discovered since we last checked. And there they were – five objects, accidentally detected by a near-Earth asteroid survey, exactly where our model predicted them to be. Once again, Mike and I sat in our seats and stared at each other in silence, allowing reality to slowly sink in.

For the first time in our joint scientific journey, we realized that Planet Nine is really out there. The theoretical model did not just explain the peculiar clustering of the orbital angles. It tied together three, seemingly unrelated aspects of the Kuiper belt into a single, unified picture: physical alignment of the distant orbits; generation of detached objects such as Sedna; and the existence of a population tracing out perpendicular orbital trajectories. As far as merits of a dynamical model go, it is difficult to ask for more. However, it is simultaneously important to keep in mind that until Planet Nine is caught on camera, it remains a theoretical prediction.

Fortunately, the prospects of confirming Planet Nine observationally are not as dim as the planet itself. Given our model's best estimates, Planet Nine has an apparent magnitude of 24–25 and currently lies in the vicinity of Orion's shield. Detecting its parallactic motion is well within the capabilities of the Subaru Telescope on Mauna Kea in Hawaii, and multiple groups have already set out on the observational hunt. It may take years, but I, for one, am confident that we will one day wake up to learn that solar photons that reflected off Planet Nine's frigid surface have landed onto the aperture of a terrestrial telescope.

For now, I wait anxiously for that day. ■

Between a rock and a cold place

Marc Rayman, mission director of NASA's Dawn mission, talks to **Laura Faye Tenenbaum** about what we are learning about Vesta and Ceres – the two largest objects in the main asteroid belt

Laura Faye Tenenbaum is senior science editor at NASA's Jet Propulsion Laboratory, e-mail laura.f.tenenbaum@jpl.nasa.gov

"A lot of people confuse Vesta and Ceres with asteroids and they aren't asteroids," explains Marc Rayman, mission director and chief engineer of NASA's Dawn mission. We are sitting in his office surrounded by a cacophony of spacecraft models, rocks and spinning science toys, including a custom-made box of "Ceres-O's" cereal. "I have one of the largest collections of space information and memorabilia in private hands you can find anywhere. I just love the stuff," he proclaims proudly. "When I was four years old, I saw a meteor – my parents called it a shooting star – and I've been a space enthusiast ever since."

I couldn't help, though, staring at his socks. They're cute socks, black with a planets-and-stars pattern. Rayman lifts a trouser leg just a smidge and I "Ooh" in admiration. Sure, it felt silly to start with socks. I'm busy. Rayman's busy. He's a mission director based in an office located behind a key-card-only access wing of an upper floor at NASA's Jet Propulsion Laboratory. And there's me yakking about his socks.

Still, the tone of our conversation is set: we bounce back and forth between our mutual fascination with legitimate cutting-edge science, with me being charmed by his passion for planetary science and his ability to gleefully rattle off exact numerical quantities. "10 320 is the number of known asteroids in the main asteroid belt larger than 10 km in diameter," he tells me. "Ceres is around a third of the total mass of all the objects in the main asteroid belt between Mars and Jupiter," he adds.

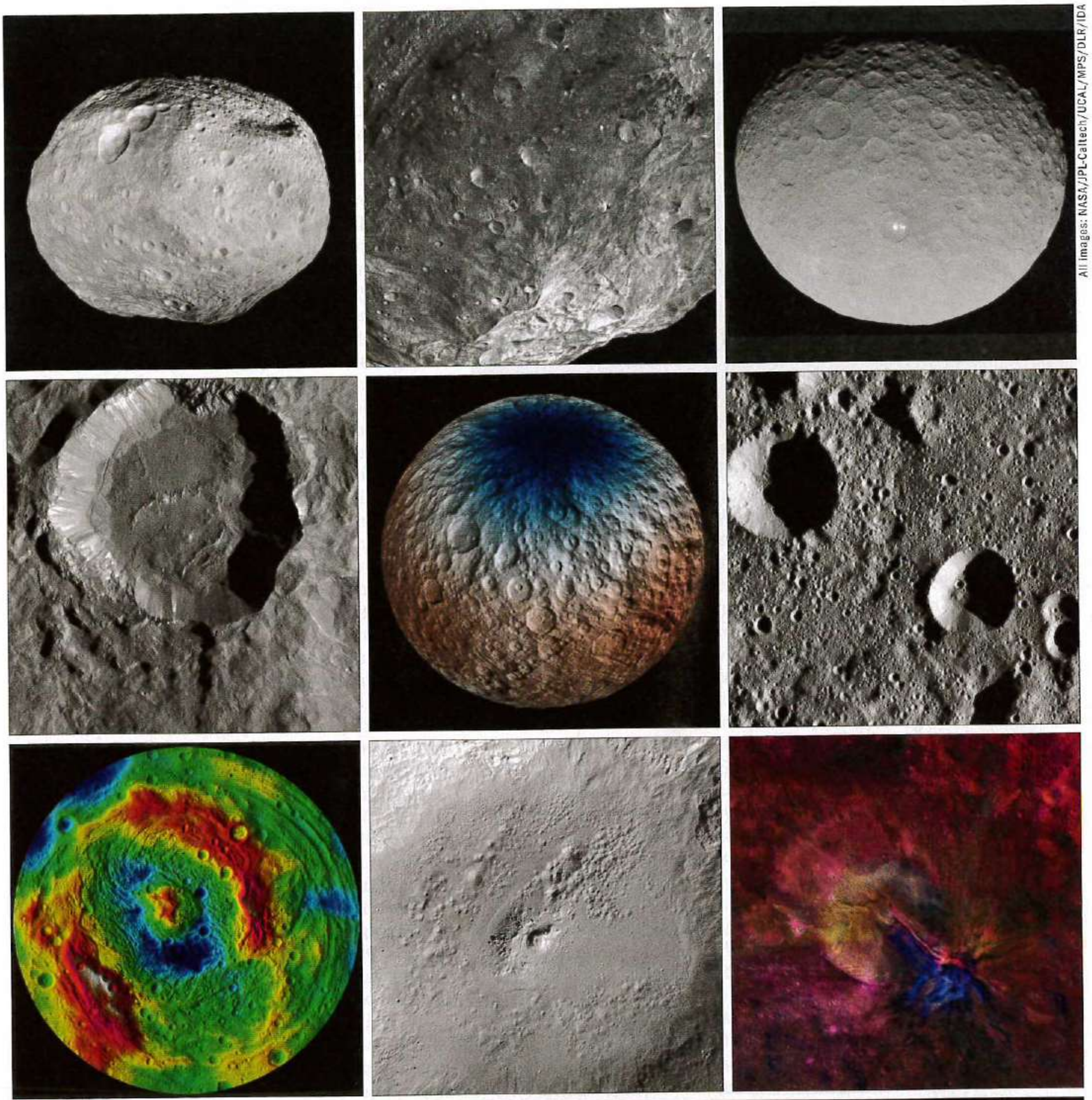
Once we get past socks, we get into history. Ceres (discovered in 1801 by Italian astronomer Giuseppe Piazzi) and Vesta (discovered in 1807 by German amateur astronomer Heinrich Olbers) are the two most massive objects in the main asteroid belt. Vesta has an equatorial diameter of 562 km, and Ceres is nearly 1000 km across. In fact, Rayman explains, "Ceres was first interpreted as the missing planet between Mars and Jupiter. You can even find schoolbooks from around the 1820s that list Ceres as well as Vesta as planets. And for almost two generations, people called them planets."

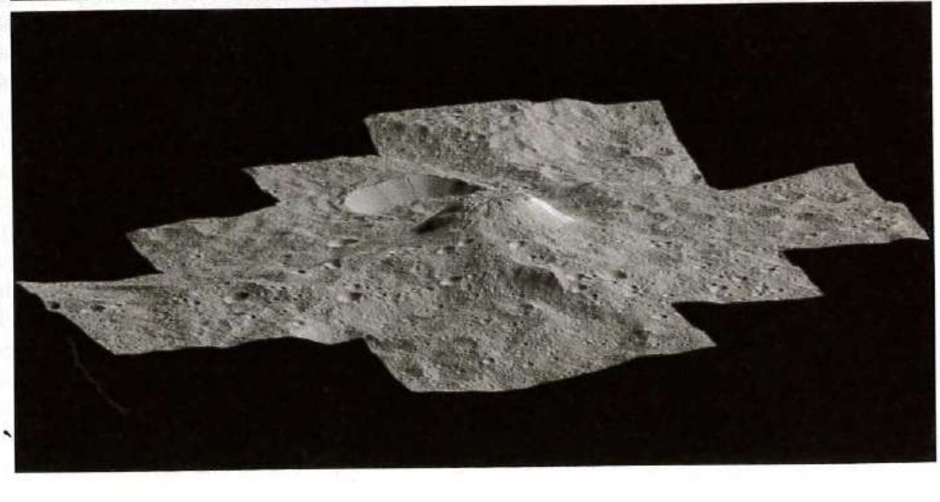
But by the mid-19th century, so many more bodies had been discovered between Mars and Jupiter that the whole lot, including Ceres and Vesta, were lumped together and called asteroids. It wasn't until 2006 that Ceres, along with Pluto, was reclassified as a dwarf planet. "Science is a process," Rayman emphasizes. "As we learn more, as scientific knowledge advances with new information, we adjust our vocabulary to reflect our new understanding."

With the exception of Ceres and Vesta, the objects in the asteroid belt never got massive enough to achieve one key requirement for definition as a planet, dwarf or otherwise: hydrostatic equilibrium. This means the shape of a planetary body is dominated by gravity and is roughly spherical. Whether or not a body's own self-gravity pulls it into a more uniform shape depends on its material composition as well as the temperatures it experiences while forming. "For example," says Rayman, "a low-viscosity material, such as a bunch of metal close to the Sun, will form into a sphere more easily than a big ball of rock." And this whole time I'd thought asteroids were just potatoes floating around in space. "There are a lot of those potatoes. And many of the little potatoes look basically the same," he assures me. "But Vesta and Ceres are not like asteroids."

I want to know more about why some planets are planets and others are dwarfs. "Earth, we pretty much have this orbit to ourselves, whereas Ceres is embedded in the asteroid belt," Rayman explains. A planet's larger mass and gravitational pull is able to suck in or eject most other objects from its orbit, whereas a dwarf planet is not massive enough to clear its orbit of other bodies. But this definition isn't perfect. "There's a continuum," he tells me, "everything from little tiny particles, the size of a grain of sand, up to the giant planets. Some of the moons of Saturn and Jupiter are bigger than the planet Mercury and significantly bigger than Pluto, and these moons range in size down to the size of your iPhone."

It was during the formation of the solar system that Ceres and Vesta came to be protoplanets. Understanding how they formed, therefore, sheds light on the rest of the solar system too, which explains why NASA wanted to send the Dawn spacecraft to the asteroid belt to study them. "A journey to the asteroid belt is like a journey back in time," Rayman says as he stretches his arms wide, trying to convey how long ago that was. "It's like looking at a construction

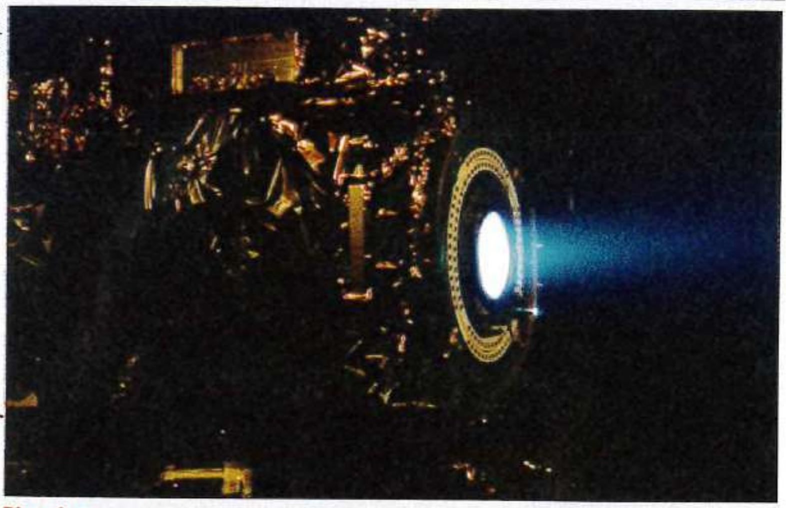




View from a probe Top row: full view of Vesta, showing clearly its irregular shape; Vesta's south pole, pictured by Dawn's framing camera; full view of Ceres, showing its spherical shape. Second row: the Kupalo crater on Ceres, named after the Slavic god of vegetation and harvest; map of the concentration of hydrogen in the regolith, the loose surface material on Ceres, based on the number of neutrons detected per second; the Chaminuka crater on Ceres, named after the Shona spirit who provides rains during drought. Third row: topographic map of Vesta showing Rheasilvia, a large impact basin; Vesta's spectacularly preserved pitted terrain – an unexpected discovery; composite image showing the flow of material inside and outside the Aelia crater on Vesta. Right: perspective view of Ahuna Mons on Ceres.

Sci-fi becomes sci-fact

NASA/JPL



Blue glow A xenon ion engine, photographed through a port of the vacuum chamber where it was being tested at NASA's Jet Propulsion Laboratory. Dawn has three ion thrusters.

Until the late 1990s, ion propulsion as a means of interplanetary travel existed only in the realm of science fiction. It crops up in the *Star Wars* franchise in the TIE fighter's "twin ion engines". And although it has not been developed in the world of *Star Trek*, it still gets a mention from Captain Kirk. "Advanced ion propulsion is even beyond our capabilities," he once told his crew.

The Starship *Enterprise* doesn't need ion propulsion, as it can rely on its warp drive. But back in the real world, the Dawn mission would be impossible without it. To travel to one destination, get into orbit, manoeuvre there, break out of orbit, travel someplace else and break into orbit there – as the Dawn spacecraft has done – is far beyond the ability of conventional propulsion technology. Ion propulsion is 10 times as efficient as conventional chemical propulsion.

According to Marc Rayman, the Dawn mission's director and chief engineer, there's a "dirty little secret of celestial mechanics", which is that the farther you are from the Sun, the slower you go. Ion propulsion is not being used to make a spacecraft go faster, but to slow it down to match orbits. Ion propulsion is very gentle. It pushes on a spacecraft as much as a piece of paper pushes on an outstretched hand. In the microgravity, frictionless conditions of space, gradually the effect of this thrust can build up. "It would take Dawn four days to accelerate from 0 to 100 km/h, so it's not a drag racer," says Rayman. "But if you thrust for a week, or month, or year or, as Dawn now has, for five years, you can achieve fantastically high velocities. Acceleration with patience is a great way to explore the solar system."

Ion propulsion produces a cool blue glow because it uses xenon as the propellant, which happens to glow blue. Dawn's three ion engines are power hungry. A large area of solar cells is needed to capture enough light to produce sufficient electrical power to ionize and accelerate xenon. The spacecraft is dominated by two solar arrays, 20 m wingtip to wingtip. When it launched in 2007, Dawn was the largest interplanetary spacecraft NASA had ever sent into space.

site to understand what's inside a building. It's like you're seeing the pieces before they grew to be a bigger planet."

Ceres and Vesta are protoplanetary remnants. They were in the process of growing into full-sized planets when massive Jupiter cut them off. Jupiter's gravity interrupted their formation process by getting into a tug of war with the Sun. The way Rayman explains it, "Jupiter is saying, 'This stuff over here is mine, you can't mess with it.' And the stuff in the asteroid belt is saying, 'I don't know what to do. I can't be a planet. Help!'" So the asteroid belt just stayed in a jacked-up interrupted mess. And that's cool because now Ceres and Vesta have retrievable records of the conditions and the processes that were acting at the *dawn* of our solar system. *Dawn*; get it?

The Dawn mission is an opportunity to explore two of the last uncharted worlds in our solar system. It's an odd juxtaposition of the excitement of going someplace new, but that someplace happening to be super old. It's like "going into the future to study the past", Rayman muses. The Dawn spacecraft blasted off from Earth in September 2007, got a gravity boost as it flew by Mars in February 2009, and finally went onto orbit around Vesta in July 2011.

Views of Vesta

Dawn found that Vesta is mostly dry, rocky and dense. It looks planet-like, even though it's misshapen and not quite spherical. Vesta's southern hemisphere has a giant impact crater with a big mountain in the centre. Rayman explains that craters often have a mountain in there because when a big piece of interplanetary debris screams down into the surface, it hits with so much energy that the rock melts and flows away from the impact site, then sloshes back, before solidifying into place. So the peak in the centre of big craters is like a snapshot of the process of how the crater formed. About a billion years ago, after Vesta had cooled off in hydrostatic equilibrium and become rigid, an asteroid about 30–50 km across smashed into it and the impact excavated a huge amount of material. This explains why Vesta looks wonky and not so spherical, and also why one in every 16 meteorites that fall to Earth comes from that impact.

Really? Yes, Vestan meteorites make up about 6% of the total mass of all meteorite falls. And those meteorites have been studied in labs for decades. "We have more material from Vesta than from Mars or even the Moon, including the 382 kg of Moon rocks brought back by Apollo astronauts," Rayman tells me. Of course he has a small chunk of Vestan meteorite in a little box. He holds it out for me to examine, explaining that Vesta has a unique infrared spectrum, just like a fingerprint, that distinguishes it from all the other stuff out there.

Much smaller bodies called Vestoids have the same unique fingerprint too. Those were broken off when the crater was excavated and the total mass, size and number of all these bodies adds up to what you would expect from the amount of Vesta that's missing. That sounded insane to me – no wonder he wanted to go there. "We needed Dawn to clinch the case that the meteorites originated from Vesta and to provide the rest of the geological context," he says proudly, "and the Dawn mission corroborated everything."

Instruments on the Dawn spacecraft take stereophotographs for making topographic maps, and determine the atomic constituents and mineralogical compositions of the bodies studied. They also measure the gravity field, which tells us about interior structure. Vesta has a dense core of iron and nickel, surrounded by a rocky mantle, surrounded by a crust. According to Rayman, "It's not just a chunk of rock; it's really more like a mini planet."

Vesta has a network of more than 90 chasms near the equator that run for hundreds of kilometres and are kilometres deep and kilometres across. They're scars from the impact that excavated the huge crater near the South Pole. "Vesta got punched so hard," says Rayman, "that the energy reverberated inside and broke up the surface hundreds of kilometres away." This could not have happened if Vesta were just a big chunk of rock, like a typical asteroid.

Asteroid navigation

After 14 months of study, in September 2012 Dawn broke out of Vesta's orbit and, using ion-propulsion technology (see box opposite), embarked on a two-and-a-half-year-long arduous climb through the main asteroid belt, on towards its new target: Ceres.

So how did the Dawn spacecraft manage to wind its way through the crowded and perilous asteroids without being smacked by some random space pea and ending up smashed to bits? We know where all the large things are, of course, but there are uncountable millions of marbles zooming around and the probability that none will whip right into Dawn seems incomprehensible. "Yes, we're used to seeing an environment in the movies where you need Han-Solo-type piloting skills to fly in-between them," Rayman assures me, "but space is big and we're not worried about getting taken out by a space pea. We've survived." Plus, there is redundancy built into the spacecraft. "We have two cameras, two radio receivers, two transmitters and two central computers. Everywhere we have a heater, we actually have two heaters," says Rayman. "There are 11480 solar cells, and we don't need every one. So if a speeding space bean takes out one of the cells, we don't care. In fact, we wouldn't even know if we lost some." Today Dawn is four times further away from Earth than the Sun and more than a million times more distant from us than the International Space Station. If it has a problem, nobody can fix it. "I love the visceral thrill of working on a spacecraft a thousand times farther away than the Moon," he says.

Arrival at Ceres

When Dawn reached Ceres in March 2015, it became the only spacecraft in almost 60 years of space exploration to ever orbit any two extraterrestrial destinations. It began exploring Ceres at a 13600 km orbit and has since spiralled down to an altitude of merely 385 km, where it is now and where it is the closest to Ceres it's ever going to be. Today the Dawn spacecraft circles Ceres in just under 5.5 hours and is closer to the surface of Ceres than the International Space Station is to Earth.

Unlike Vesta, Ceres has a lot of water – 25% of its mass – which is low density compared to rock or metal. (For comparison, water is less than 1% of the Earth's mass.) This may be because Ceres probably formed a million or a few million years after Vesta. A million years can make a difference, especially if it was during a crucial phase of solar system development. "If you form early when there's still a lot of radioactive matter around, then you get very hot and if you have water, it boils away," explains Rayman. "If you form a few million years later, much of the raw material is decayed so you hang on to your water."

NASA/JPL-Caltech/UCAL/MPS/DLR/IDA

Shining bright The Occator crater, which contains the brightest area on Ceres. These reflective salt flats formed after the impact caused salty water to rise to the surface, which then froze.

There's even some evidence that Ceres may not have formed where it is now. Dawn detected ammonia on Ceres, which is very volatile and, during solar system formation, wouldn't have existed as a solid in the warm inner part of the solar system where Ceres is now. This means Ceres may have formed farther from the Sun, incorporated the ammonia as ice, and then as the planets underwent gravitational jostling and moved around, Ceres may have been perturbed or pushed to where it is now. So Ceres and Vesta may have formed at slightly different times and at very different locations, which would explain why they would have incorporated different materials.

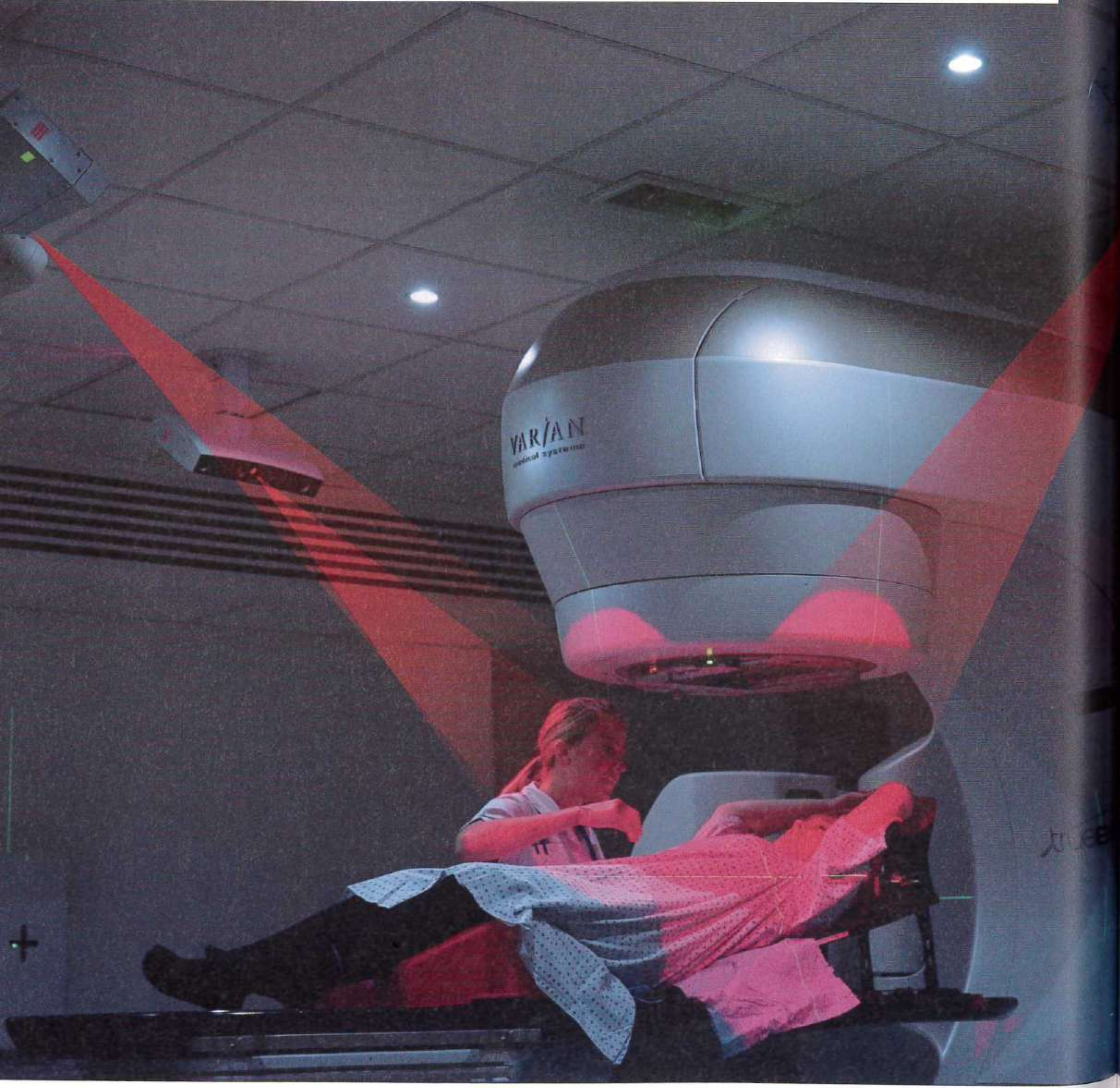
One feature on Ceres mesmerizes Rayman, as he puts it, "like a light casting forth on the cosmic seas". The shiny 92 km diameter Occator crater glows brightly due to reflective salt flats that formed in an impact crater. After the impact, briny salt water made its way to the surface of Ceres and froze in the cold vacuum of space. The water molecules then turned to gas and departed, and all that was left behind was the salt. They're the only extraterrestrial salt flats we know of.

Dawn's stereoscopic view has shown us that Ceres has a variety of terrains and about 130 locations of the bright material. The science team decided to name all of the dwarf planet's features in line with Ceres' own name – Ceres is the Roman goddess of agriculture – drawing from deities and festivals related to agriculture around the world. As well as Occator, named after a Roman helper god of Ceres, other crater names include Toharu, the Pawnee god of food and vegetation, and Rao, the Mangarevan god involved in the planting of turmeric.

"It's so profound that humankind has the capability to send spacecraft to destinations so distant you really cannot imagine it. These are robotic emissaries to the stars," Rayman declares. "I've been looking up at the sky since I was four years old and to think we have spacecraft out there is amazing." ■

ACCURATE TARGETING OF TUMOURS

lignRT system monitors the patient's surface area during radiotherapy treatment, using ceiling-mounted stereoscopic cameras. This allows the patient to be oned accurately and tracks for any movement during radiation therapy



Radiotherapy is a widely used treatment for cancer, allowing doctors to shrink tumours that cannot be surgically removed because of their size. However, there is a risk of damage to healthy tissue from radiation beams if the patient moves. Science writer Tereza Pultarova talked to Norman Smith from Vision RT, a finalist for the 2017 MacRobert Award, about its technology that accurately tracks a patient's position before and during treatment.

In the UK, one in every two people are likely to receive a cancer diagnosis at some point in their lives, and about 50% of them will require radiation therapy, which often successfully cures patients.

Radiotherapy works by targeting high-energy photon beams into tumours to destroy cancer cells. However, the radiation can also be harmful to healthy tissue, so healthcare professionals do their utmost to ensure that only the target area receives the dose. However, slight movements that patients naturally make during treatment can be almost impossible to detect, and these can lead to radiation damage to healthy tissue and potential long-term health problems.

Generally, in radiotherapy treatment, laser beams are used to help position the patient's body before the treatment begins. Since several radiotherapy fractions (a series of treatment sessions that make up the entire course) are usually spread over a number of weeks, repeated accurate positioning is needed. To aid this, the patient is often given tattoo marks in several places so that the radiotherapist can determine the exact location of the tumour inside the body, based on a previously taken CT (computerised tomography) scan.

In order to ensure that patients can be set up precisely and radiotherapy is delivered as accurately as possible, technology company Vision RT developed AlignRT, a completely non-contact system that continuously tracks the patient's position in 3D before and during treatment with better than one millimetre accuracy.

A pseudorandom pattern is projected onto the patient's body, which is picked up by the cameras and used to develop a 3D image of the patient's surface area to precisely calculate their location during treatment

CREATING A SYSTEM

After graduating in electrical engineering from the University of Cambridge and completing a PhD in medical image processing at Imperial College London, Norman Smith, CEO of Vision RT, joined a startup that was developing stereoscopic imaging techniques for various applications. Stereoscopic imaging systems mimic human visual perception to see surroundings in three dimensions; they consist of two cameras positioned at a known distance from each other, in the same way that humans have two eyes to perceive depth.

During this period, Smith visited a few radiotherapy clinics and was surprised at how primitive some of the techniques for setup and monitoring were. He was confident that stereoscopic technology would be able to monitor not just a few tattoo marks, but the entire patient before and during radiotherapy treatment, and would also remove the need for the tattoo reference points on the body, which can remain a permanent reminder for patients of their cancer. While it was here that the idea for the AlignRT technology was born, the company that Smith worked for was not interested in developing the idea further.

In 2001, Smith and co-founder and CTO Ivan Meir began operating as Vision RT from the attic of Smith's parents-in-law's house in North London. Gideon Hale, Vice-President Operations, joined the organisation 18 months later. The journey from vision to reality was not straightforward; at the time, there were no suitable 'off-the-shelf' stereoscopic camera systems available so they designed and engineered their own proprietary cameras, electronic hardware, processing software and user interface. Apart from the camera chips and lenses, all the system's components are manufactured in the UK.

The system continuously monitors the patient surface using three separate 3D camera modules that are ceiling-mounted in the radiotherapy treatment room and view the treatment table from different angles. The camera modules also contain a projector that illuminates the patient's body with a pseudorandom pattern on the surface of their body. This pattern is detected by the cameras and custom-written stereo-matching software to find corresponding points between pairs of calibrated stereo camera images. Through the process of triangulation, 3D coordinates are calculated for each set of 2D image points, which results in a 3D surface model comprising tens of thousands of points. The data from all 3D cameras is combined and the surface position is determined to sub-millimetric accuracy at a rate of 2 to 10 hertz (Hz) to precisely define the location of the patient as they undergo radiotherapy.

This accurate surface map is then dynamically matched to a reference surface model derived from a CT image, and treatment is planned using this. This allows the location of the tumour, based on the patient's body surface, to be tracked in all six degrees of freedom (the freedom of movement of a rigid body in a three-dimensional space) to ensure that the treatment is being delivered correctly.

ACCURACY, EASE AND COMFORT

In addition to real-time 3D mapping of the surface, the company has developed an easy-to-use interface software that, via a simple colour bar display, gives directions that allow the radiotherapy operator to position the patient faster and more accurately. Moreover, instead of relying on a human operator to stop the beam manually if

eiling-mounted modules contain a projector and stereoscopic camera. These need to be precisely aligned

unexpectedly system senses the movements from and automatically ation delivery, damage to healthy ther benefit of ment is that it s the need for to be held in ariety of invasive ion frames or ch were previously o restrict patient Historically, taff would also patient's position the tattooed osed-circuit om a neighbouring patient moved, manually stop n beam, but this nable to pick up ments and requires gilance.

surface mapping camera positions to aligned and rigid. d by the fact that radiotherapy treatment rooms are usually solid concrete-walled and roofed structures, but it also means that the camera/projector modules must be rigid and thermally stable, which can be very difficult to achieve with an optical measurement system. The company solved this through careful mechanical design and an innovative thermal management solution, which ensures that the modules are operated at a controlled temperature.

Any detected motion must be synchronised to the treatment delivery machine (the linear accelerator), so the company has designed its own electronics modules for this and interfaced these, in collaboration with the different manufacturers, to their radiotherapy treatment delivery machines. The processing software, which at its core uses a mathematically complex and computationally challenging matching technique, must be both fast and accurate over the whole image to track any patient movement at high frame rates. The whole system calibration is checked daily and to do this the company has designed easy-to-use calibration phantoms that are mounted on the treatment couch, with built-in hardware and software consistency checks.

CONFIRMED RESULTS

The company's first prototype was tested at the Royal Marsden Hospital, a cancer specialist centre, in 2002. This confirmed that the system could track an object to within a millimetre, and the following year, Vision RT submitted its data to the American Society of Radiation Therapy and Oncology (ASTRO), the world's largest professional radiotherapy organisation. On acceptance of its paper for oral presentation, the company decided to attend ASTRO 2003 to exhibit its prototype technology at the associated industry trade show.

A chance encounter at the event between Smith and Meir and Dr George Chen, a professor at the Department of Radiation Oncology at Harvard Medical School and a leading authority in the field, initiated a productive relationship. Dr Chen had been attempting to develop something similar with MIT for three years, but had been unsuccessful. Within a year, Vision RT had installed a prototype system at Massachusetts General Hospital, Harvard Medical School's largest teaching hospital and one of the world's leading biomedical research facilities.

By 2005, two scientific papers were published in peer-reviewed journals; soon after, the company received clearance to market the technology in the US and the first units were sold, initially to leading academic institutions that were focused more on technical efficacy than usability. As Vision RT's market expanded, feedback from more routine users complaining about the ergonomics of the system required the engineers to completely redesign the system's user interface to make it very easy to operate. During subsequent years, a new and improved camera/projector system was developed, as well as an enhanced calibration technique to enable the exceptional accuracy that is required for radiosurgery treatment where the radiation beam is both narrower and of significantly higher intensity.

EXPLORING NEW AREAS

Vision RT long ago left behind the cramped attic of Smith's parents-in-law's home and its team of five has expanded to more than 150 people. Now, the technology is used in 70% of the top 50 cancer centres in the USA and in more than 30 countries around the world. The system is becoming a standard in radiotherapy treatment. The company has pioneered a new field of surface-guided radiotherapy treatment (SGRT) and has built up and supported a 'SGRT community', consisting of almost 1,000 healthcare professionals, which trains, shares and helps develop the technique and the AlignRT product.

The company has also signed a distribution agreement with Varian Medical Systems, the world's largest manufacturer of radiotherapy treatment delivery systems, through which a Varian-branded version of the AlignRT 3D surface-imaging technology has become part of the company's offering; it is incorporated into many of Varian's radiotherapy systems.

The accuracy and rapid mapping of the system has enabled an advanced form of treatment for left-breast tumours. Because of the closeness of the heart to these tumours, damage to cardiac blood supply is a common complication. However, if the patient takes a deep breath, this moves the heart away from the chest wall. By monitoring when the patient is holding their breath, the AlignRT technique can ensure that the radiation is only delivered to the tumour during this period and not to the heart. Using the simple alignment software that had already been designed to enable the radiographer to position the patient, Vision RT has produced a simple tablet-based bar graph display that the patient can use to ensure that they have taken a deep enough breath to move the chest wall, and hence the tumour and heart, into the right position for treatment.

The software aids healthcare professionals in rapid positioning of patients prior to radiotherapy, and highlights any movement they make from their intended position during treatment

The treatment of left-breast cancer has been a success story; a recent clinical study in North Carolina showed that no patients who were treated with the guidance of AlignRT experienced damage to heart blood supply, in comparison to 27% in a previous study using traditional techniques.

With Vision RT having over 50 patents to date and its clinical evidence being evidenced in more than 60 peer-reviewed papers, it seems that the practice of SGRT can only go from strength to strength.

BIOGRAPHY

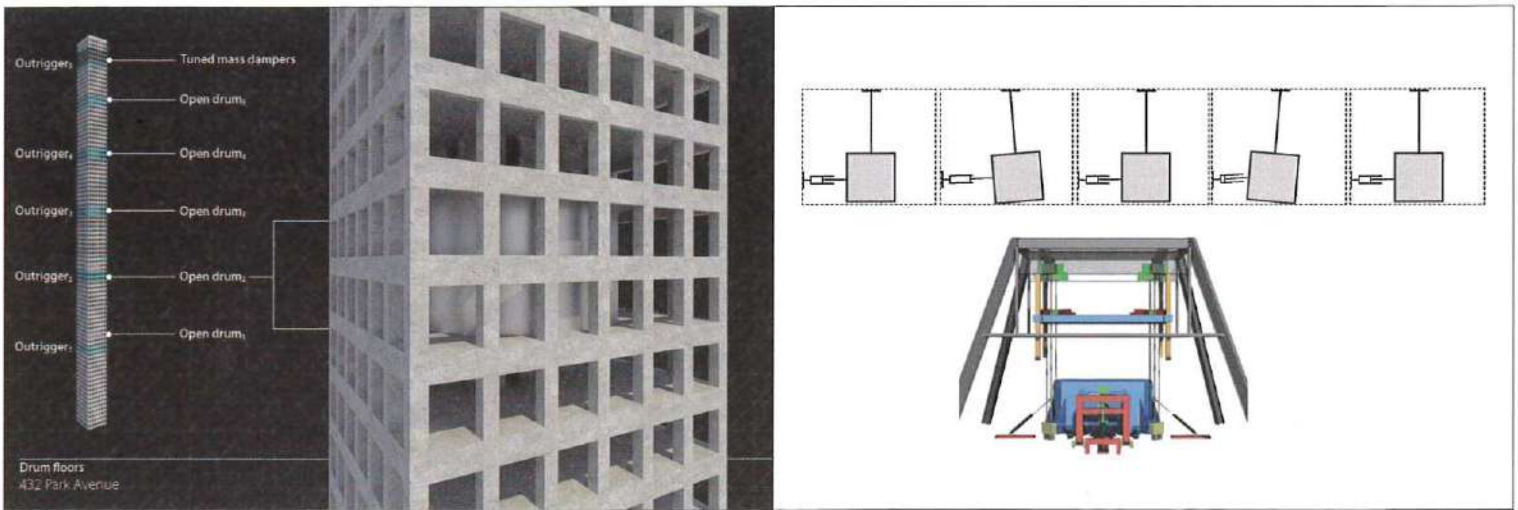
Dr Norman Smith is CEO and co-founder of Vision RT. He studied engineering at the University of Cambridge and holds an MSc and PhD in medical imaging from Imperial College London. Dr Smith is a Fellow of the Institution of Engineering and Technology, and is named inventor on several patents.

The author would also like to thank Professor David Delpy CBE FREng FRS for his help in putting together this article.

THE SKY'S THE LIMIT

venue is one of the most recent additions to the New York City skyline. The building stands at 426.5
storeys) high. At about every 12th storey, the building has been left windowless and 'open' floors have
ted, to reduce vibration in windy conditions © Nicola Evans

Tall buildings are rising in cities all over the world, at a rate and with a variety never seen before. Engineer and writer Hugh Ferguson talked to skyscraper designer and London-based structural engineer Kamran Moazami, about one of New York's most recent skyscrapers – 432 Park Avenue – and the engineering challenges of designing tall buildings.



(Left): The square-shaped concrete core of the building is connected by 'outriggers' (double-storey concrete frames) to the exterior girder-column grid at roughly every 12th floor so that they act monolithically and increase the overall lateral stiffness. (Right): Two mass-tuned dampers were also added to the top of the building to control its movement. A tuned-mass damper is a mass that is supported by a pendulum arrangement and connected to the structure by means of springs and/or dampers

In the heart of Manhattan, where land values are among the highest in the world, stands 432 Park Avenue, one of New York City's newest skyscrapers and a towering example of what new engineering techniques, combined with high-performance materials, can achieve.

New York was the birthplace of the skyscraper, notably with the Chrysler Building and Empire State Building in the early 1930s, both of which are steel-frame buildings of rectilinear shapes. In the 1960s, the skyscraper had something of a resurgence with the introduction of tubes (usually in steel) for perimeter and interior columns and perimeter diagonal bracing, which greatly reduced the weight of steel required and hence the cost. Many buildings over 40 storeys that have been constructed since the 1960s use a tube system adapted from the structural engineering principles of Bangladeshi-American structural engineer Fazlur Khan. This included the John Hancock Center in Chicago, and the World Trade Center twin towers in New York (1973).

Tall buildings continue to spring up throughout the world in response to many factors, such as increasing urbanisation, a desire to create iconic buildings, and the discovery that people across the world love grand views. Now, more than half of the world's 20 tallest buildings are in China (with four elsewhere in the Far East, three in the USA and two in the Middle East). Before 2000, two thirds of skyscrapers were commercial: since then, more than two-thirds have been residential or mixed-use.

SLENDER AND STABLE

At 426.5 metres, 432 Park Avenue is one of the world's 20 tallest buildings. It is the second tallest building in New York City and the third tallest in the USA. The building is entirely residential and currently stands as the tallest residential tower in the Western Hemisphere. However, much more significantly, with its compact 28.5 metre-square footprint, it has an aspect ratio (height/width) of 15:1, a slenderness that would have been unthinkable a decade ago. This has helped the developer to gain more usable space out of a comparatively small plot, and to give the residents unrivalled views of the Manhattan skyline. It also presented interesting challenges for the building's engineers.

432 Park Avenue had to be designed to transfer its own weight down to the foundations, to resist seismic and wind loads, and – most challenging of all with such a slender building – to manage the movement of the building under wind loading so that no movement would be detectable. All tall buildings move in the wind, but occupants, particularly residents, do not want to feel the sway. That meant keeping the lateral acceleration of the building (its movement in wind) below around 0.1 m/s2 (metre per second squared) in a 'once-in-a-year' gale.

On most tall buildings, extensive wind tunnel testing is an integral part of the structural analysis and design. This may include: high-frequency force balance tests; multi-degree of freedom aeroelastic modelling, which explores the independently acting factors that influence the interaction between inertial, elastic, and aerodynamic forces that occur when the building is exposed to wind; wind studies done at large scale on just one section of the building at a time; cladding pressure and wind studies to ensure that cladding panels, windows and fixings will not be blown off in a gale; pedestrian-level comfort testing, to ensure downdraft wind on the building and any street-level wind tunneling does not create discomfort for nearby pedestrians; and wind-induced aeroacoustic studies, to check and ensure that wind will not cause any whistling or noise-generated issues.

At the time, 432 Park Avenue was one of the most slender buildings in the world, designed by engineering consultant WSP. Therefore, wind-related testing was particularly rigorous, with

Dn most tall buildings, extensive wind tunnel esting is an integral part of the structural nalysis and design

ound five force-balance tests icked up by several all-day orkshops to establish the otimum configuration, followed a few aeroelastic tests on the al design.

First, the building had to made as stiff as possible to sist overall bending, while still ving large, open areas on the or plan for attractive living aces. This was achieved by eating a 9 metre by 9 metre ncrete shear-wall core around e lift shafts, which formed e building's central spine. ss conventionally, the strong e was supplemented by a mework of concrete columns d spandrel beams forming building envelope and oiding the need for externally unted cladding. Cast-in-situ ors span between the central e and the perimeter frames. ensure that the concrete imeter framing and interior e respond monolithically to ctural demands, they were nected by massive double-ey concrete frames, known outriggers', which were cealed in the plant rooms at ut every 12th floor.

Despite its lateral stiffness, tower still tended to move cceptably in varying wind ditions, and the lateral--carrying system had e 'tuned' to minimise lacement, acceleration and vibration. This was solved by adding mass to the upper levels, achieved by increasing the typical 250-millimetre thickness of the concrete floors to 450 millimetres. Two 650 tonne mass-tuned dampers were also added to the top of the building: these are large steel weights supported by cables as pendulums and connected laterally to the structure by viscous dampers, which absorb the energy of the moving weights and transfer the associated forces into the building structure, slowing the building's acceleration to acceptable limits.

Early wind tunnel testing had shown that the building exhibited significant 'vortex shedding', which is an oscillating airflow phenomenon that can occur when wind flows past a building at certain velocities. Vortices are formed at the back of the building, detaching periodically from either side. Each low-pressure vortex tends to pull the building towards the centre of the vortex, so the effect can be to induce vibration, particularly if the frequency of vortex shedding approaches the resonant frequency of the structure. The solution at 432 Park Avenue was ingenious and innovative: by leaving the building windowless at precise levels and creating 'open' floors – a technique comparable to making

(Top): A rendering of 111 West 57th Street. Its aspect ratio of 24:1 will make it the world's most slender building. (Bottom): Shear walls run the full length of the east and west exteriors and have been thickened to as much as one metre. Like 432 Park Avenue, it also has open floors that the wind will pass through to reduce vibration

holes in the sail of a boat – the wind loading was reduced and so was the vortex shedding. Conveniently, these levels could be designed to coincide with the plant rooms, and to some extent the outriggers, at about every 12th floor.

Although these 'open' floors take up valuable floor space, this is more than compensated for by the additional stability that allowed the height of the building to be increased to 86 storeys.

The concrete required for the building was no ordinary concrete. For the lower sections carrying larger vertical and lateral loads, it had to have a specified compressive strength of more than 100 MPa ('high strength' concrete is considered to have a compressive strength of 50 MPa or more). All structural concrete was designed for enhanced durability by minimising air content and the water/cementitious materials ratio, and with a higher-than-normal modulus of elasticity to minimise deformation. To aid placing and to improve the finished appearance, it had to be able to be pumped to great heights. Since there was to be no cladding to cover potential blemishes on the exterior of the building, architectural exposed concrete was specified in an attractive white colour and was placed with near-perfect workmanship. Although the exterior concrete should be maintenance-free, the exterior of the building required access for glass cleaning and replacement, which will be done using a telescopic building maintenance unit (BMU) mounted on the roof.

EVEN TALLER TOWERS

Now, just three blocks away, 432 Park Avenue's successor is nearing completion. Not content with an aspect ratio of 15:1, 111 West 57^{th} Street has a ratio of 24:1, which will make it the world's most slender building. At 438 metres, it is slightly taller than its neighbour and shares many features: both are high-end residential buildings, both use high-strength concrete, and both have a tuned mass damper on the top and gaps allowing the wind to pass through to minimise vortex shedding.

The main difference is that the architect and developer for the latter wanted clear, unobstructed views northwards over Central Park and south towards Lower Manhattan. The solution was a concrete core, linked to two concrete shear walls (a structural system composed of braced panels) running the height of the building on the east and west sides and allowing clear views north and south, so that the overall structure resembles a giant cantilevered concrete I-beam standing on its end. The tower is slightly tapered, and the external walls will be clad in terracotta and bronze rather than architecturally exposed concrete. Even more slender buildings are now being planned, although an aspect ratio of 24:1 is approaching the limit of what is currently feasible.

EVOLUTION OF SKYSCRAPERS

The buildings at 432 Park Avenue and 111 West 57^{th} Street are responding to the specific parameters of the New York City market, including strong demand for high-end residential properties with outstanding views, and locally available high-strength coarse aggregates needed for making ultra-high-strength concrete (a similar compressive strength in London, for example, would require imported aggregate, and is therefore a much more expensive concrete). In different parts of the globe, the parameters or constraints are likely to be different and so too are the solutions.

The original rectilinear steel buildings most usually associated with skyscrapers have largely been succeeded by concrete or composite concrete-and-steel, and the equally ubiquitous office buildings have given way to varieties of mixed-use towers: modern skyscrapers are

SAFER SKYSCRAPERS

Skyscrapers are now among some of the safest buildings in the world, if only because they must be thoroughly engineered to the finest detail, and not just for structural safety. For example, the fixings of every external cladding panel should allow for sufficient movement to accommodate the building's sway under anticipated conditions.

Most modern tall buildings have a fire strategy, which covers such issues as means of escape, detection and alarm, fire suppression, smoke control, firefighter access and facilities, compartmentation, and internal and external spread of fire. Most high-rises now include dedicated fire stairs and some have lifts that can be used for fire escape, which require special details such as pressurised lobbies where people can wait for the lifts and an independent cooling system for the lift motor room. The main fire element of tall building design is ensuring that compartmentation is maintained until the fire is exhausted or controlled. Spread of fire on the exterior of a building is usually mitigated by choosing insulation materials of limited combustibility, provision of adequate fire-stopping, cavity barriers around openings, and main compartmentation lines. For example, in August 2016, a fire burned dramatically for two hours on the outside of Dubai's 84-storey Torch Tower, where some of the cladding systems were not of limited combustibility and fire-stopping was inadequate. Despite this, other elements of the fire strategy worked well, particularly suppression that ensured safe escape for occupants, and consequently there were no casualties.

ƝGINEERING CHALLENGES OF TALL BUILDINGS

ꞌd

ꞌd in 2012, the Shard is London and the UK's tallest
ɜt 310 metres and 95 storeys ('Building the Shard' *Ingenia*
ɿaped as an irregular pyramid with highly complex
ꞌ. The Shard is a modern mixed-use tall building with retail
ꞌe, offices in the lower levels, a hotel in the middle and
l near the top. A strong central concrete core and a hat
engages all perimeter columns form the spine of the
ɜnd the remainder varies with use: structural steel was the
solution for the offices, where deep steel beams could
ɿty of space for the extensive services required. For the
flats, where acoustic separation was more important and
ɜns were shorter owing to the tapering of the building,
ꞌloors were preferred, which were thinner so that two
ɜys could be added within the same overall building
ɪe tower then reverts to steel for the viewing gallery and

ɪdland

ɿetre high, 60-floor Newfoundland residential tower in
ɿarf, London, straddles the Jubilee Line tube tunnels,
close to the surface at the tower's location. This required
ing between and beside the tunnels, as well as a major
fer structure to connect the building's loads with the
ꞌever, to avoid disturbance to the tunnels, it was necessary
ɪe weight of the building to a minimum. The solution was
of diagonally placed steel members on the outside of the
reating a diamond pattern, and the use of post-tensioned
ꞌloor slabs connecting the diagrid to the concrete
diagrid was so light and strong that the thickness (and
the weight) of the shear walls in the concrete core could
d to just 300 millimetres.

ꞌelf-contained cities in
ɿ a mix of residences,
ɜls, restaurants and
ꞌ.
stronger materials
ɔed, there is no
ɿnit to how high
could be built.
ꞌeseeable limits are
the larger footprints
ground level and
rt links to service the
ɔants, for example the constraints of providing fast and efficient vertical transportation, and economic viability: larger buildings cost more, take longer to build, and take longer to let, so developers need even deeper pockets. However, with increased urbanisation, a public appetite for tall buildings and the ingenuity of engineers, the surge in skyscrapers worldwide is set to increase still further – and some of them will be even taller.

Torre Mayor

The 225-metre high, 55-storey Torre Mayor in Mexico City was Latin America's tallest building when it opened in 2003 and is now Mexico's fourth tallest. The design priority for this building was seismic design, as it stands in the lakebed area where the heaviest damage from the catastrophic Michoacán 1985 earthquake was recorded. Designed to resist an 8.5 Richter earthquake, Torre Mayor has an arrangement of 96 viscous fluid dampers (with technology borrowed from the shock-absorbers of a car) attached to the diagonal cross-bracing on the perimeter of the building, which safely absorb the earthquake's energy. A 7.6 Richter earthquake in 2003 did no damage: indeed, the occupants did not even notice that a tremor had taken place. The structure also responded as expected when the 7.1-magnitude earthquake of Axochiapan occured in September 2017.

22 Bishopsgate

When it is completed in 2019, 22 Bishopsgate will be London's second tallest building at 278 metres with 62 floors. This will be even more of a 'vertical village' including retail, restaurants, an auditorium, various leisure facilities, including a climbing wall on the 25th floor, and offices. It will be the first building in the UK to be accredited for standards to improve building users' health and wellbeing. The main challenge here was to address what had gone before: a previous scheme was abandoned in 2012 because of the recession, with just the foundations and seven storeys of the core constructed. The core was deconstructed, but for the new tower to be economical, a way had to be found to place an entirely different building on the existing foundations (including London's deepest piles). This required elaborate analysis and design at the base of the building to transfer the loads to the foundations such that the full strength of the existing piles was mobilised, but no individual pile was overloaded.

BIOGRAPHY

Kamran Moazami is Managing Director, Property and Buildings, at WSP. He studied structural engineering at Columbia University in New York. After obtaining his master's degree, he joined New York skyscraper firm, Cantor Seinuk, where he worked on several high-rise buildings. In 1996, he relocated to the UK to head up the company's London office. Later on, Cantor Seinuk was acquired by London-based firm WSP.

Hugh Ferguson also talked to Nick Offer, Head of London Building Services for WSP.

All projects mentioned in this article have been structurally designed by WSP

Glossary

Acceleration Rate of change of velocity. Units are m/s^2.

Activity/count rate The number of radioactive emissions in a certain time.

Air resistance (drag) The force from the air that opposes movement.

Alpha (radiation/particles) A type of radioactive emission with low penetrating power blocked by paper.

An alpha particle is made up of two neutrons and two protons (a helium nucleus).

Alternating current (a.c.) A current that changes direction as the supply voltage changes from + to −, or − to +.

Ammeter An instrument used to measure the size of an electric current.

Ampere (amp) The unit of electric current.

Amplitude The maximum displacement of a wave from the equilibrium position.

Analogue signals Signals carried as continuous waves that vary in frequency and amplitude.

Anode The positively-charged electrode.

Artificial satellite A satellite put into orbit from the Earth.

Atmosphere The layer of gases around the Earth.

Atom The smallest part of an element that can exist. Atoms have a nucleus consisting of protons and neutrons around which are shells of electrons.

Atomic number The number of protons present in an atomic nucleus (and the number of electrons present in the neutral atom).

Background radiation The radioactivity that is always present in the environment.

Battery A number of electrical cells joined together.

Beta (radiation/particles) A type of radioactive emission with moderate penetrating power blocked by thin sheets of aluminium.

Beta particles are high-energy electrons.

Big Bang theory A theory that considers that the Universe started from a gigantic explosion.

Black hole An object in space that is so dense and its gravitational field so strong that light and other forms of electromagnetic radiation cannot escape from it.

Braking distance The distance a vehicle travels before stopping after the brakes have been applied.

Capacitor A device designed to store electrical charge.

Cathode The negatively-charged electrode.

Cell (electrical) The single unit from which batteries are made.

Centre of mass The point where all the mass of an object can be thought to be concentrated.

Chain reaction A reaction in which a nucleus is split and neutrons released that can split other nuclei to produce a continuous chain of events.

Charge A feature of atomic particles. Protons and electrons have a charge. Electrons have a negative charge and protons have a positive charge. Opposite charges attract; like charges repel.

Circuit breaker A device that uses the action of an electromagnet to switch off an electrical supply very rapidly.

Comet An object made of ice and rock which orbits the Sun in a different plane to the planets.

Compression (forces) The process of being squashed.

Compression (waves) The region in a longitudinal wave where the vibrating particles of the medium are closer together than normal.

Conduction (electrical) The transfer of electrical energy along a material by free electrons.

Conduction (heat) The transfer of heat energy along a material.

Conductor (electrical) A substance allowing electrical charge to pass through.

Conductor (heat) A substance allowing heat energy to pass through.

Convection The transfer of heat energy in a liquid or a gas (fluid) caused by differences in density. Warmer, less dense fluids rise. Cooler, more dense fluids sink.

Converging lens Any lens that is thicker in the middle than it is at the edges.

Core (Earth) The innermost part of the Earth.

Core (electromagnets) The central part of electromagnet around which current-carrying coils of wire are wound.

Cosmic ray Rays and particles from space reaching Earth.

Coulomb Unit of electric charge.

Crest The point of maximum displacement in a transverse wave.

Critical angle When a ray of light, travelling in a more dense medium, hits the boundary between the more dense medium and the less dense medium and only just emerges by refraction, the angle of incidence of the ray in the more dense medium is called the critical angle.

Crust The surface layer of the Earth.

Cycle (vibration) For a transverse wave one cycle is one trough and one crest. In a longitudinal wave one cycle is one compression and one rarefaction.

Decay (atomic) The break up of unstable nuclei resulting in the production of radioactive emissions.

Decelerate To slow down.

Diffraction The spreading out of a wave as it passes through a narrow gap or moves past an object.

Digital signals Signals carried as a series of 'on' and 'off' pulses.

Diode An electrical device that only conducts electricity in one direction.

Direct current (d.c.) Electric current that does not change direction.

Diverging lens Any lens that is thicker at the edges than it is the middle.

Drag The force from the air that opposes movement.

Dynamo (generator) Device supplying a voltage from the relative motion of a conductor with a magnetic field.

Earthing The linking of a low resistance wire to a metal object to provide a low resistance path to the Earth's surface for an electric current.

Efficiency The ratio of useful energy transferred by device to total energy transferred to device.

Elastic collision A collision that involves no overall change in kinetic energy.

Elastic potential energy The energy stored in an object when work has been done to change its shape.

Electric charge A quantity of electricity.

Electric current The flow of electrons or ions. The rate of transferring electric charge. Units are amperes (amps)

Electrical energy Energy transferred by a charge.

Electrode A negatively or positively charged conductor.

Electrolysis The process of splitting up a chemical compound using an electric current.

Electromagnetic induction The production of a voltage or current across a conductor in relative motion within a magnetic field.

Electromagnetic spectrum The range of frequencies and wavelengths of electromagnetic waves.

Electromagnetic waves Transverse waves that have a common speed in air or a vacuum.

Electrons Negatively-charged sub-atomic particles orbiting in shells around the atomic nucleus.

Electrostatic forces Forces due to stationary electric charge. Like charges repel, unlike charges attract.

Element A substance made up of atoms which contain the same number of protons so contain only one type of atom, and which cannot be broken down into anything simpler by chemical means.

Fetus The name given to an unborn child more than 8 weeks after conception.

Focus The point through which parallel rays of light incident on a converging lens will be refracted.

Fossil fuels The non-renewable energy resources: crude oil, natural gas and coal.

Free electron The electrons in metals that move around inside the metal and do not remain in orbit around a nucleus. The presence of these free electrons allows the metal to conduct electricity and heat.

Frequency The number of cycles (vibrations) per second. Units are Hertz (Hz).

Friction A force which opposes the movement of an object.

Fuse A wire fitted in plugs that is designed to melt if too large a current flows through it.

Fusion (atomic) The joining of small nuclei to form a large nucleus. The process transfers heat energy to the surroundings.

Galaxy A vast number of star systems held together by gravitational forces.

Gamma (radiation) A type of radioactive emission with high penetrating power blocked by concrete/lead. Gamma radiation is part of the electromagnetic spectrum and has a very high frequency.

Geiger–Müller tube (GM tube) A detector of radioactive emissions.

Generator (dynamo) Device supplying a voltage from the relative motion of a conductor within a magnetic field.

Geostationary satellite A satellite which takes 24 hours to orbit the Earth.

Geothermal energy The energy produced in the Earth by natural heating process.

Global warming An international problem caused partly by the increase in the amounts of carbon dioxide and methane in the atmosphere which results in an increase in the average temperature of the Earth.

Gravitational potential energy The energy stored in an object due to the vertical height through which it has been lifted.

Gravity (gravitational force) A force of attraction that acts between all objects.

Greenhouse effect The effect in the atmosphere of heat energy being absorbed by gases such as carbon dioxide and methane.

Half-life The time taken for half a given number of radioactive atoms to decay to different atoms.

Hertz (Hz) The unit of frequency.

Hydroelectric Electrical power generated by the flow of moving water.

Input sensors Devices that detect changes in the environment.

Insulator (electrical) A substance not allowing an electric current to flow and charges to move.

Insulator (heat) A substance not allowing a transfer of heat energy from a hot region to a cold region.

Ion An atom or group of atoms which have lost or gained electrons to become positively or negatively charged.

Ionise To remove or add electrons to atoms or groups of atoms so giving them positive or negative charges.

Isotope Atoms of the same element which contain different numbers of neutrons.

Joule The unit of energy.

Kilowatt 1000 watts.

Kilowatt hour A unit of electrical energy.

Kinetic energy The energy possessed by an object due to its motion.

LDR (light dependent resistor) An electrical component the resistance of which decreases when light shines on it.

Light year The distance a light ray travels in one year.

Lithosphere The outer shell of the Earth made from the crust and the upper part of the mantle.

Logic gate A type of electronic switch used to process information.

Longitudinal wave A wave in which the vibrations of the particles are in the same direction as the energy transferred along the wave.

Magma Molten rock below the Earth's crust.

Magnet An object that attracts magnetic materials such as iron, steel, nickel and cobalt.

Magnetic field The region around a magnet where a magnetic material experiences a magnetic force.

Mantle The layer of the Earth between the crust and the core.

Mass number The total number of protons and neutrons in an atomic nucleus.

Mass The amount of matter an object contains Units are kg.

Milky Way The galaxy containing our solar system.

Moment The size of the turning effect of a force, measured in Nm.

Momentum Defined as mass × velocity. Units are kg m/s.

Moon A natural satellite in orbit around a planet.

Motor effect The motion of a current-carrying conductor in a magnetic field

Neutron A particle with no electrical charge found in the nucleus of most atoms. Its mass is similar to that of a proton.

Newton The unit of force (N).

Non-renewable (finite) energy resources Energy resources that, once used, cannot be replaced.

Normal The line drawn at right angles to a surface.

Nuclear fission The breaking up of a large atomic nucleus to release energy.

Nucleon The protons and neutrons in the nucleus of an atom.

Nucleus (atom) The central part of an atom that contains positively-charged protons and uncharged neutrons.

Ohm The unit of electrical resistance.

Orbit The regular path taken by an object which passes around another object.

Output devices The part of an electronic system controlled by the processor. It transfers electrical enery to other forms of energy.

Parallel circuits Closed electrical circuits that provide several pathways for an electric current.

Pivot A point that objects turn around.

Planet A very large object which orbits the Sun.

Potential difference The voltage between two points in a circuit.

Potential divider A combination of resistors in series, used to split the voltage of a battery into two parts.

Power The rate of transfer of energy. Units are watts.

Primary coil The input coil in a transformer.

Processor The part of an electronic system that decides what action is needed.

Proton A positively-charged particle found in the nucleus of an atom. It has a mass similar to that of a neutron and the number of protons present decides which element is present.

P waves Longitudinal seismic waves which travel through solids and liquids.

Radiation (heat transfer) A process by which heat is transferred.

Radiation (nuclear) The random emission of energy from an atomic nucleus as the result of the breakdown of unstable nuclei.

Radioactive (radiocarbon) dating The use of half-life to date ancient organic objects.

Radioactive decay The emission of particles or rays from an unstable atomic nucleus.

Radioactive emissions The particles and rays produced as the result of the breakdown of unstable nuclei.

Radioactive tracer A radioactive substance, usually with a relatively short half-life, that is passed into the body and used to detect, for example, the presence of cancers, tumours or the direction of blood flow. Tracers can be used in the treatment of cancers and tumours. Tracers can also be used to monitor the flow of liquids and gases in underground pipes.

Radioactivity The random emission of energy from an atomic nucleus as the result of the breakdown of unstable nuclei.

Radioisotope A radioactive isotope.

Radionuclides Materials which produce ionising radiation, such as X rays, gamma radiation, alpha particles and beta particles.

Random Spontaneous not regular.

Rarefaction The region in a longitudinal wave where the vibrating particles of the medium are further apart than normal.

Real image An image that can be shown on a screen.

Red giant A relatively cool giant star.

Red shift The effect on the spectrum of a galaxy moving away from us.

Refraction The change in direction of a wave when it passes from one medium to another due to a change in speed when passing from one medium to another.

Relay An electromagnetic switch.

Renewable energy resources Energy resources that will always be available.

Resistance A measurement describing the difficulty of electric current flow in a conductor. Units are ohms.

Resistor A device for controlling the current in a circuit.

Satellite An object which orbits a planet.

Secondary coil The output coil in a transformer.

Seismic waves These are waves created in the Earth by vibrations due to earthquakes.

Series circuits Closed electrical networks giving only one pathway for an electric current.

Solar system A system made up of the Sun, planets, moons, asteroids and comets.

Speed The distance an object travels in a unit of time. Units are m/s.

Star A source of light due to heat caused by nuclear fusion.

Sun A star at the centre of a solar system.

S waves Transverse seismic waves that can only travel through solids.

Tectonic plates The separate slow-moving adjacent sections of the Earth's lithosphere that move because of convection currents within the Earth's mantle caused by the natural radioactive processes within the Earth.

Terminal velocity The constant speed reached by a falling object when the forces acting on it (in the direction of its motion) are balanced.

Thermistor An electrical component in which the resistance decreases when it gets warm.

Thinking distance The distance travelled by a car during the driver's reaction time.

Total internal reflection This takes place at the boundary of two materials when light travelling in the more dense material strikes the boundary at an angle of incidence greater than the critical angle.

Transformer A device that changes the size of an alternating voltage.

Transistor A device that can be used as a high speed electronic switch.

Transverse wave A wave in which the vibrations of the particles are at right angles to the direction of the energy transferred along the wave.

Trough The point of maximum displacement in a transverse wave in the opposite direction to a peak.

Turbine A device that turns a generator.

Ultrasound Sound of too high a frequency to be heard by humans.

Universe Made up of innumerable galaxies.

Velocity The speed of an object in a particular direction. Units are m/s.

Vibration The movement needed to produce a wave.

Virtual image An image that cannot be shown on a screen.

Volt The unit of potential difference 1 volt = 1 joule/coulomb.

Voltage The electrical energy difference of a unit charge moved across two points in a circuit; energy transferred per unit charge.

Voltmeter An instrument used to measure potential difference.

Watt The unit of power.

Wavelength The distance between adjacent crests in a wave equivalent to the distance taken by one complete cycle.

Waves Vibrations that transfer energy but not matter.

Wave speed The distance travelled by a wave in a second. Units are m/s.

Weight The force due to gravity on an object. Units are newtons.

White dwarf A small very dense star.

Work That which is done when a force moves an object a certain distance. Units are joules.