Index

B. The particulate nature of matter / B.3 Gas laws

The big picture

? Guiding question(s)

- How are the macroscopic characteristics of a gas related to the behaviour of individual molecules?
- What assumptions and observations lead to universal gas laws?
- How can models be used to help explain observed phenomena?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

In this subtopic we will explore how conceptual Physics from other topics allows us to model the behaviour of ideal gases.

Pressurised carbon dioxide is dissolved in fizzy drinks. The tyres of cars, bikes and buses are inflated with air to move us from A to B, and helium gas is injected into fibre optic wifi cables to stop bubbles from forming in the glass. **Figure 1** shows the bubbles exploding in a fizzy drink.

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Figure 1. Carbon dioxide gas is used to make drinks fizzy.

Credit: helivideo, Getty Images

Can you think of other ways that gases are used in everyday life?

Prior learning

Before you study this subtopic, make sure that you understand the following:

- Conservation of momentum (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/))
- Impulse and change in momentum (see subtopic A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/))
- Kinetic energy and gravitational potential energy (see subtopic A.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43083/))
- Molecular theory in solids, liquids and gases (see subtopic B.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43777/))
- Density (see subtopic B.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43777/))
- Temperature (see section B.1.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/temperature-scales-id-44050/) and see section B.1.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/changing-temperature-and-changing-phase-id-44051/))

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Practical skills

Once you have completed this subtopic, you can observe the gas laws by going to Practical 4: Investigating an ideal gas law (/study/app/math-aa-hl/sid-423-cid-762593/book/investigating-an-ideal-gas-law-id-46508/).

B. The particulate nature of matter / B.3 Gas laws

What are ideal gases?

B.3.1: Pressure B.3.2: Amount of substance B.3.3: Ideal gases and the kinetic theory

B.3.8: Conditions for an ideal gas to approximate a real gas

Learning outcomes

By the end of this section you should be able to:

- Calculate pressure using the equation:

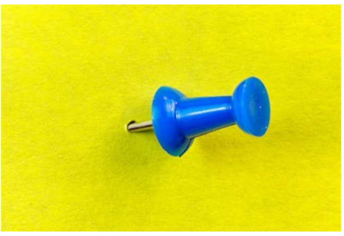
$$P = \frac{F}{A}$$

- Define the mole and calculate the amount of substance using the equation:

$$n = \frac{N}{N_\mathrm{A}}$$

- Define what an ideal gas is, describe its properties and state the conditions under which an ideal gas best approximates a real gas.

Look at **Figure 1**. What do these image have in common? When you have come up with your answer, click the ‘Show or hide solution’ button to understand some of the physical laws which govern the interactions shown.



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Credit: PATSTOCK, Getty Images

Credit: Mike Schirf, Getty Images

Credit: traumlichtfabrik, Getty Images

Figure 1. What do the following images have in common?

All the images are connected through the relationship between pressure, force and area.

The sharp point of the thumbtack (pin) is a much smaller area than the end that you push with your thumb. This results in a higher pressure so the thumbtack is pushed into the wall. Or, the larger part of the thumbtack, against which you push, spreads the force over a larger area than the point, which reduces the pressure, so you do not hurt your thumb.

The ski spreads the weight of the skier over a larger area than their feet. This results in a low pressure so the skier does not sink into the snow. Also, the ski poles have a relatively small area, which results in a larger pressure and allows the poles to be dug into the snow.

The camel has comparatively large feet so the force of its weight is spread over a large area. This results in a low pressure so the camel does not sink into the sand.

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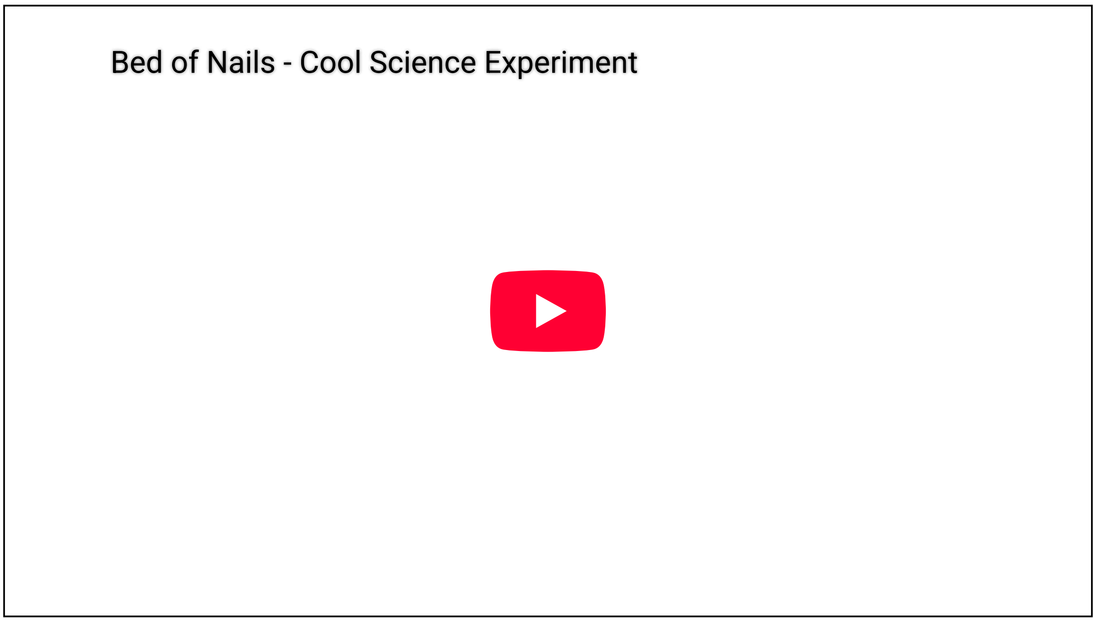
Pressure

A balloon will burst if it is placed on a single sharp nail, but it is possible for a balloon to be supported by many sharp nails at once without bursting. Why is this? Watch the demonstration in **Video 1** and consider the science behind it.



Video 1. Demonstration of pressure being related to the area over which a force is distributed.

More information for video 1

1

00:00:00,400 --> 00:00:03,036

Kim: We're talking science and circuses.

2

00:00:03,136 --> 00:00:05,155

No, I don't know the circus of science.

What is this?

3

00:00:05,239 --> 00:00:07,007

Steve Spangler: The science,

this is kind of fun.

4

00:00:07,074 --> 00:00:09,643

You know, I tell you that

all these questions come from Facebook

5

00:00:09,710 --> 00:00:11,345

and people ask the craziest questions.

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Kim: Okay?

6

00:00:11,411 --> 00:00:12,513

Steve Spangler:

You know, in the summertime,

7

00:00:12,579 --> 00:00:13,847

little circus kind of comes through town,

8

00:00:13,914 --> 00:00:14,848

Kim: Yeah.

Steve Spangler: so you see people

9

00:00:14,915 --> 00:00:16,617

and, and the, you know,

you always like the rides,

10

00:00:16,683 --> 00:00:18,185

but the geek show is the best one.

11

00:00:18,252 --> 00:00:19,219

Kim: Oh yeah.

Steve Spangler: You know,

12

00:00:19,286 --> 00:00:20,854

the, the guy who eats the glass

13

00:00:20,921 --> 00:00:22,823

or pounds the nail or away

that kind of stuff.

14

00:00:22,890 --> 00:00:24,558

Kim: Right!

Steve Spangler: The bed of nails came up.

15

00:00:24,625 --> 00:00:25,592

The bed...

Kim: Oh!

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16

00:00:25,659 --> 00:00:27,694

Steve Spangler: And you know how expensive

that is on my budget.

17

00:00:27,828 --> 00:00:29,196

So I had to do a small version,

18

00:00:29,396 --> 00:00:30,664

Kim: A mini version

Steve Spangler: of the bed of nails.

19

00:00:30,731 --> 00:00:31,665

Steve Spangler: Look at this.

This is a Kim: Mini mi!

20

00:00:31,732 --> 00:00:32,566

Steve Spangler: is the small ver...

21

00:00:32,633 --> 00:00:34,501

I can only afford one nail.

So there it is right there.

22

00:00:34,635 --> 00:00:36,503

Kim: Okay.

Steve Spangler: One tiny little nail.

23

00:00:36,570 --> 00:00:37,738

Let's do it. Okay. Kim: Okay!

24

00:00:37,838 --> 00:00:39,373

Steve Spangler: So here's what

happens. Here's the setup.

25

00:00:39,673 --> 00:00:40,774

Here are little posts

26

00:00:40,841 --> 00:00:42,910

Student view

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that are here like this

and we'll do the balloon.

27

00:00:42,976 --> 00:00:43,977

[blows balloon]

28

00:00:44,211 --> 00:00:45,812

Now I was gonna have

you put your hand there.

29

00:00:46,046 --> 00:00:47,047

Kim: Oh no, that's okay.

30

00:00:47,114 --> 00:00:48,115

Steve Spangler: But I said

this would be better.

31

00:00:48,182 --> 00:00:51,018

Okay, so Kim, watch this.

This is the bed of nail singular.

32

00:00:51,185 --> 00:00:54,121

Here's what happens

is we simply put this on.

33

00:00:54,188 --> 00:00:55,989

We rest it on the nail ever so gently.

34

00:00:56,056 --> 00:00:58,125

And this goes on top like this.

35

00:00:58,525 --> 00:01:00,761

And now Kim, here you go.

36

00:01:00,861 --> 00:01:01,962

Put your hand here.

37

00:01:02,029 --> 00:01:03,497

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You should be able to

push it all the way down.

38

00:01:03,597 --> 00:01:05,933

It won't pop. Go for it. Ready? Keep it.

39

00:01:05,999 --> 00:01:07,000

[balloon explodes]

40

00:01:07,067 --> 00:01:08,535

[Kim laughs]

Steve Spangler: Oh, darn it!

41

00:01:08,602 --> 00:01:10,804

I guess the guy goes home

with a little, I'm so sorry.

42

00:01:10,871 --> 00:01:12,673

Kim: All that strength.

I don't, I know it wasn't that.

43

00:01:12,739 --> 00:01:13,807

Steve Spangler:

I don't think the one nail,

44

00:01:13,874 --> 00:01:15,843

I've never seen a bed of nail trick.

45

00:01:15,976 --> 00:01:17,344

Kim: No. I was gonna say,

there's gotta be more.

46

00:01:17,411 --> 00:01:19,613

Steve Spangler:

No. So how about this. That's it!

47

00:01:19,680 --> 00:01:20,614

That's much better.

Student view

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Kim: Okay!

48

00:01:20,681 --> 00:01:23,016

Steve Spangler: So how about

2, 4, 6, 8, 10 nails.

49

00:01:23,083 --> 00:01:23,917

Kim: 10 nails.

Steve Spangler: That would be better.

50

00:01:23,984 --> 00:01:26,019

Kim: Okay!

[blows balloon]

51

00:01:26,086 --> 00:01:27,020

Steve Spangler: This will be better.

52

00:01:27,254 --> 00:01:28,889

Now here is the physics behind it.

53

00:01:29,022 --> 00:01:32,025

All of that pressure was put on one nail.

54

00:01:32,092 --> 00:01:35,796

And so all of our pressure pushing down

was in one point of that balloon.

55

00:01:35,929 --> 00:01:36,897

Bad idea.

56

00:01:36,964 --> 00:01:38,699

Now if we distributed over 10,

57

00:01:38,765 --> 00:01:41,001

still not a good idea,

but put it in there and take a look.

58

00:01:41,235 --> 00:01:42,736

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So this goes here like this.

59

00:01:42,803 --> 00:01:44,104

And the reason we put the board on top

60

00:01:44,171 --> 00:01:45,639

is 'cause you'd never

put your hand on top.

61

00:01:45,706 --> 00:01:46,740

Kim: No, I don't wanna do that.

62

00:01:46,807 --> 00:01:47,674

Steve Spangler: Now this is kind

of amazing.

63

00:01:47,741 --> 00:01:50,010

So put your hand here

and slowly push down.

64

00:01:50,077 --> 00:01:52,980

Push You got much further

than you did before.

65

00:01:53,046 --> 00:01:53,914

Kim: Yes.

66

00:01:53,981 --> 00:01:55,549

Steve Spangler: It's going to

keep going. Keep look at that.

67

00:01:55,616 --> 00:01:56,550

That's pretty amazing.

68

00:01:56,617 --> 00:01:57,584

Steve Spangler: Keep going.

Kim: Yes.

69

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00:01:57,651 --> 00:01:59,653

Steve Spangler: Keep going.

Keep going. You're doing great!

70

00:01:59,853 --> 00:02:01,455

Steve Spangler: That's even...

Kim: Eventually.

71

00:02:01,522 --> 00:02:02,689

Steve Spangler: You did it.

Kim: Okay.

72

00:02:02,756 --> 00:02:04,024

Steve Spangler: Okay.

But that was 10.

73

00:02:04,091 --> 00:02:06,260

So the lesson here

is we distributed the weight.

74

00:02:06,360 --> 00:02:08,896

So at the circus, when you see the person

75

00:02:08,962 --> 00:02:10,063

with their bare back,

76

00:02:10,130 --> 00:02:11,098

Steve Spangler: on the bed of nails,

Kim: back on the bed of nails,

77

00:02:11,164 --> 00:02:13,767

Steve Spangler: you have to sit there

and say, was is it dangerous?

78

00:02:13,834 --> 00:02:15,936

Sure, it's dangerous.

'cause each one of those are sharp.

79

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00:02:16,203 --> 00:02:18,005

Every single point could pop the nail.

80

00:02:18,071 --> 00:02:19,973

But now watch,

I'll turn to a clear balloon.

81

00:02:20,374 --> 00:02:21,408

[blows balloon]

82

00:02:21,508 --> 00:02:24,478

And Eileen on camera

is gonna look at this.

83

00:02:24,545 --> 00:02:26,780

You're actually gonna

see the nails push up

84

00:02:26,847 --> 00:02:28,615

and almost into the balloon.

85

00:02:28,682 --> 00:02:31,618

So watch this. This fits here.

Like this. Lemme put it here.

86

00:02:31,785 --> 00:02:34,054

And now this is on top like we did before.

87

00:02:34,221 --> 00:02:36,890

And now it's a distribution of weight.

So look at this.

88

00:02:36,957 --> 00:02:38,692

Steve Spangler: So as you push,

Kim: Oh look, they're going through.

89

00:02:38,759 --> 00:02:39,860

Steve Spangler:

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Look at this, look at that.

90

00:02:39,927 --> 00:02:44,164

It's not piercing it, but look

at how much we can push down.

91

00:02:44,231 --> 00:02:46,567

So no wonder the guy

doesn't leak when he stands up

92

00:02:46,667 --> 00:02:49,803

and drinks the water and the water

doesn't pour out of his back.

93

00:02:50,037 --> 00:02:51,805

You're distributing the pressure.

94

00:02:51,872 --> 00:02:53,607

There's a nice life lesson in there too.

95

00:02:53,674 --> 00:02:54,975

Just leave it to kids to come up.

96

00:02:55,042 --> 00:02:56,476

These are student council kids.

97

00:02:56,710 --> 00:03:01,415

They distribute the stress over,

the task over a lot of, look at that.

98

00:03:01,481 --> 00:03:03,450

Steve Spangler: That's crazy!

Kim: That's crazy!

99

00:03:03,517 --> 00:03:04,852

Steve Spangler: And we're fine.

100

00:03:04,918 --> 00:03:08,655

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Isn't that amazing?

Tada! So what a nice life lesson.

101

00:03:08,789 --> 00:03:10,824

And you and I are both

going to back to school nights right now.

102

00:03:10,891 --> 00:03:11,992

Kim: Mm-hmm.

Steve Spangler: We're seeing

103

00:03:12,059 --> 00:03:13,393

amazing teachers doing demonstrations.

Kim: Love it.

104

00:03:13,460 --> 00:03:14,962

Steve Spangler: You haven't had your back

to school night yet.

105

00:03:15,028 --> 00:03:16,930

Do a demonstration

if you're a science teacher,

106

00:03:17,097 --> 00:03:18,699

because parents love this.

107

00:03:19,066 --> 00:03:20,901

Talk about your philosophy

of education,

108

00:03:20,968 --> 00:03:22,936

how important

it's for collaboration,

109

00:03:23,003 --> 00:03:25,372

how important

it's for creativity and innovation.

110

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00:03:25,439 --> 00:03:28,008

How important it

is for kids to think creatively.

111

00:03:28,108 --> 00:03:30,210

Look at that.

that's the kind of thing you never forget.

112

00:03:30,277 --> 00:03:31,211

Kim: Think and apply science

113

00:03:31,278 --> 00:03:32,346

Kim: to their life.

Steve Spangler: Yes.

114

00:03:32,412 --> 00:03:34,014

Steve Spangler: I can't even pop

this stupid.

115

00:03:34,081 --> 00:03:35,015

Kim: I love it!

Steve Spangler: All right,

116

00:03:35,082 --> 00:03:36,016

I'm putting this on your desk.

117

00:03:36,083 --> 00:03:37,551

This is your keepsake for today.

Got it.

118

00:03:37,618 --> 00:03:38,485

Kim: I love it!

119

00:03:38,552 --> 00:03:39,386

Kim: My mini bed of nails.

120

00:03:39,453 --> 00:03:41,255

Steve Spangler: Hey, we post a lot

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of things either @9news.com

121

00:03:41,321 --> 00:03:43,690

or if you visit my Facebook

page slash Steves Spangler.

122

00:03:43,824 --> 00:03:45,859

We're posting a ton

of stuff in both places.

123

00:03:45,993 --> 00:03:47,227

Kim: It's looking good. Okay!

124

00:03:47,294 --> 00:03:48,161

Steve Spangler: There you go.

Kim: Thank you.

125

00:03:48,228 --> 00:03:49,830

Kim: We'll be right back.

Steve Spangler: Why it wouldn't even pop.

126

00:03:49,963 --> 00:03:51,098

I mean, I cried so hard.

127

00:03:51,398 --> 00:03:52,699

[soft music plays]

128

00:03:53,467 --> 00:03:54,801

[music fades out]

Practical skills

Inquiry 1: Exploring and designing — Controlling variables

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While carrying out the demonstration, Steve Spangler controlled a number of variables to ensure that the experiment was **valid**. Watch **Video 1** again and identify these control variables. Describe how they improved the validity of the experiment. Can you suggest any other variables that should have been controlled in order to improve the validity of the experiment?

The reason that the balloon bursts when there is only one nail is that all the applied force is spread over an area the size of the point of the nail. When the balloon is placed on top of a large number of nails, and the same force is applied, the force is spread over an area many times as big, so the balloon does not burst.

This leads us to the concept of pressure, which is the force applied per unit area in a direction perpendicular to the surface over which it is applied. It can be calculated using the equation shown in **Table 1**.

Table 1. Equation for pressure.

Equation	Symbols	Units
$P = \frac{F}{A}$	P = pressure	newton per metre squared (N m^{-2}) or pascals (Pa)
	F = force exerted perpendicular to the surface	newtons (N)
	A = area over which the force is distributed	metres squared (m^2)

Study skills

The standard unit for pressure is the pascal, Pa, which is equivalent to 1 newton per metre squared. In order to calculate the pressure in pascals, it is important to ensure that the area is in metres squared.

$$1 \text{ Pa} = 1 \text{ N m}^{-2}$$

but

$$1 \text{ Pa} \neq 1 \text{ N cm}^{-2}$$

To convert a length from centimetres to metres, it must be divided by 100.

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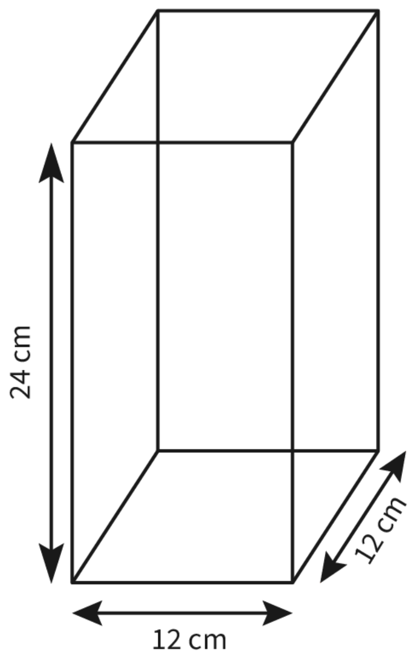
To convert an area from square centimetres to square metres, it must be divided by 100^2.

This means that an area of $1\ \text{cm}^2$ is equivalent to $\frac{1}{100^2}\ \text{m}^2$.

In order to calculate the dimensions of a shape in centimetres, convert each length to metres before calculating the area.

Worked example 1

Calculate the pressure, in pascals, exerted on the floor by a box of weight 250 N with the dimensions shown in the diagram.



More information

The image depicts a diagram of a rectangular box. The box is shown in a 3D perspective with dimensions labeled on its edges. The height of the box is marked as 24 cm, while the width and depth are both marked as 12 cm. Arrows on the edges indicate the direction of these measurements. The diagram is meant to provide information for calculating pressure exerted on a surface by the box, with a given weight of 250 N as stated in accompanying text.

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Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$F = 250 \text{ N}$ $l = 12 \text{ cm}$ $= 0.12 \text{ m}$ $w = 12 \text{ cm}$ $= 0.12 \text{ m}$ $h = 24 \text{ cm}$ $= 0.24 \text{ m}$
Step 2: Calculate the area of the face of the box in contact with the floor.	$A = l \times w$ $= 0.12 \times 0.12$ $= 0.0144 \text{ m}^2$ The height of the box is not relevant to the question.
Step 3: Write out the equation.	$P = \frac{F}{A}$
Step 4: Substitute the values given.	$= \frac{250}{0.0144}$
Step 5: State the answer with appropriate units and the number of significant figures used in rounding.	$= 17\ 361 \text{ Pa} = 17 \times 10^3 \text{ Pa} = 17\,\text{kPa}$ (2

You can see that an object exerting a force acting over an area causes pressure. There are forces, and therefore pressure, acting on your skin as you read this paragraph. What pressure can you feel? Perhaps the pressure of the solid seat you are sitting on, or of the solid floor beneath your feet.

What about the pressure of the air on your skin? This pressure is caused by collisions between air particles and your skin. Every second, billions of particles collide with your skin.

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Ideal gases

Air is a gas. In this section, you are going to learn about gas behaviour and how gases exert pressure.

Section B.1.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/molecular-theory-in-solids-liquids-and-gases-id-44049/) covers the behaviour of the particles of a substance in its gaseous phase. Over more than a century, scientists from multiple countries investigated particles and came up with the kinetic model of an ideal gas.

An ideal gas is a gas in which:

- there is a very large number of particles, which allows statistical averages to be taken
- the volume of each particle is negligible (small enough to be ignored) compared to the volume of the container
- there are no intermolecular forces between the particles
- the particles move randomly in all directions at high speeds
- collisions between particles and between particles and the walls of the container are perfectly elastic – kinetic energy is conserved
- the duration of a collision is negligible compared to the time between collisions
- the potential energy between particles is zero.

An ideal gas is a model designed to approximate a real gas. We use the ideal gas model to make predictions about the behaviour of the molecules of a real gas. Ideal gases do not exist but are good approximations of real gases when the real gas:

- is at a high temperature (so the speed of the particles is high and the duration of collisions is short)
- is at a low pressure
- is at a low density (so that the volume of the particles is negligible compared to that of the whole gas).

Theory of Knowledge

When does modelling of 'ideal' situations become 'good enough' to count as knowledge?

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Drag and drop the words into the correct spaces in **Interactive 1** to describe the properties of an ideal gas.

The particles in an ideal gas move at very ______ speeds.

The internal energy of the gas is due to the ______ of the particles.

Compared to the volume of the gas, the volume of the ______ is very small.

Compared to the time between collisions, the duration of collisions between particles or between particles and the walls of their container is very ______.

Collisions between particles or between particles and the walls of their container are ______.

potential energy	short	particles	elastic
kinetic energy	high	low	inelastic
	empty space	long	

Check

Interactive 1. Properties of Ideal Gas.

Making connections

The ideal gas model is a simplification that allows us to make predictions about real gases. What other simplified models are relied upon to communicate the understanding of complex phenomena?

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Gas pressure is caused by the particles colliding with the walls of the container, each individual collision results in a particle experiencing a change of momentum. If a gas is in a sealed container and its temperature is constant, how do you think increasing the number of particles in the container will affect its pressure? Drag the correct word to complete the sentence in **Interactive 2** then click on 'Show solution' to see an explanation.

For a fixed volume of gas at constant temperature, increasing the number of gas particles will cause the gas pressure to ________ .

decrease | increase | stay the same

Check

Interactive 2. Effect of Increasing Number of Particles on Pressure.

As gas pressure is caused by collisions between gas particles and the walls of the container, increasing the number of particles will increase the number of collisions between particles and the container walls in a given amount of time, thus increasing the gas pressure.

Moles and the Avogadro constant

In order to quantify the amount of gas particles in a given situation, we need to understand the unit of measurement of 'amount of substance' – the mole.

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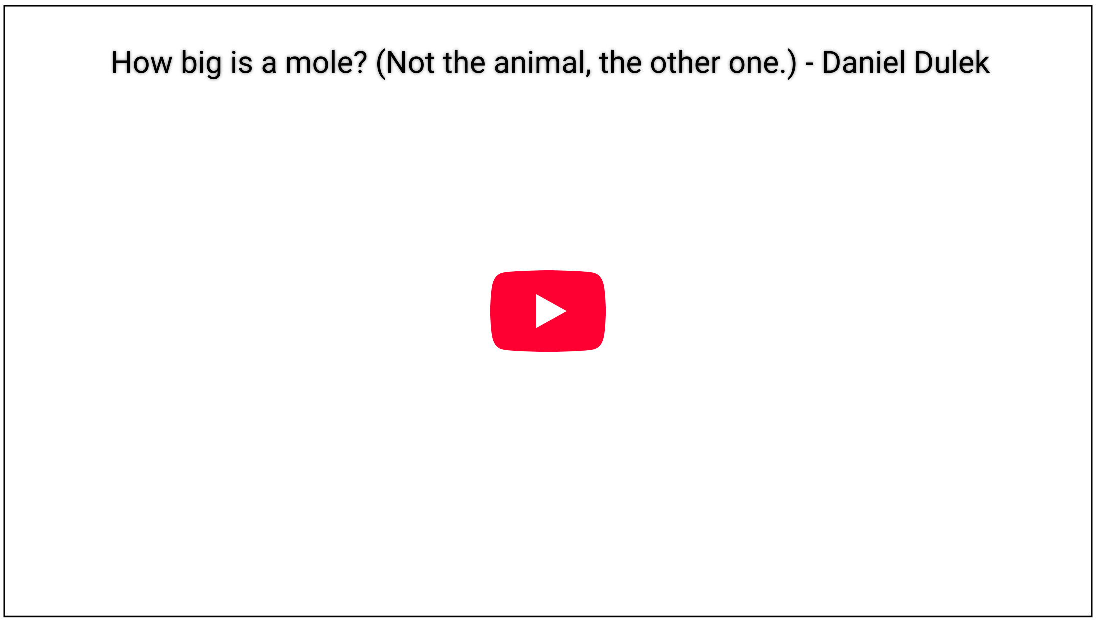
As particles are so tiny, and there are so many of them, even inside a small volume, scientists often deal with the number of moles of particles. Watch **Video 2** about moles and the Avogadro constant and make notes on the following:

- Three facts shared in the video.
- Two ways that Avogadro’s discovery is useful to the scientific community.
- One question you have after watching the video.



Video 2. Moles and the Avogadro constant.

Theory of Knowledge

When Avogadro came up with the theory that two different gases with the same volume, temperature and pressure contain the same number of particles, the theory that matter was made up of atoms was not widely accepted. What role did reason and intuition play in Avogadro’s discovery? How did these same factors prevent others from accepting it?

The mole is the SI unit for amount of substance and it has the symbol n.

One mole is the amount of substance that contains N_A particles, where N_A is the Avogadro constant 6.02×10^{23} mole^{-1}.

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Study skills

The Avogadro constant, N_A, is given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet.

It is the number of particles in one mole of a substance, and it has the unit mol^{-1}.

Some sources may make reference to Avogadro's number, which is simply the number 6.02×10^{23} without any unit.

Study skills

The word **particles** can refer to single atoms, such as helium, He. Or it can refer to molecules, such as oxygen, O_2, or carbon dioxide, CO_2.

For example, one mole of carbon (C) contains 6.02×10^{23} particles, and one mole of helium (He) contains 6.02×10^{23} particles. In this case, the particles are atoms.

One mole of oxygen (O_2) also contains 6.02×10^{23} particles, but in this case, the particles are molecules.

Nature of Science

Aspect: Science as a shared endeavour

From 1971 to 2018, the definition of the mole was 'the amount of substance that contains the same number of particles as there are atoms in 12.0 g of carbon-12'. (You do not need to know this definition.)

As this definition involved grams, it relied on the definition of the fundamental unit of mass - the kilogram. In 2018, the definition of the mole was updated to the one given above, which makes it clear that the mole depends on counting a quantity, instead of measuring a mass.

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This is a decision that was made by scientists in the fields of biology, chemistry and physics, and it has an impact on their work. What do you think are some advantages and disadvantages of collaboration between scientists across different fields?

Drag and drop the numbers into the correct places in **Interactive 3** to show the number of moles of each substance.

Drag the values into the correct boxes

6.02×10^{23} atoms of helium is moles.

There are 4.82×10^{24} molecules in moles of hydrogen.

3.01×10^{23} molecules of oxygen is moles.

There are 1.81×10^{24} molecules in moles of nitrogen.

3 0.5 1 8

Check

Interactive 3. How Many Moles of Each Substance?

More information for interactive 3

A drag and drop interactive to calculate the number of moles of each substance using Avagadro's constant.

There is a statement at the top of the interactive that states: "Drag the values into correct boxes".

Below the statement, there are four fill-in-the-blank type of questions. Each question has the number of atoms or molecules and a blank is provided for the number of moles of a substance. The user must determine the number of moles of the given substance using Avagadro's constant (6.02×10^{23} mole^{-1}).

The four statements are as follows:

6.02×10^{23} atoms of helium is ________ moles.

There are 4.82×10^{24} molecules in ________ moles of hydrogen.

3.01×10^{23} molecules of oxygen is ________ moles.

There are 1.81×10^{24} molecules in ________ moles of nitrogen.

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There are four possible answers on the right-hand side of the interactive, which can be dragged and dropped in the blank spaces of the four statements.

The four options are as follows: 8, 3, 0.5 and 1.

The user must drag and drop the options into the corresponding blanks on the statements. The users can check the correct answers by clicking on the “Check” option located at the bottom left corner.

The interactive helps users learn how to calculate the number of moles of different substances using Avagadro’s constant.

Read below for the solution:

6.02×10^{23} atoms of helium is **1** moles.

There are 4.82×10^{24} molecules in **8** moles of hydrogen.

3.01×10^{23} molecules of oxygen is **0.5** moles.

There are 1.81×10^{24} molecules in **3** moles of nitrogen.

You completed **Interactive 3** using logic and your understanding of what a mole is. However, sometimes the large numbers involved mean that it is more appropriate to organise the calculation as an equation. In this case, the amount of a substance can be calculated using the equation shown in **Table 2**.

Table 2. Equation for amount of substance.

Equation	Symbols	Units
$n = \frac{N}{N_A}$	n = amount of substance	moles (mol)
	N = number of molecules	unitless
	N_A = Avogadro constant, $6.02 \times 10^{23}\ \text{mol}^{-1}$	Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet

Worked example 2

A glass contains 11 moles of water.

Calculate the number of water molecules in the glass.

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Solution steps	Calculations
Step 1: Write out the values given in the question.	$n = 11$
Step 2: Write out the equation.	$n = \frac{N}{N_\mathrm{A}}$
Step 3: Rearrange the equation to make N the subject.	$N = nN_\mathrm{A}$
Step 4: Substitute the values given.	$= 11 \times 6.02 \times 10^{23}$
Step 5: State the answer with appropriate units and the number of significant figures used in rounding.	$N = 6.62\times10^{24}$ $= 6.6\times10^{24}$ molecules of water (2

Try the following activity to check your understanding of ideal gases.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Reflecting at all stages of the assessment and learning cycle
- **Time required to complete activity:** 30 minutes
- **Activity type:** Individual activity

Download the worksheet and complete the practice questions.

Worksheet (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_upload B.3.1 ACTIVITY What are ideal gases.fda1c2983cdee6dcb6f3.pdf)

Remember to show all your working. You can check your answers on the last page.

5 section questions

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Question 1

SL HL Difficulty:

Which of the following is **not** an assumption of an ideal gas?

1. The internal energy of the ideal gas is due to the potential energy and the kinetic energy of the gas particles. ✓
2. The volume of the individual particles is negligible compared to the volume of the gas as a whole.
3. The duration of collisions between particles or between particles and their container is negligible compared to the time between collisions.
4. Collisions between particles and between particles and their container are elastic.

Explanation

The internal energy of the ideal gas is only due to the kinetic energy of the gas particles because there are no intermolecular forces between the particles.

Question 2

SL HL Difficulty:

An ideal gas is a good approximation of a real gas when it is at 1 low ✓ pressure, 2 low ✓ density and 3 high ✓ temperature.

Accepted answers and explanation

#1 low
lower
reduced

#2 low
lower
reduced

#3 high
higher
increased

General explanation

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The pressure and density of the real gas must be low so the volume of the particles is negligible compared to that of the whole gas. The temperature must be high so the particles have high amounts of kinetic energy.

Question 3

SL HL Difficulty:

Calculate the pressure exerted on a table by a rectangular box of weight 72 N and the area of its base is 1200 cm^2.

1 600 Pa ✓

2 0.002 Pa

3 0.06 Pa

4 17 Pa

Explanation

$F = 72 \text{ N}$

$$A = 1200 \text{ cm}^2 \\ = \frac{1200}{100^2} \\ = 0.12 \text{ m}^2$$

$$P = \frac{F}{A} \\ = \frac{72}{0.12} \\ = 600 \text{ Pa (2 s.f.)}$$

Question 4

SL HL Difficulty:

5.2 × 10^{25} molecules of oxygen are sealed in a container.

Calculate the number of moles of oxygen in the container.

Give your answer to an appropriate number of significant figures.

The number of moles of oxygen is 1 86 ✓ moles.

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Accepted answers and explanation

#1 86

86.4

86,4

General explanation

$$N = 5.2 \times 10^{25}$$

$$\begin{aligned} n &= \frac{N}{N_\text{A}} \\ &= \frac{5.2 \times 10^{25}}{6.02 \times 10^{23}} \\ &= 86.38 \text{ moles} \\ &= 86 \text{ moles (2 s.f.)} \end{aligned}$$

Question 5

SL HL Difficulty:

Two sealed bottles, X and Y, contain 7.23×10^{24} and 3.61×10^{24} molecules of helium gas, respectively.

What is the ratio $\frac{n_\text{Y}}{n_\text{X}}$?

1 $\frac{1}{2}$ ✓

2 2

3 $\frac{1}{4}$

4 4

Explanation

$$N_\text{X} = 7.23 \times 10^{24}$$

$$N_\text{Y} = 3.61 \times 10^{24}$$

$$\begin{aligned} n_\text{X} &= \frac{N}{N_A} \\ &= \frac{7.23 \times 10^{24}}{6.02 \times 10^{23}} \\ &= 12 \text{ moles (2 s.f.)} \end{aligned}$$

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$$\begin{aligned} n_{\mathrm{Y}} &= \frac{N}{N_A} \\ &= \frac{3.61\times 10^{24}}{6.02\times 10^{23}} \\ &= 6.0 \text{ moles (2 s.f.)} \end{aligned}$$

$$\begin{aligned} \frac{n_{\mathrm{Y}}}{n_{\mathrm{X}}} &= \frac{6.0}{12} \\ &= \frac{1}{2} \end{aligned}$$

B. The particulate nature of matter / B.3 Gas laws

How do ideal gases behave?

B.3.4: Ideal gas law and empirical gas laws B.3.5: Equations for the behaviour of ideal gases

B.3.6: Gas pressure and particle collisions with surfaces B.3.7: Internal energy of an ideal monatomic gas

Learning outcomes

By the end of this section you should be able to:

- Relate simulated experimental data to the empirical gas laws and thereby deduce the ideal gas law equation.
- Apply the first, second and third gas laws.
- Calculate the properties of a gas using the equations:

$$\frac{PV}{T} = \text{constant},$$

$$PV = nRT$$

and

$$PV = Nk_{\mathrm{B}}T$$

- Calculate the internal energy of an ideal gas using the equations:

$$U = \frac{3}{2}Nk_{\mathrm{B}}T$$

and

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$$U = \frac{3}{2} nRT$$

- Apply the concepts of force and momentum to explain how gas pressure arises.
- Calculate the pressure of an ideal gas using the equation:

$$P = \frac{1}{3} \rho v^2$$

Imagine that you are sitting in your wetsuit, preparing to dive into the ocean. You have a guide rope, a pair of diving fins and your lungs. You take a deep breath and plunge into the water. This kind of diving, without a scuba tank, is known as free diving (**Figure 1**).

Figure 1. Free diving.

Credit: Tamer Gunal, Getty Images

For every ten metres you descend, the pressure on your body increases by 101 kPa and the pressure in your lungs adjusts to match. You reach the ocean floor. After a few seconds, you slowly begin your ascent and, as you ascend, the air pressure in your lungs decreases again. You reach the water's surface, your head comes out of the water and you slowly exhale the air from your lungs.

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Free divers can hold their breath for as long as nine minutes, during which time the pressure in their lungs changes significantly. How is it possible that the pressure in their lungs changes when the number of particles of air in their lungs does not change?

The ideal gas laws

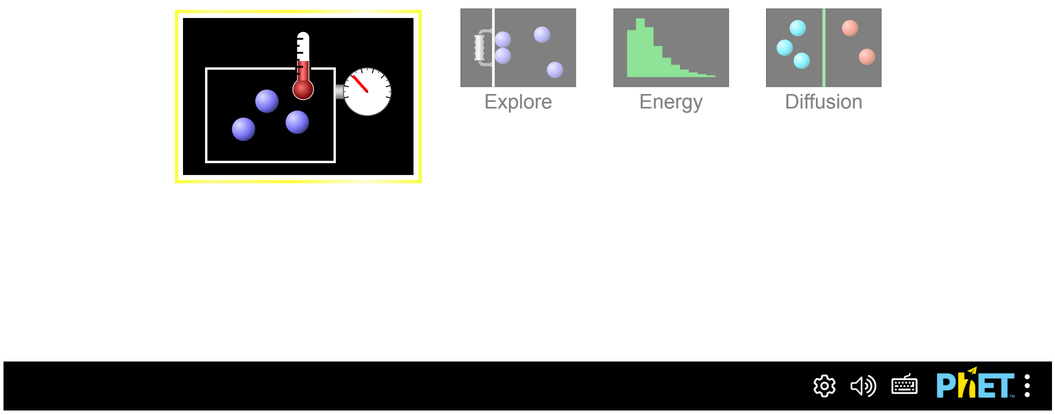
Between 1662 and 1802, scientists carried out experiments to find out how gases behave under certain conditions. The discoveries made as a result of these experiments are known as the empirical gas laws.

An ideal gas is one that obeys these gas laws at all temperatures, pressures and volumes. Work through the activity below to discover the three gas laws for yourself.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Being curious about the natural world
- **Time required to complete activity:** 1 hour
- **Activity type:** Group activity

Use the PhET Colorado Gas Properties simulation to investigate the three gas laws. Work in groups of three, with each person investigating one of the laws, then share your findings.



Interactive 1. Properties of an ideal gas.

Student view

More information for interactive 1

The Gas Properties interactive simulation explores the behavior of an ideal gas through four modules: Ideal, Explore, Energy, and Diffusion. The Ideal module focuses on investigating temperature, pressure, volume, and particle interactions in a gas system, helping users understand fundamental gas laws and kinetic molecular theory.

Users can manipulate variables such as temperature, pressure, volume, and particle number to observe real-time changes in gas behavior. The simulation features a gas container where particles move randomly after being introduced via a hand pump, along with a thermometer, pressure gauge, and heating/cooling unit for modifying thermal energy. By introducing light or heavy gas particles, users can explore how different conditions affect gas properties. The control panel allows users to hold certain variables constant, such as volume or pressure, enabling targeted investigations into gas laws like Boyle's and Charles' laws. Additional tools, including a stopwatch, collision counter, and width adjustment, enhance data collection and analysis.

Through this interactive simulation, users gain a deeper understanding of the statistical nature of gas behavior. They can observe how pressure fluctuates due to particle collisions with the container walls and how temperature changes influence particle motion and pressure. By conducting experiments, recording multiple temperature and pressure values, and calculating uncertainties, users develop experimental and data analysis skills. The simulation reinforces the direct relationship between temperature and pressure at constant volume, demonstrating the kinetic molecular theory in action and emphasizing the impact of temperature on molecular motion.

The first gas law

1. Select 'Ideal'. Use the 'Particles' box to add molecules to the container. Once you have decided how many molecules to add, do not add any more, to keep the mass of gas constant.
2. Select kPa from the dropdown box under 'Pressure'.
3. Click the 'Temperature' button in the 'Hold Constant' box to keep the temperature constant.
4. Click the 'Width' checkbox in the 'Hold Constant' box to turn on the measurements of the width of the container.
5. Click and hold the handle of the container and move it to the left, to make the volume as large as possible.
6. Record the volume (m^3) and pressure ($\times 10^3$ Pa) in a suitable table. (Note: the width of the container is shown in nm. Assume that doubling the width doubles the volume and record the width as a volume.)
7. Use the handle to decrease the width of the container by 1 nm. Record the new volume and pressure.
8. Repeat step 7 seven times.

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9. Plot a graph of pressure in Pascals on the *y*-axis against volume in m^3 on the *x*-axis.
10. Draw an appropriate line of best fit.
11. Write a sentence to describe the relationship between pressure and volume, then click the button to reveal the answer.

The first gas law, also known as Boyle's law states that for a constant mass of gas at constant temperature, the pressure of the gas is inversely proportional to its volume.

The second gas law

1. Select 'Ideal'. Use the 'Particles' box to add molecules to the container. Once you have decided how many molecules to add, do not add any more, to keep the mass of gas constant.
2. Select kPa from the dropdown box under 'Pressure'.
3. Click the 'Pressure' button in the 'Hold Constant' box to keep the pressure constant.
4. Click the 'Width' checkbox in the 'Hold Constant' box to turn on the measurements of the width of the container.
5. Record the temperature (K) and volume (m^3) of the gas in a suitable table. (Note: the width of the container is shown in nm. Assume that doubling the width doubles the volume and record the width as a volume.)
6. Use the slider on the 'Heat' and 'Cool' bucket to increase the temperature of the gas. Record the new volume.
7. Repeat for seven different values of temperature.
8. Plot a graph of volume in m^3 on the y-axis against temperature in kelvin on the *x*-axis.
9. Draw an appropriate line of best fit.
10. Write a sentence to describe the relationship between volume and temperature, then click the button to reveal the answer.

The second law, often known as Charles' law, states that, for a constant mass of gas at constant pressure, the volume of the gas is directly proportional to its temperature in kelvin.

The third gas law

1. Select 'Ideal'. Use the 'Particles' box to add molecules to the container. Once you have decided how many molecules to add, do not add any more, to keep the mass of gas constant.
2. Select kPa from the dropdown box under 'Pressure'.

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3. Click the ‘Volume’ button in the ‘Hold Constant’ box to keep the volume constant.
4. Click the ‘Width’ checkbox in the ‘Hold Constant’ box to turn on the measurements of the width of the container.
5. Record the temperature (K) and pressure (kPa) in a suitable table.
6. Use the slider on the ‘Heat’ and ‘Cool’ bucket to increase the temperature of the gas. Record the new pressure.
7. Repeat for seven different values of temperature.
8. Plot a graph of pressure in Pascals on the y-axis against temperature in kelvin on the x-axis.
9. Draw an appropriate line of best fit.
10. Write a sentence to describe the relationship between pressure and temperature in kelvin, then click the button to reveal the answer.

The third law, which is also called the pressure law, states that, for a constant mass of gas at constant volume, the pressure of the gas is directly proportional to its temperature in kelvin.

Theory of Knowledge

While the first, second and third gas laws are attributed to the Irish physicist Robert Boyle, French physicist Jacques Charles and French physicist and inventor Guillaume Amontons respectively, the gas laws were the product of over a hundred years of work by various scientists who are now not so well remembered. When a scientific discovery is made, who should ‘own’ that scientific knowledge?

The ideal gas law equation

These gas law relationships can be written as equations and represented as graphs as shown in **Table 1**.

Table 1. The gas law relationships.

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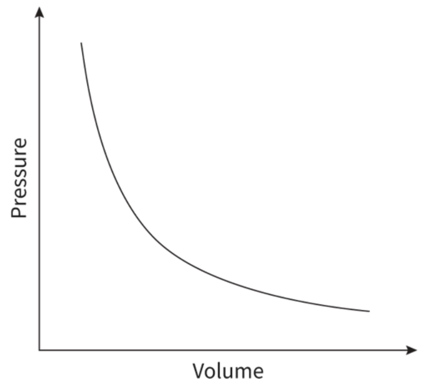
<table>
<tr><th>Gas law</th><th>Equation</th><th>Graph</th></tr>
<tr><td>First gas law
or Boyle's law
For a fixed number of moles of gas at constant temperature, the pressure of the gas is inversely proportional to its volume.</td><td>$P \, \alpha \, \frac{1}{V}$
or
$PV = \text{constant}$</td><td>
More information
The graph illustrates an inverse relationship between pressure and volume. The X-axis represents volume, increasing from left to right. The Y-axis represents pressure, increasing from bottom to top. The plotted curve starts high on the Y-axis and slopes downward as it moves right, indicating that as volume increases, pressure decreases. This is a typical representation of Boyle's Law, where the product of pressure and volume is constant for a given amount of gas at constant temperature.
[Generated by AI]</td></tr>
</table>

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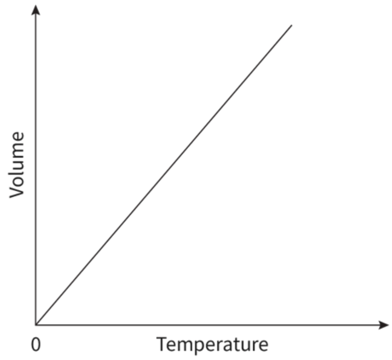
Gas law	Equation	Graph
Second gas law or Charles' law For a fixed number of moles of gas at constant pressure, the volume of the gas is directly proportional to its temperature in kelvin.	$V \, \alpha \, T$ or $\frac{V}{T} = \text{constant}$	 More information The image is a line graph illustrating the relationship between temperature and volume. The X-axis represents Temperature, marked with increasing values from left to right, while the Y-axis represents Volume, marked with increasing values from bottom to top. The graph begins at the origin point where both Temperature and Volume are zero and features a straight line ascending diagonally, indicating a direct proportional relationship between temperature and volume. [Generated by AI]

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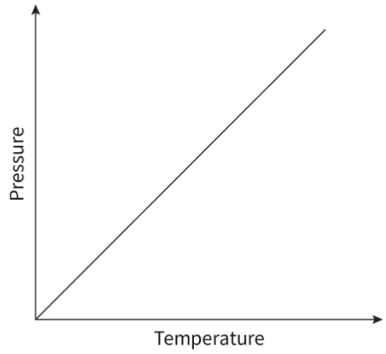
Gas law	Equation	Graph
Third gas law or Gay-Lussac's law For a fixed number of moles of gas at constant volume, the pressure of the gas is directly proportional to its temperature in kelvin.	$P \alpha T$ or $\frac{P}{T} = \text{constant}$	 More information The graph illustrates a linear relationship between pressure and temperature. The X-axis represents temperature, starting from the origin and increasing to the right with no specific labels or units shown. The Y-axis represents pressure, increasing upward from the origin with no specific labels or units indicated. A single line starts from the origin (0,0) and extends diagonally to the top right, suggesting that as temperature increases, pressure also increases proportionally. [Generated by AI]

International Mindedness

In the 21st century, there are a wealth of resources that make international collaboration between scientists easier than ever. How do you think international collaboration has changed since the 1600s, when Robert Boyle recorded his observations of the relationship between the pressure and volume of a gas?

These three laws governing the behaviour of an ideal gas can be used to derive a single equation, known as the combined gas law equation, shown in **Table 2**.

Table 2. Combined gas law equation.

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Equation	Symbols	Units
$\frac{PV}{T} = \text{constant}$	P = pressure	pascals (Pa)
	V = volume	cubic metres (m^3)
	T = absolute temperature	kelvin, K

This can also be written as:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Worked example 1

A gas is contained in a sealed cylinder of 0.8 m^3 at a temperature of 20 °C and a pressure of 7.2 kPa.

The gas is heated inside the container to a temperature of 40 °C.

Calculate the new pressure of the gas.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$V_1 = 0.8\ \text{m}^3$ $T_1 = 20\ ^\circ\text{C}$ $P_1 = 7.2\ \text{kPa} = 7.2 \times 10^3\ \text{Pa}$ $V_2 = 0.8\ \text{m}^3$ $T_2 = 40\ ^\circ\text{C}$ $T_1 = 20 + 273 = 293\ \text{K}$ $T_2 = 40 + 273 = 313\ \text{K}$
Step 2: Write out the equation.	$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$

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Solution steps	Calculations
Step 3: Rearrange the equation to make P_2 the subject.	$P_2 = \frac{P_1 V_1 T_2}{T_1 V_2}$
Step 4: Substitute the values given.	$P_2 = \frac{7.2 \times 10^3 \times 0.8 \times 313}{293 \times 0.8}$
Step 5: State the answer with appropriate units and the number of significant figures used in rounding.	$= 7691 \text{ Pa} = 7.7{\times}10^3 \text{ Pa or } 7.7 \text{ kPa (2}$

Creativity, activity, service

Strand: Creativity
Learning outcome: Demonstrate that challenges have been undertaken, developing new skills in the process

A cartesian diver is used to illustrate the effect of pressure on the volume of a gas. A small piece of tubing containing a little air is placed into a sealed bottle full of water. By applying pressure from the outside, you can make the tubing inside sink or float.

Try making a cartesian diver. If you squeeze the bottle subtly, it can look like magic.

See some instructions on how to make a cartesian diver here (https://sciencetoymaker.org/the-cartesian-diver/cartesian-diver-instructions/).

So far, we have only considered a fixed amount of gas. But what will happen to the pressure if you double the number of particles in a fixed volume at a fixed temperature?

Amedeo Avogadro, who came up with the Avogadro constant, also discovered by experiment that, for a gas at constant temperature and pressure, the number of gas particles, *N*, is directly proportional to the volume of the gas, $N \ \alpha \ V$.

As the number of particles is proportional to the number of moles of substance, n, this can be written as $n \ \alpha \ V$ or $\frac{n}{V} = \text{constant}$ for a gas at constant temperature and pressure, i.e. $\frac{P}{T} = \text{constant}$.

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This can be combined with the empirical gas law equation to give the equation shown in **Table 3**. R is the molar gas constant, a universal constant that represents the proportionality between the quantities in the empirical gas laws.

Table 3. Ideal gas law equation.

Equation	Symbols	Units
$PV = nRT$	P = pressure	pascals (Pa)
	V = volume	cubic metres (m^3)
	n = amount of substance	moles (mol)
	R = gas constant	8.31 J K^{-1} mol^{-1} Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet
	T = absolute temperature	kelvin (K)

Worked example 2

12 moles of an ideal gas are in a container with a volume of 2.3 m^3 at a temperature of 18 °C.

Calculate the pressure of the gas.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$n = 12$ moles $V = 2.3\ \mathrm{m}^3$ $T = 18\ ^\circ\mathrm{C}$ $T = 18 + 273$ $= 291\ \mathrm{K}$

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Solution steps	Calculations
Step 2: Write out the equation.	$PV = nRT$
Step 3: Rearrange the equation to make P the subject.	$P = \dfrac{nRT}{V}$
Step 4: Substitute the values given.	$= \dfrac{12 \times 8.31 \times 291}{2.3}$
Step 5: State the answer with appropriate units and the number of significant figures used in rounding.	$= 12\,617\ \text{Pa} = 1.3{\times}10^4\ \text{Pa or } 13\ \text{kPa (}$

Worked example 3

A sealed syringe of volume 10 cm^3 contains 0.8 moles of air at a temperature of 280 K.

The plunger of the syringe is pushed in so that the volume of the gas is reduced to 2.5 cm^3, and the gas is heated to a temperature of 560 K.

Deduce the ratio $\dfrac{P_{\text{initial}}}{P_{\text{final}}}$.

Solution steps	Calculations		
Step 1: Write out the values given in the question.	Initial	Initial	
	P	?	
	V	$10\ \text{cm}^3$	2
	n	0.8	
	T	280 K	

Student
view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Solution steps	Calculations
Step 2: Write out the equation.	$PV = nRT$
Step 3: Cancel the constants.	$PV \,\alpha\, T$
Step 4: Rearrange the equation to make P the subject.	$P \,\alpha\, \frac{T}{V}$
Step 5: Analyse what this means.	P is directly proportional to T, so if T increases by a factor, P increases by the P is inversely proportional to V so if V increases by a factor, P decreases by th
Step 6: Calculate how much T and V have increased by.	The scale factor of T is found by: $\frac{T_{\text{final}}}{T_{\text{initial}}} = \frac{560}{280}$ $= 2$ So P increases by a factor of 2. The scale factor of V is found by: $\frac{V_{\text{final}}}{V_{\text{initial}}} = \frac{2.5}{10}$ $= \frac{1}{4}$ V has decreased by a factor of 4 so P increases by a factor of 4.

Student view

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Solution steps	Calculations
Step 7: Combine the two scale factors.	*P* increases by a factor of $2 \times 4 = 8$
Step 8: State the final answer	$\frac{P_{\text{initial}}}{P_{\text{final}}} = \frac{1}{8}$

Rather than working with moles of a substance, it is common to work with the number of particles of a gas, *N* (see section B.3.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/what-are-ideal-gases-id-44290/)). You can rewrite the equation $PV = nRT$ as:

$$P = \frac{nRT}{V}$$

Substitute the equation for *n*,

$$n = \frac{N}{N_{\text{A}}}$$

$$P = \frac{NRT}{N_{\text{A}}V}$$

$$\frac{R}{N_{\text{A}}} \text{ is } \frac{8.31}{6.02 \times 10^{23}}, \text{ which is } 1.38 \times 10^{-23} \text{ J K}^{-1}$$

This value is known as the Boltzman constant, k_{B} (see section B.1.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/temperature-scales-id-44050/)).

Study skills

Student view

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Note that you divided one constant by another, resulting in a new constant. Remember that these constants can be found in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet. The Boltzmann constant k_B and the molar gas contant R, represent the same proportionality relationships but are expressed with different units.

Gas pressure can also be calculated using the equation in **Table 4**.

Table 4. Equation for gas pressure.

Equation	Symbols	Units
$PV = Nk_{\text{B}}T$	P = pressure	pascals (Pa)
	V = volume	cubic metres (m^3)
	N = number of particles	unitless
	k_{B} = Boltzmann constant	1.38×10^{-23} J K^{-1} Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/)of the DP physics data booklet
	T = absolute temperature	kelvin (K)

Study skills

$PV = Nk_{\text{B}}T$ is very similar to the equation $PV = nRT$, which can make choosing the appropriate equation confusing.

When carrying out calculations, begin by writing out all the values given in the question, next to their symbols, for example, $T = 230\ \text{K}$. Look at section 1.3.B (/study/app/math-aa-hl/sid-423-cid-762593/book/the-particulate-nature-of-matter-id-45161/) of the DP physics data booklet to find the equation that has these symbols.

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Worked example 4

Calculate the number of particles of oxygen in a tank of volume 0.026 m^3 at a temperature of 32 °C and pressure of 101 kPa.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation.	$V = 0.026\ \mathrm{m}^3 T = 32\ ^\circ\mathrm{C}\ P = 101\ \mathrm{kP}$ $= 101 \times 1($ $T = 32 + 273$ $= 305\ \mathrm{K}$
Step 2: Write out the equation.	$PV = Nk_BT$
Step 3: Rearrange the equation to make N the subject.	$N = \dfrac{PV}{k_BT}$
Step 4: Substitute the values given.	$= \dfrac{101 \times 10^3 \times 0.026}{1.38 \times 10^{-23} \times 305}$
Step 5: State the answer with appropriate units and the number of significant figures used in rounding.	$N = 6.239 \times 10^{23}$ $= 6.2 \times 10^{23}\ (2\ \text{s.f.})$

Internal energy of ideal gases

Making connections

- How does a consideration of the kinetic energy of molecules relate to the development of the gas laws?
- How can gas particles of high kinetic energy be used to perform work?

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/what-are-ideal-gases-id-44290/print/) Assign

According to the ideal gas assumptions, there are no intermolecular forces between particles in an ideal gas. So all of the internal energy must be kinetic energy. But how can we measure this?

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The temperature of a substance is a measurement of the average random kinetic energy of a single particle in the substance. The faster the particles move, the higher the temperature. As energy is measured in joules and temperature in kelvin, which are not equivalent, we need to use a physical constant to convert between the two.

In this case, we use $\frac{3}{2}k_B$, where k_B is the Boltzmann constant. This conversion gives us the average kinetic energy of one particle. The total kinetic energy, and therefore the total internal energy of the gas, also depends on the number of particles, N. So the equation becomes that shown in **Table 5**.

Table 5. Equation for internal energy for an ideal monatomic gas.

Equation	Symbols	Units
$U = \frac{3}{2}Nk_BT$	U = internal energy	joules (J)
	N = number of particles	unitless
	k_B = Boltzmann constant	1.38×10^{-23} J K^{-1} Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet
	T = absolute temperature	kelvin (K)

Concept

The equations used in DP physics for calculating the internal energy of a gas are valid for ideal monatomic gases, meaning gases which behave according the principles of an ideal gas and are comprised of a single type of atom.

Calculate the internal energy of 6.2×10^{23} particles of an ideal gas at a temperature of 305 K.

Student view

$$N = 6.2 \times 10^{23}$$

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$$T = 305\ \mathrm{K}$$

$$\begin{aligned} U &= \frac{3}{2}Nk_BT \\ &= \frac{3}{2} \times 6.2 \times 10^{23} \times 1.38 \times 10^{-23} \times 305 \\ &= 3914\ \mathrm{J} \\ &= 3.9 \times 10^3\ \mathrm{J}\ \text{or}\ 3.9\ \mathrm{kJ}\ (2\ \text{s.f.}) \end{aligned}$$

Given that Nk_B is equal to nR, so the equation can also be written as shown in **Table 6.**

Table 6. Alternate equation for internal energy for an ideal monatomic gas.

Equation	Symbols	Units
$U = \frac{3}{2}nRT$	U = internal energy	joules (J)
	n = amount of substance	moles (mol)
	R = gas constant	8.31 J K^{-1} mol^{-1} Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet
	T = absolute temperature	kelvin (K)

Exercise 1

Click a question to answer

Student view

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Ideal gases and gas pressure

Making connections

How does the concept of force and momentum link mechanics and thermodynamics?

The momentum of an object is the product of its mass and its velocity, and, during a collision, the force exerted on the object is given by the rate of change of momentum (see section A.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43136/)). This concept applies to collisions between macroscopic objects, such as cars, and it also applies to collisions between microscopic objects. In this case, the collisions between gas particles and the walls of their container.

A single particle of mass m, travelling at a velocity v, collides with the wall of its container and bounces back. Because the collision is elastic, the magnitude of the particle's velocity (speed) is the same, but the direction has reversed, thus there has been a change in velocity. The collision and change in velocity is equally well described as a change in momentum.

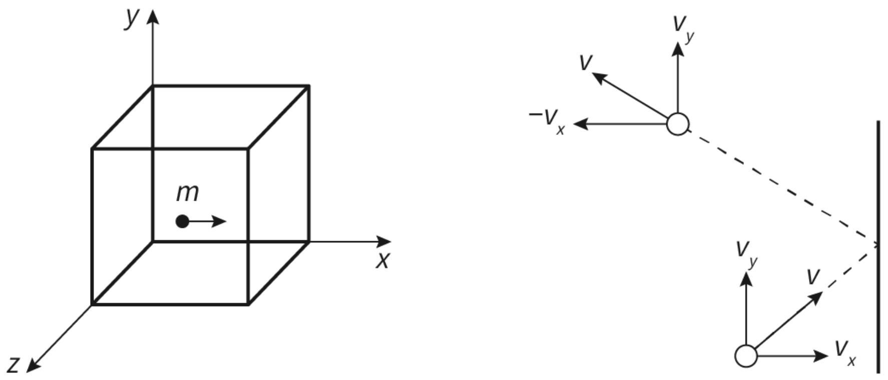
As there is a change in momentum happening in time t, there is a force exerted on the wall of the container. $\text{Pressure} = \frac{\text{force}}{\text{area}}$ (see section B.3.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/what-are-ideal-gases-id-44290/)) and therefore a pressure is exerted on the wall of the container. This pressure can be calculated using the equation shown in **Table 7**.

Table 7. Equation for pressure.

Equation	Symbols	Units
$P = \frac{1}{3}\rho v^2$	P = gas pressure	pascals (Pa)
	ρ = density	kilograms per cubic metre (kg m^{-3})
	v = average velocity of particles	metres per second (m s^{-1})

When any object, including a gas particle, moves, its velocity has components in the x, y and z planes. The $\frac{1}{3}$ in the equation represents the fact that a single gas particle has an equal probability of moving in any of these three directions with average translational speed v (**Figure 2**).

Student view



A gas confined to a cube   Collision of a gas particle with the wall

Figure 2. A gas particle moving in a box.

More information for figure 2

The image depicts two related diagrams. On the left, a cube is shown with axes labeled x, y, and z, indicating a three-dimensional space. Inside the cube, a gas particle labeled 'm' is moving along the x-axis. The right side of the image illustrates the collision of a gas particle with a wall. The particle's velocity vectors are shown with components labeled v (total velocity), vx (component on the x-axis), and vy (component on the y-axis). The particle rebounds, showing a change in direction, with vectors indicating negative and positive components post-collision. The diagrams detail the movement and interaction of gas particles in confined spaces and upon impact.

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Worked example 5

A sample of nitrogen gas is kept at room temperature and atmospheric pressure (1.01×10^5 Pa) in a sealed container. Its mean density at room temperature is 1.20 kg m^{-3}. Calculate the average velocity of the nitrogen particles.

Solution steps	Calculations
Step 1: Write down the known quantities using the appropriate symbols.	$P = 1.01 \times 10^5$ Pa → pressure $= 1.20 \text{ kg m}^{-3}$ → density

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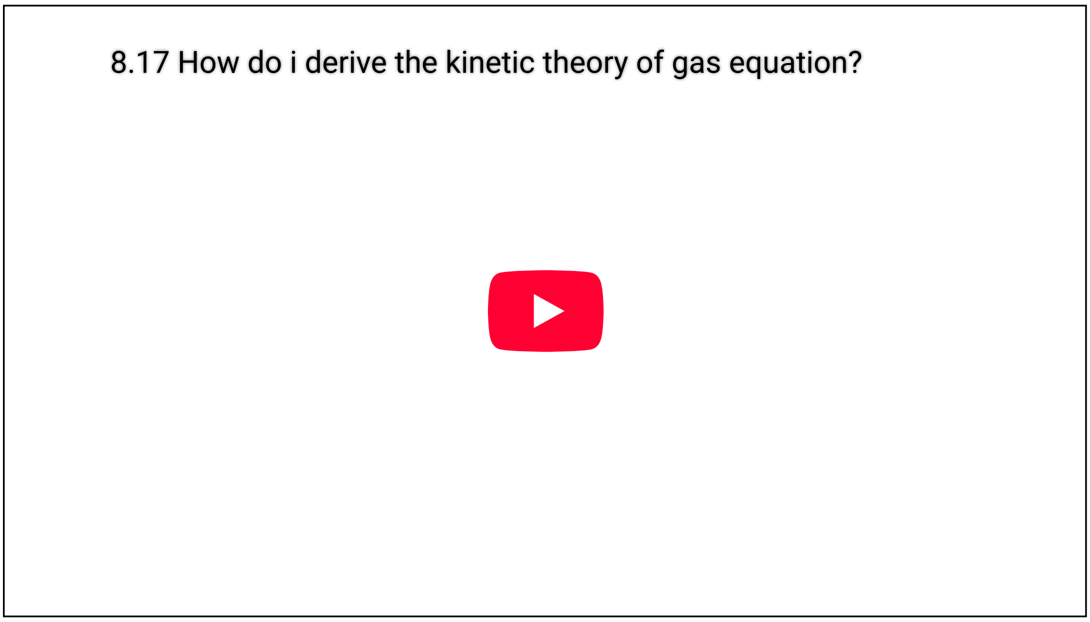
Solution steps	Calculations
Step 2: In the data booklet, find the equation relating gas pressure and density to the average velocity of the gas particles.	$P = \frac{1}{3}\rho v^2$
Step 3: Rearrange the equation for the velocity and substitute the numbers into the rearranged equation.	$v = \sqrt{\frac{3P}{\rho}}$
Step 4: Substitute the values given.	$= \sqrt{\frac{3 \times 1.01 \times 10^5}{1.20}}$
Step 5: State the answer with appropriate units and the number of significant figures used in rounding.	$v = 502\,\mathrm{m\,s^{-1}}$

Study skills

This course does not require you to derive the equation $P = \frac{1}{3}\rho v^2$, but if you want to deepen your understanding, watch the video, which shows how the equation is derived.

Note that the tutorial uses the symbol c instead of *v*.



Video 1. Kinetic theory of gas equation.

Student view

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Exercise 2

Click a question to answer

At any point in an ideal gas, pressure acts equally in all directions. Gas pressure is caused by the collisions between gas particles and the walls of their container.

Can you apply this understanding to explain what happens when:

- the temperature of a gas is increased.

When the temperature of a gas increases, the kinetic energy of the particles increases, meaning that particles collide more frequently with the walls of their container and with more force, thus increasing the gas pressure.

- the volume of a gas is decreased.

When the volume of a gas decreases, there is less space for the particles to move, meaning that they collide more frequently with the walls of their container, thus increasing the gas pressure.

Try the following activity to check your understanding of ideal gases.

Activity

- **IB learner profile:** Knowledgeable
- **Approaches to learning:** Thinking skills — Reflecting at all stages of the assessment and learning cycle
- **Time required to complete activity:** 30 minutes
- **Activity type:** Individual activity

Student view

Download the worksheet and complete the practice questions.

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Worksheet (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_upload
B.3.2 ACTIVITY The ideal gas law equation.4c7a7fb6f5f541755ff5.pdf)

Remember to show your working. You can check your answers on the last page.

5 section questions

Question 1

SL HL Difficulty:

A gas in a sealed container at 12 °C has a pressure of 100 kPa.

Calculate its pressure when the temperature increases to 40 °C.

Give your answer to an appropriate number of significant figures.

The pressure is 1 110 ✓ kPa

Accepted answers and explanation

#1 110

General explanation

$$T_1 = 12\ ^\circ\mathrm{C}$$

$$\begin{aligned} P_1 &= 100\ \mathrm{kPa} \\ &= 1.0\times10^5\ \mathrm{Pa} \end{aligned}$$

$$T_2 = 40\ ^\circ\mathrm{C}$$

$$\begin{aligned} T_1 &= 12 + 273 \\ &= 285\ \mathrm{K} \end{aligned}$$

$$\begin{aligned} T_2 &= 40 + 273 \\ &= 313\ \mathrm{K} \end{aligned}$$

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

$$\begin{aligned} P_2 &= \frac{P_1 T_2}{T_1} \\ &= \frac{1.0\times10^5\times313}{285} \\ &= 109\,825\ \mathrm{Pa} \\ &= 110\,000\ \mathrm{Pa}\ \text{or}\ 110\ \mathrm{kPa}\ (2\ \text{s.f.}) \end{aligned}$$

Student
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Question 2

SL HL Difficulty:

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The third gas law states that for a gas of constant mass and volume, the pressure is 1 directly prop... ✓ to the temperature in kelvin.

Accepted answers and explanation

#1 directly proportional
proportional
proportionate

General explanation

When the temperature of the gas increases, the kinetic energy of its particles increases, resulting in increased collisions between the particles and the walls of their container, and therefore increased pressure.

Question 3

SL HL Difficulty:

0.25 moles of nitrogen is sealed in a 250 cm^3 container at a pressure of 180 kPa.

Calculate the temperature of the gas.

Give your answer to an appropriate number of significant figures.

The temperature is 1 22 ✓ K.

Accepted answers and explanation

#1 22

General explanation

$$n = 0.25 \text{ moles}$$

$$V = 250 \text{ cm}^3$$

$$\begin{aligned} P &= 180 \text{ kPa} \\ &= 1.8\times10^5 \text{ Pa} \end{aligned}$$

$$\begin{aligned} V &= \frac{250}{100^3} \\ &= 2.5\times10^{-4} \text{ m}^3 \end{aligned}$$

$$PV = nRT$$

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$$\begin{aligned} T &= \frac{PV}{nR} \\ &= \frac{1.8 \times 10^5 \times 2.5 \times 10^{-4}}{0.25 \times 8.31} \\ &= 21.66 \text{ K} \\ &= 22 \text{ K } (2 \text{ s.f.}) \end{aligned}$$

Question 4

SL HL Difficulty:

Determine the velocity of carbon dioxide molecules at a pressure of 140 kPa and a density of 1.98 kg m^{-3}.

Give your answer to an appropriate number of significant figures.

The velocity is 1 460 ✓ m s^{-1}

Accepted answers and explanation

#1 460

General explanation

$$\rho = 1.98 \text{ kg m}^{-3}$$

$$\begin{aligned} P &= 140 \text{ kPa} \\ &= 1.4 \times 10^5 \text{ Pa} \end{aligned}$$

$$P = \frac{1}{3}\rho v^2$$

$$\begin{aligned} v &= \sqrt{\frac{3P}{\rho}} \\ &= \sqrt{\frac{3 \times 1.4 \times 10^5}{1.98}} \\ &= 460.57 \text{ m s}^{-1} \\ &= 460 \text{ m s}^{-1} \text{ } (2 \text{ s.f.}) \end{aligned}$$

Question 5

SL HL Difficulty:

Determine the temperature of 3.2 moles of an ideal gas with an internal energy of 12 kJ.

Give your answer to an appropriate number of significant figures.

The temperature is 1 300 ✓ K

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Accepted answers and explanation

#1 300

General explanation

$$n = 3.2 \text{ moles}$$

$$\begin{aligned} U &= 12 \text{ kJ} \\ &= 1.2\times10^4 \text{ J} \end{aligned}$$

$$U = \frac{3}{2}RnT$$

$$\begin{aligned} T &= \frac{2U}{3Rn} \\ &= \frac{2\times1.2\times10^4}{3\times8.31\times3.2} \\ &= 300.84 \text{ K} \\ &= 300 \text{ K (2 s.f.)} \end{aligned}$$

B. The particulate nature of matter / B.3 Gas laws

Summary and key terms

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/summary-and-key-terms-id-44293/print/) Assign

- Pressure is the force applied per unit area, measured in newtons per metre squared, or pascals.
- When we make measurements involving gas particles, there are usually such large numbers of them that we use a quantity called the mole to quantify how many particles there are. Avogadro's constant is the number of particles in one mole of a substance.
- An ideal gas is a gas that follows all of the gas laws at all temperatures, pressures and densities. It is a model that approximates a real gas when the pressure and density of the real gas are low and its temperature is high.
- The first, second and third gas laws can be used to derive the ideal gas law equation, which describes a relationship between the temperature, pressure and volume of an ideal gas.
- As there are no intermolecular forces between particles of an ideal gas, its internal energy is due only to the kinetic energy of its particles, and can be calculated from the number of moles or particles of the gas and its absolute temperature.
- In an ideal gas, pressure acts equally in all directions. Gas pressure is caused by the collisions between particles and the walls of their container due to the change in

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momentum during a collision. The pressure of a gas depends on the density of the particles and their average velocity.

Key terms

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Interactive 1. Ideal Gas Laws: Understanding Key Terms.

Figure 1 shows a concept diagram for the gas laws covered in this subtopic.

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To calculate pressure due to a force spread over an area

$P = \frac{F}{A}$

P = pressure in pascals, Pa
F = force perpendicular to surface in Newtons
A = area over which force is spread in metres squared, m²

To calculate the amount of substance in moles

$n = \frac{N}{N_A}$

n = amount of substance in moles, mol
N = number of molecules (no unit)
N_A = Avogadro constant, 6.02×10^{23} mol^{-1}

The ideal gas law tells us that

$\frac{PV}{T}$ = constant

P = pressure in pascals, Pa
V = volume in metres cubed, m^3
T = temperature in kelvin, K

The first gas law

For a constant mass of gas at constant temperature, the pressure of the gas is inversely proportional to its volume

The second gas law

For a constant mass of gas at constant pressure, the volume of the gas is directly proportional to its temperature in kelvin

The third gas law

For a constant mass of gas at constant volume, the pressure of the gas is directly proportional to its temperature in kelvin

The three gas laws combine to give the ideal gas law equation

$PV = Nk_BT$
$PV = nRT$

P = pressure in pascals, Pa
V = volume in metres cubed, m^3
T = temperature in kelvin, K
n = amount of substance in moles, mol
N = number of molecules, no unit
k_B = Boltzmann constant, 1.38×10^{-23} JK^{-1}
R = gas constant, 8.31 JK^{-1} mol^{-1}

Student
view

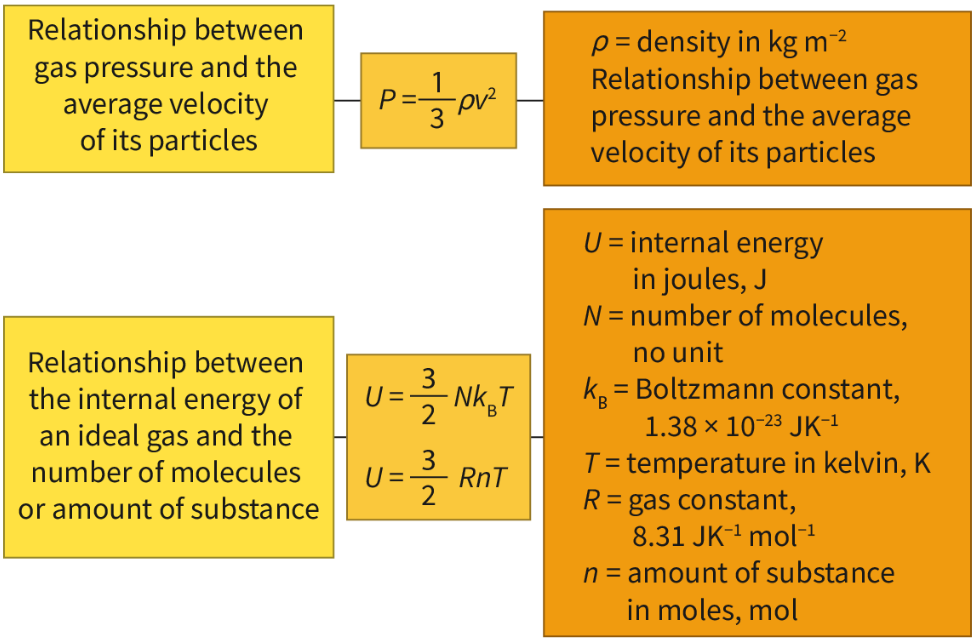

Figure 1. Concept diagram for gas laws.

More information for figure 1

The concept diagram illustrates key gas laws with corresponding equations and explanations. The diagram is structured around several boxed sections connected by arrows.

1. **Pressure Calculation:** The first section describes how to calculate pressure using the formula (P = \frac{F}{A}), where (P) is pressure in pascals (Pa), (F) is force in newtons, and (A) is the area over which force is spread in square meters.

2. **Amount of Substance:** The second section focuses on calculating the amount of substance in moles using (n = \frac{N}{N_A}), where (n) is the amount of substance, (N) is the number of molecules, and (N_A) is Avogadro's constant (6.02 × 10^23 mol^-1).

3. **Ideal Gas Law:** The diagram illustrates the ideal gas law with the formula (PV = nRT). It combines three gas laws:

4. The first gas law states that pressure is inversely proportional to volume at constant temperature.
5. The second gas law asserts that volume is directly proportional to temperature at constant pressure.
6. The third gas law indicates that pressure is directly proportional to temperature at constant volume.

7. **Other Relationships:**

8. The relationship between gas pressure and average velocity is given by (P = \frac{1}{3} \rho v^2), where (\rho) is density.

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9. The internal energy of an ideal gas is indicated by (U = \frac{3}{2}Nk_BT) and (U = \frac{3}{2}RnT), with associated explanations for each symbol, such as (U) for internal energy and (R) for the gas constant (8.31 JK^-1 mol^-1).

Each section includes explanations of variables and constants used in the equations, providing a comprehensive overview of the relationships within gas laws.

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B. The particulate nature of matter / B.3 Gas laws

Checklist

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/checklist-id-44294/print/) Assign

What you should know

After studying this subtopic, you should be able to:

- Calculate pressure using the equation:

$$P = \frac{F}{A}$$

- Define the mole and calculate the amount of substance using the equation:

$$n = \frac{N}{N_{\mathrm{A}}}$$

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/how-do-ideal-gases-behave-id-44292/print/) Assign

- Define what an ideal gas is, describe its properties and state the conditions under which an ideal gas best approximates a real gas.
- Relate simulated experimental data to the empirical gas laws and thereby deduce the ideal gas law equation.
- Apply the first, second and third gas laws.
- Calculate the properties of a gas using the equations:

$$\frac{PV}{T} = \text{constant},$$

$$PV = nRT$$

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and

$$PV = Nk_BT$$

- Calculate the internal energy of an ideal gas using the equations:

$$U = \frac{3}{2}Nk_BT$$

and

$$U = \frac{3}{2}RnT$$

- Apply the concepts of force and momentum to explain how gas pressure arises.
- Calculate the pressure of an ideal gas using the equation:

$$P = \frac{1}{3}\rho v^2$$

Practical skills

Once you have completed this subtopic, go to Practical 4: Investigating an ideal gas law (/study/app/math-aa-hl/sid-423-cid-762593/book/investigating-an-ideal-gas-law-id-46508/) in which you can model the ideal gas behaviour.

B. The particulate nature of matter / B.3 Gas laws

Investigation

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/investigation-id-44295/print/) Assign

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Research skills – Using search engines and libraries effectively
- **Time required to complete activity:** 2 hours
- **Activity type:** Individual activity

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Your task

Carry out detailed research into a real-world application of gas pressure. You could choose one of the following applications or research to come up with your own:

- pressurised aeroplane cabins
- oxygen tanks used by high-altitude climbers, such as those climbing Mount Everest
- pressure in submarines.

You should:

- describe the real-world application
- identify which of the gas laws applies
- explain how the gas law(s) applies
- suggest whether or not the real gas is behaving as an ideal gas in the chosen context
- explain how the macroscopic properties (properties that can be observed with the naked eye) of the gas are related to the behaviour of individual particles.
  For example, if an inflated balloon of air is immersed in a tank of liquid nitrogen, the balloon shrivels up and becomes smaller. This macroscopic observation of the decrease in the balloon's volume can be explained by the second gas law, which states that the volume of a gas is directly proportional to its absolute temperature. However, it is more complicated than this. The second gas law requires that the pressure of the gas is constant. However, in this example, this is not the case as the decrease in temperature causes a decrease in the kinetic energy of the particles and a decrease in the pressure of the gas. Real gases best approximate ideal gases at high temperatures and low pressures. In this case, the real gas has been cooled to a low temperature by the liquid nitrogen, so it does not approximate an ideal gas.

You could present your findings as a poster. Or you could present it as a video or a podcast if you have access to a mobile phone or a video camera.

Study skills

While doing this activity, think critically about the relevance and reliability of the information you find. One way to analyse this is using a source reliability check such as the five Ws:

- **W**HO wrote the article and what qualifies them as an expert in this subject?
- **W**HAT type of source is it?

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

- WHERE is the article from, for example, who is the publisher?
- WHY does the source exist (to persuade, to inform, etc.)?
- HOW does the source compare to others on the same topic?

What other methods do you know of to analyse source relevance and reliability.

Do not forget that you should also credit your sources of information using a single standard method of referencing and citation. You can use any method you like as long as you use it correctly and consistently, but your school or college may have a standard referencing style to be used throughout the IB. Although there are many online reference generating tools available, you should know how to write an in-text citation and reference, so that you can make sure that those generated on the internet are correct.

B. The particulate nature of matter / B.3 Gas laws

Reflection

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/reflection-id-47874/print/) Assign

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44289/).

- How are the macroscopic characteristics of a gas related to the behaviour of individual molecules?

Student view

Overview
(/study/ap
aa-
hl/sid-
423-
cid-
762593/c

- What assumptions and observations lead to universal gas laws?
- How can models be used to help explain observed phenomena?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

⚠ Once you submit your response, you won't be able to edit it.

0/2000

Submit

Rate subtopic B.3 Gas laws

Help us improve the content and user experience.

Student
view