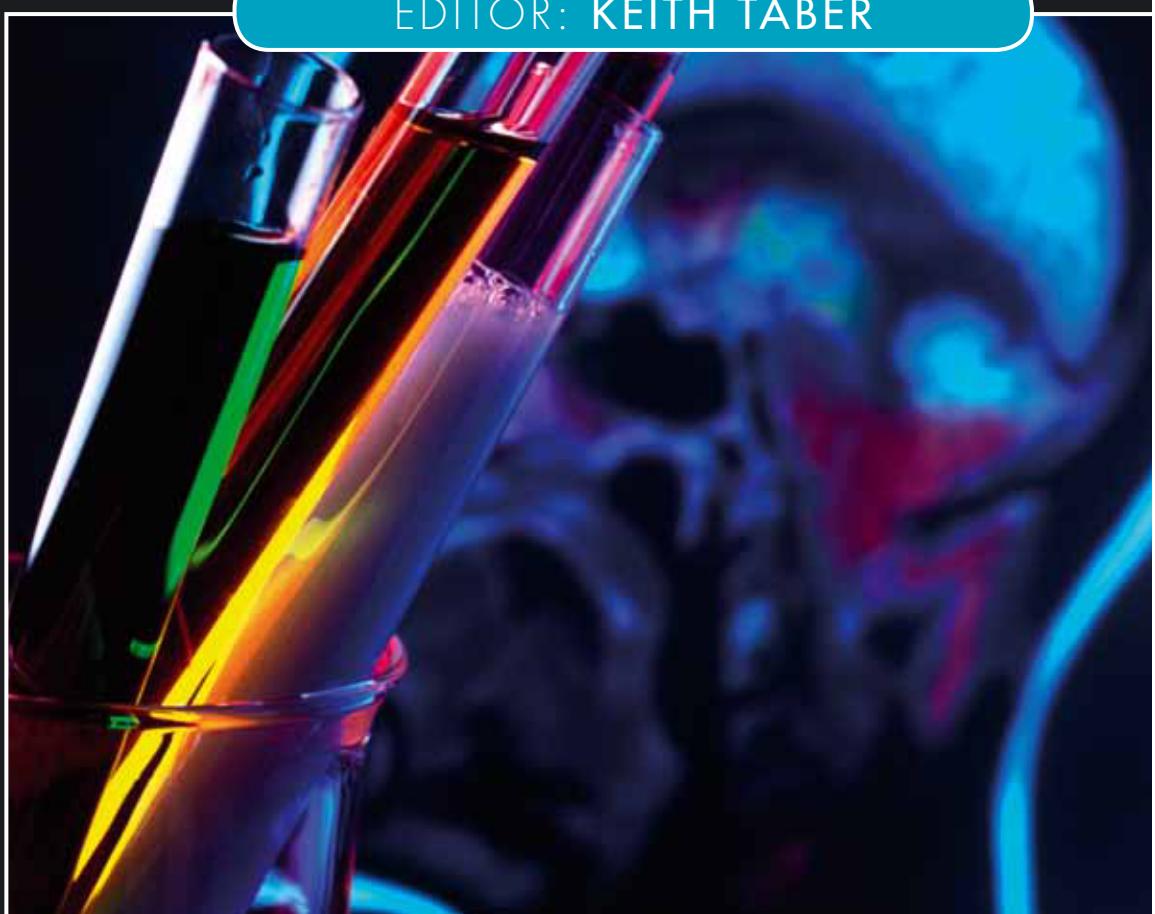


ASE SCIENCE PRACTICE

teaching secondary
CHEMISTRY
NEW EDITION

EDITOR: KEITH TABER



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ASE SCIENCE PRACTICE

teaching secondary
CHEMISTRY
SECOND EDITION

EDITOR: KEITH S. TABER



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Introduction



Keith S. Taber

This book is part of a series of handbooks for science teachers commissioned by the Association for Science Education. This particular handbook is intended to support the teaching of chemistry at secondary level (taken here as ages 11–16 years), whether as a discrete subject or as part of a broader science course. The book has been written with a particular awareness of the needs of new teachers and of those teaching chemistry who would not consider it their specialism within the sciences. However, the book should prove to be of interest and value to anyone teaching chemistry topics at secondary level. The book has been written by a team of authors who collectively have a wide range of experience in teaching chemistry, supporting and developing teachers of chemistry, and undertaking research into teaching and learning in chemistry topics.

It is sometimes easier to characterise something by explaining what it is not. This book is not a chemistry textbook for teachers, although inevitably it discusses chemistry content as part of the process of describing and recommending approaches to teaching the subject. There are many good chemistry books available at various levels, and any teacher who is concerned about their knowledge and understanding in aspects of chemistry should first do some work to develop their own subject knowledge before considering approaches to teaching. So-called ‘pedagogic content knowledge’ will only be sound when we are building on subject knowledge that is sound (else we become very effective at teaching poor chemistry).

The handbook does not set out to act as a teaching guide for any particular curriculum or syllabus. We intend the book to be equally useful across different courses: whether the course is arranged as a set of traditional topics or organised in some other way, for example teaching concepts through the contexts of major areas of application of chemistry such as food, transport, fabrics, etc. The book is not tied to a particular stream or ability level of student. In some places chapters make explicit suggestions for differentiating between different groups of students, but you should always consider how the advice given here can best inform the teaching of your particular classes.

Nor does the book set out to be a manual for teaching chemistry in the sense of providing comprehensive coverage of all content that might potentially be included in a secondary chemistry course. Such a manual would inevitably be both voluminous and very quickly out of date as chemistry and chemistry teaching move on.

Ideas for effective chemistry teaching

The philosophy behind the present book is that it is more important to inform teachers about effective teaching approaches than to train them to apply specified teaching schemes in particular topics. Some of the recommendations we offer in the handbook are based on a good deal of classroom experience and draw on specific research into students' learning difficulties and effective innovations in teaching. The specific suggestions made for teaching these aspects of the subject can certainly be considered as the best research-informed advice currently available to teachers.

However, teaching is a contextualised process: students, facilities, curriculum requirements and so much more can make a difference to what counts as good teaching in a particular classroom on a particular day. So just as important as the specific suggestions for teaching particular concepts is the range of approaches adopted by authors across the chapters. Drawing upon the range of teaching and learning activities described here can inform the development of teaching that is both varied and responsive to the needs of particular students and classes. Although not everything that could possibly be covered is included in the book, the thinking behind the examples that are presented here offers the basis for developing effective teaching that can be adopted across chemistry teaching (and often well beyond).

Teaching about the nature of chemistry

In accordance with the philosophy outlined above, the reader will find a varied set of chapters included in the book. For example, features of the nature of chemistry as a science are highlighted in some chapters. Teaching about the nature of science (which has sometimes been referred to as 'how science works'), which recognises how all students need to understand science (i.e. should be scientifically literate) for their role as citizens (as consumers, voters, etc.), has become increasingly important. Such a perspective needs to inform all science teaching and readers may wish to think how the ideas highlighted in a number of the chapters here (such as the nature and role of models in developing understanding of the world) can be more widely applied.

Another key difference between the chapters is the centrality of the topics discussed. The first five chapters set out key ideas that are needed to understand any area of chemistry, whereas the other chapters stand alone to a much greater extent. It is also useful to note that while almost all of the chapters are clearly about chemistry, the

chapter about Earth science overlaps strongly with several other sciences, and in particular draws on geology. Given the increasing importance of interdisciplinary work in science and – even more so – the importance of understanding the environment in science and in society more widely, this chapter reminds us that chemistry links with, builds upon, and feeds into, a wide range of scientific work.

A final difference between chapters that will be very obvious to readers is the extent to which practical work features. It is said that chemistry is a practical subject. This is certainly true, but – as a science – chemistry is just as much a theoretical subject: it is the interplay of theory and evidence that is at the heart of scientific work. Chemistry as a science is based upon observations that lead to the development of categories and the identification of patterns, and to ways of making sense of, and understanding, the phenomena. This involves the construction of models and theories, which can motivate empirical investigations that can then inform further rounds of theorising and experimentation. In particular, much of chemistry as a science can be considered to be about building models and selecting those that are useful to scientists despite inevitably having limited ranges of application. The notions of acids (Chapter 6) or oxidation (Chapter 7) certainly reflect this, being concepts that are the products of human imagination, designed to reflect the patterns found in nature and to have utility to chemists as tools for thinking, explaining, predicting and so supporting practical and technological work. Understanding chemical ideas in this way, as creative products of scientific work (rather than simply being descriptions of the way the world is), should help students make sense of how chemists have modified these concepts over time (as described in the case of acids in Chapter 6), and why sometimes we seem to operate with a range of not entirely consistent models (oxidation in terms of oxygen or electrons: Chapter 7; oxidation in terms of oxidation states: Chapter 9).

An activity which illustrates this general point in relation to particle theory (the topic of Chapter 2) is included in a publication available from SEP (the Science Enhancement Programme, details of which are given in the ‘Other resources’ section at the end of this introduction). The first of two group-work tasks in this activity ‘Judging models in science’ asks students to consider two types of particle models – particles like tiny hard billiard balls; particles as molecules with ‘soft’ electron clouds – and to consider which model better explains a range of evidence based on the observable properties of matter. Students will find that each model is useful for explaining some phenomena, but neither fits all the evidence – and of course both models are still found useful in science.

A key aspect of this Janus-faced nature of chemistry (looking to both the phenomena and the theories) is that chemistry is discussed in terms of the macroscopic/molar/phenomenal level and in terms of submicroscopic particle models which are used to make sense of those phenomena. These models exemplify the nature of science (offering an extremely powerful explanatory scheme for making sense of the nature of the material world), but are known to be challenging for students.

A central feature of the way chemistry is presented and discussed in classrooms is the set of representations (such as formulae and chemical equations) used. This is often seen as a third 'level' distinct from the molar and submicroscopic levels, but is more helpfully understood as a specialised language that allows us to shift between those two levels (see Chapter 3). Translating between observable phenomena, symbolic representations and theoretical models is a key part both of teaching, and learning, chemistry.

Practical work and 'experiments' in chemistry teaching

Given the nature of chemistry as a discipline, and of school chemistry as a curriculum subject, it is essential that students are introduced to the phenomena that the theories and models are meant to help us understand. Without experiencing these phenomena, there is little motivation for adopting the theoretical ideas. Within school science, practical work has long been seen as a key part of chemistry lessons in many countries (and especially in the UK). Yet research also suggests that a good deal of the practical work undertaken by students has limited impact on learning (or even on student motivation to continue studying the subject).

Readers should consider carefully whether practical work undertaken is going to be the most effective way of meeting the purposes of teaching. In some cases this will certainly be so. So the chapter on inorganic analysis, an area of secondary chemistry that is not always given as much attention as it once was, is largely developed around practical work that students can carry out. This makes sense, as the aims of teaching this topic include the ability to carry out analytical procedures and interpret bench observations to identify particular chemical species present. Other chapters vary considerably in the amount of laboratory practical work recommended. In some cases teacher demonstrations are recommended as being more effective ways of ensuring students can be helped to appreciate the chemical interpretations of observations

– as a teacher you can draw students' attention to the chemically relevant and away from the salient but incidental. In some topics alternative forms of engaging, active learning are suggested to help students learn concepts not easily appreciated from the laboratory work possible in school contexts. Ultimately, however, theory and practical experience both have important roles to play and need to be coordinated across secondary school learning.

One specific issue that has vexed me in this context is the use of the term 'experiment' to describe school science practical work. Very few chemistry practicals carried out in most schools have any genuine claim to be experiments (authentic investigations to test out hypotheses, rather than to illustrate what is already set out as target knowledge to be learnt), and using the term experiment loosely may undermine learning about the nature of science, when we know that students commonly use technical terms such as 'experiment', 'theory', 'proof' and so forth in very vague and inconsistent ways. However, within the culture of school chemistry the term experiment is often used for any laboratory practical activity, especially one that is undertaken by students (rather than being a demonstration). Some authors here have followed the common usage and referred to laboratory practical activities as experiments. This is fine in talk among teachers and technicians, but it may be wise to consider carefully which practical activities should be presented to students as experiments. It is probably best limited to those where they are genuinely testing some kind of hypothesis – where students are seeking to discover something they do not actually already know.

Ensuring safety during practical work



Many standard chemistry practicals have been carried out safely in schools for decades and there have seldom been serious accidents. Yet clearly there are particular potential hazards involved in some practical work. It is important to keep the potential risks of practical activities (whether observed by, or undertaken by, the students) in perspective, yet to remember that student safety must be your paramount concern. In this book, the margin icon shown here is used to alert you to particular safety issues that you should be aware of. Recommended activities are considered suitable for classroom use by the authors. However, assessing risk is not just about the activity, but also the people and the conditions. The same practical may be viable with some teaching groups and not others.

It is, therefore, very important to undertake careful risk assessments before deciding to do any practical activities in the

classroom. Your risk assessment needs to consider the experience and skills of the person(s) carrying out the activity (teacher or students), how responsible the particular students are and the facilities available in the teaching room (presence of a fume cupboard, adequate ventilation, sufficient access to sinks, plenty of space for students to move around, support of teaching assistants, assistance of a qualified technician, etc.)

For any practical activity (including teacher demonstrations) the teacher should carry out a risk assessment. This might include:

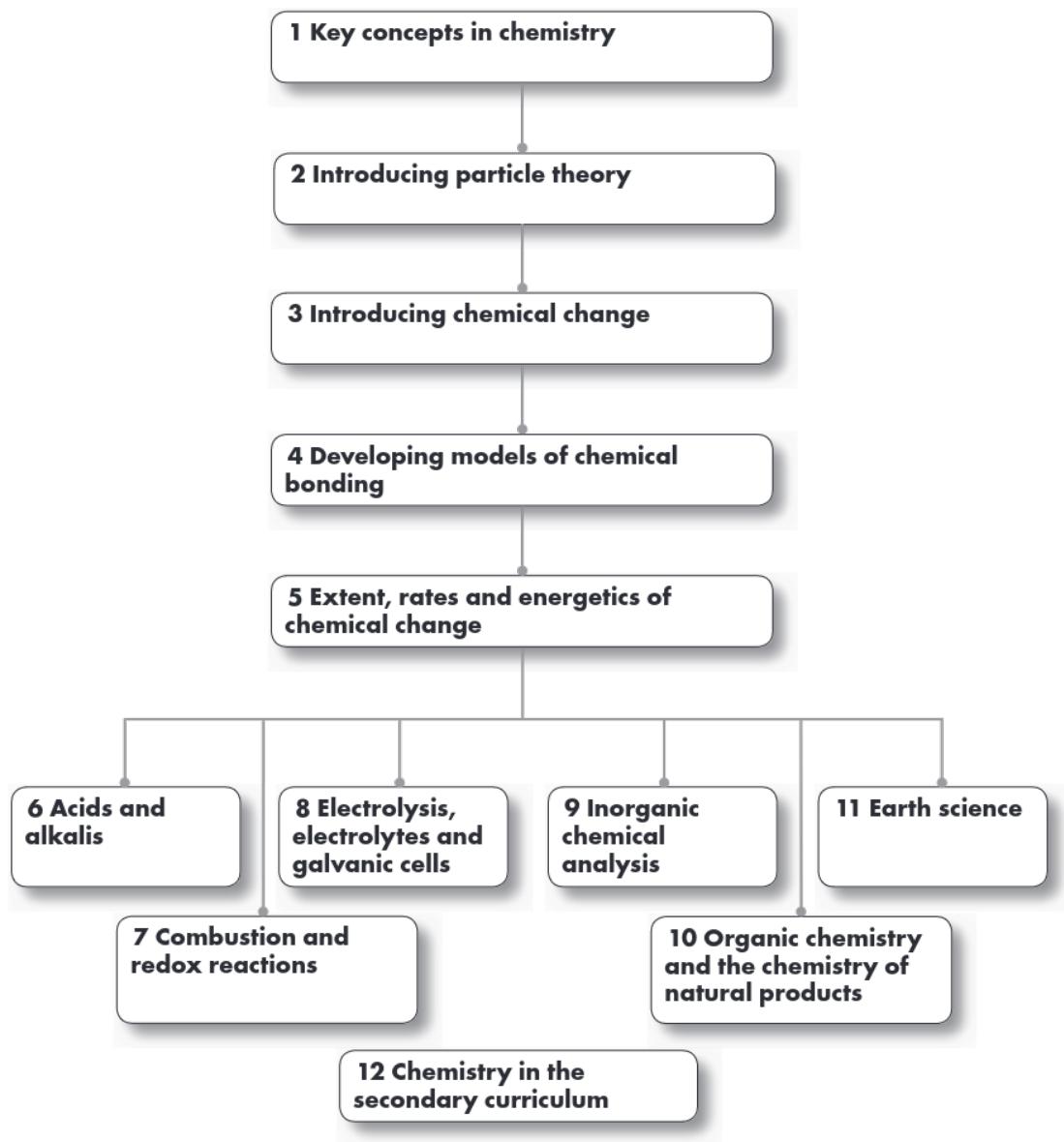
- checking the model risk assessment supplied by their employer (this may be supplied by another agency, such as CLEAPPS or SSERC in the UK, to which the employer subscribes) and adjusting the model risk assessment as appropriate.
- referring to the hazards of the starting material and the products by consulting safety data sheets provided by the supplier, and adjusting the model risk assessment as appropriate,
- consulting more experienced teachers or experienced technicians.

As a result, the significant findings should be recorded and the appropriate control measures implemented. Whatever the outcomes of a risk assessment, including the risk of annoying hard-working technical staff, you should always be prepared to suspend or cancel laboratory work during a lesson if at any point you judge that student behaviour or some other factor makes continuing unwise.

The structure of the book

The book contains twelve chapters. The first three discuss the teaching of the most basic chemical ideas, which underpin all other chemistry topics. These are ideas that will need to be met early on in the secondary school, but will be developed in more sophisticated ways throughout the secondary years. Chapters 4 and 5 discuss other fundamental ideas which build upon those discussed in Chapters 1–3, and provide the basis for the level of theoretical exploration of chemistry expected of many upper-secondary level classes (as well as setting out the theoretical basis that is developed in post-secondary study). The next six chapters draw upon, and often assume knowledge of, these basic ideas, but need not necessarily be taught in the order they appear in the handbook. The final chapter has a slightly different flavour; it reflects upon how decisions are made about which chemistry topics should be a part of the secondary education for different groups of students. For readers in some contexts such decisions will be made centrally by curriculum authorities, but in many teaching contexts

there may be important decisions to be made about which science topics should be part of a core curriculum, and which can be seen as either possible enrichment or as important for some, but not all, groups of students.



The structure of the chapters

As suggested above, the nature of the eleven topic-based chapters in this book reflects the diversity of topics found in a chemistry course, as well as the different teaching approaches judged worth recommending by the authors who have particular expertise in those topics. However, all of these chapters include a number of common features. Each chapter is divided into sections according to main subsections of the chapter topic, and each includes a schematic diagram of the chapter structure. Each chapter offers guidance on a route through the topic. These chapters also discuss the prior knowledge and relevant experience that students will bring to the study of the topic at secondary level, as well as highlighting the common learning difficulties and alternative conceptions that students are known to have in the topic. Although the authors here can offer guidance on the likely range of prior knowledge and common alternative conceptions to be found in many classes, each group of students is different, and – indeed – each learner is an individual with their own personal understanding of the world and their own way of interpreting what they are taught in chemistry classes.

This is something I am well aware of from my own work, where I have spent a good deal of time asking secondary-age students to tell me about their understanding of various science topics. There are some very common alternative ideas (alternative conceptions or misconceptions) that are found in just about any class. For example, it is very likely that in any upper secondary science or chemistry class you teach, at least some (and in many classes it will be most) of the students think that chemical reactions occur so that individual atoms can fill their electron shells. (If you cannot see what is wrong with that idea, then you may find Chapter 4 quite interesting.)

However, it is also the case that if you spend enough time asking students to tell you their ideas relating to science topics, you are likely to uncover some idiosyncratic notion they hold which is at odds with accepted scientific knowledge and which you have never heard suggested before. Student individuality and creativity is such that this is likely to remain the case even when you have been teaching chemistry for some decades! Some examples of student thinking about chemistry topics can be found on the ECLIPSE project website (full details of which are given in the ‘Other resources’ section at the end of this introduction), offering a taste of the diverse and often unexpected ways that different learners make sense of the topics they meet in school science lessons. (Note, the icon here is used in the margin where references are made to useful websites.)



As what students already think is a strong determinant of what they will learn in your lessons, it is worth spending some time exploring their ideas and in particular undertaking diagnostic assessment at the start of major topics to check on prior learning and elicit any strongly held alternative conceptions. In an ideal world teachers would have time to talk at length to each of their students. More realistically, ideas can be explored through open-ended classroom discussion that invites students' ideas in an accepting way and explores their consequences (and relationship with available evidence), before 'closing down' discussion to present the scientific models. This presentation of the 'scientific story' can then be done in ways that anticipate student objections and emphasise the reasons for the scientific explanations being adopted in the scientific community – especially where these explanations contradict students' own thinking. Classroom materials for diagnostic assessment have been published in many science topics and some are referred to in this volume.

The chapters here draw upon research evidence, although in common with other handbooks in the series, the chapters do not include in the text references to the research literature. However, recommendations for further reading and suggestions for resources likely to be found useful by teachers are listed at the end of chapters.

Keith S. Taber
Cambridge, 2012

Other resources

Books

The *ASE Guide to Secondary Science Education* (Martin Hollins, editor) offers a broad range of advice and information for those teaching science in secondary schools. ASE Publications.

An introduction to how students learn in chemistry and the nature and consequences of their alternative ideas, as well as a range of classroom resources to diagnose student ideas, can be found in *Chemical Misconceptions – Prevention, Diagnosis and Cure*. Taber, K.S. (2002). London: Royal Society of Chemistry. Volume 1: Theoretical background; Volume 2: Classroom resources.

To explore further ideas for teaching about the nature of science, readers might refer to the companion handbook in this series, *Teaching Secondary How Science Works*. Vanessa Kind and Per Morten Kind (2008). London: Hodder Education.

CLEAPSS provides support for practical work, and in particular health and safety information for school science. CLEAPSS is the source for such useful resources as the *Secondary Science Laboratory Handbook* and *Secondary Science Hazcards* (providing safety information and model risk assessments for handling chemicals). www.cleapss.org.uk

For a research-based discussion of effective practical work in school science see *Practical Work in School Science: A Minds-on Approach*. Abrahams, I. (2011). London: Continuum.

The group-work activity 'Judging models in science' is included in *Enriching School Science for the Gifted Learner*. Taber, K.S. (2007). London: Gatsby Science Enhancement Programme. Available from 'Mindsets Online': www.mindsetsonline.co.uk

Websites



An introduction to the common alternative ideas ('misconceptions') that students often develop in chemistry is provided in Kind, V. (2004). *Beyond Appearances: Students' Misconceptions about Basic Chemical Ideas* (2nd edn). London: Royal Society of Chemistry. Available at: www.rsc.org/Education/Teachers/Resources/Books/Misconceptions.asp

The Royal Society of Chemistry provides a wide range of resources to support chemistry teaching, which may be searched at: www.rsc.org/learn-chemistry

Examples of how students think about and explain chemistry (and other science) topics can be found at the ECLIPSE (Exploring Conceptual Learning, Integration and Progression in Science Education) project website:

www.educ.cam.ac.uk/research/projects/eclipse

A range of resources for chemistry teachers recommended by colleagues on two email discussion lists (Chemistry-Teachers@yahoogroups.co.uk and Chemed-L@mailer.uwf.edu) are listed at: <http://camtools.cam.ac.uk/access/wiki/site/~kst24/teaching-secondary-chemistry-resources.html>

The magazine *Education in Chemistry*, published by the Royal Society of Chemistry, includes a regular feature called 'Exhibition Chemistry' offering 'ideas for chemistry demonstrations to capture the student's imagination'. These are accompanied by a video of the demonstration which can be viewed on the web:

www.rsc.org/Education/EiC/topics/Exhibition_chemistry.asp

2

Introducing particle theory

Philip Johnson

2.1 Melting and solidifying

- Melting points
- Defining a substance

2.2 A 'basic' particle model

- The solid and liquid states
- Introducing the basic particle model

2.3 Boiling and condensing

- Predicting the gas state
- Boiling water
- Boiling points
- 'Gases'

2.4 Dissolving

- Recognising and explaining dissolving
- Solutes in the liquid and gas states
- Empty space in the liquid and solid states
- Intrinsic motion and the liquid state
- Solubility

2.5 Evaporation into and condensation from the air

- Evaporation and boiling
- Temperature and energy
- Explaining evaporation below boiling point
- Factors affecting the rate of evaporation
- Reconciling boiling and evaporation
- Condensation from a water-air mixture

2.6 More on the gas state: pressure, weight and diffusion

- The gas state and pressure
- Mass and weight of the gas state
- Diffusion involving the gas state

2.7 What, no 'solids, liquids and gases'?

- Three types of matter?
- The concept of a substance is important

Why teach particle theory?

Chemistry is all about substances. Substances can be involved in three kinds of change: change of state, mixing and chemical change. Our descriptions of phenomena are in terms of substances. When a lump of lead changes to a runny liquid, it is still said to be the same substance. When a sugar crystal dissolves in water, the substance sugar is still thought to be there. The substances wax and oxygen change to the substances water and carbon dioxide in a candle flame. Why do such descriptions make sense? Liquid is very different from solid, so how can liquid lead be the same substance as solid lead? The crystal disappears, why not the sugar? How is it that substances can cease to exist with new ones created in their place?

These descriptions owe their sense to particle theory, where a substance is identified with a particle. Observations are theory led, and particle theory at varying levels of sophistication determines the way chemists speak and think about the material world. Therefore, if we want students to really understand chemistry, we need to develop their understanding of particle theory. At entry level, a ‘basic’ model referring to the particles of a substance is good enough for changes of state and mixing. At greater resolution, identifying a substance with an ‘atom structure’ (which atoms are bonded to which) accommodates chemical change. This chapter confines itself to the introduction of a ‘basic’ particle model, leaving atoms to Chapter 3.

Previous knowledge and experience

■ The concept of a substance

The following picture of students’ thinking is based on extensive research. To the uninitiated, what chemists mean by a substance is not at all obvious. (Chapter 1 discusses this at length.) Most materials in everyday experience are mixtures of substances; few are relatively pure samples of substances. Moreover, everyday thinking assigns identity to a sample of material by its history rather than its current properties. The focus is on where something has come from and what has happened to it. Although the idea of mixing is readily appreciated, materials ‘as found’ are not necessarily categorised as either substances or mixtures of substances. For example, there would be no distinction between milk (a mixture of substances) and sugar (a substance, sucrose) as ingredients. Rust is still thought to be iron, but in a different form (or a mixture of iron and something else); the preoccupation is with its origin. Whereas, from the chemist’s point of view, rust is a new substance in its own right because of its properties; the substance iron no longer exists.

Students are generally mystified by the gas state and are very far from thinking that ‘gases’ are even material like that which presents in the solid or liquid states. Difficulties with the gas state are not surprising. Historically, the idea of a gas being a substance was not established until the early eighteenth century with Black’s work on carbon dioxide. Recognising gases as substances was an important precursor to Lavoisier’s experiments with oxygen and his founding of modern chemistry. Much of school chemistry involves one or more reactants and/or products in the gas state. Understanding the gas state is pivotal in understanding chemistry.

The concept of a substance is something that needs to be learnt and goes hand in hand with particle theory. Without substances, particles have no identity. The distinction between pure samples and mixtures is also crucial; there are no ‘milk’ particles in the same sense as there are sugar (sucrose) particles. (Note that we should not talk about ‘pure substances’ since the term is misleading. The question of purity relates to the sample not to the idea of a substance. For example, in this beaker is there only water? Substances are just substances – there are not pure and impure substances.)

■ Alternative particle models

The ‘basic’ particle model poses challenges. To the eye, matter appears to be continuous and imagination is needed to think in terms of extremely small, discrete particles. Initially, some students may construct an image of particles embedded in continuous matter. Unfortunately, textbooks sometimes show such images and talk about particles ‘in’ a solid/liquid/gas, which could lead students astray. Here, the particles are not the substance, they are extra to it. Ideas of particle movement are consistent with this model since movement will be determined by the state of the continuous matter (for example, particles can move around ‘in’ a liquid). Identifying the particles with the substance helps to avoid such misconceptions, for example, ‘sugar particles’, ‘water particles’ and ‘oxygen particles’.

Those students who do see the particles as being the substance often start by attributing macroscopic properties to the particles. For example, students may think that a copper particle is hard, malleable, conducts electricity and is copper coloured. It takes time to appreciate that the physical nature of the particles is irrelevant, with the characteristic properties of the states determined only by movement and spacing, not by what individual particles are like.

The different kinds of movement associated with the different states are not so problematic for students. However, the intrinsic nature of the movement is more demanding, especially for the solid

state. The most challenging aspect of the model is the notion of empty space. Logically, if the particles are the substance, there must be nothing between the particles – anything of a material nature would be more particles. However, students are inclined to think there is something in between. Many will say ‘air’, although what is meant is often very vague.

Choosing a route

The chapter overview presents a sequence which develops understanding in a cumulative progression where each step builds on previous steps. It seeks to avoid introducing too many ideas at once but also ensures that the key ideas involved in an event are not overlooked. What is necessary and sufficient for a coherent account at the desired level of understanding is the aim.

Assuming students do not already hold the concept of a substance, melting behaviour is an accessible first step. Melting at a precise temperature indicates a pure sample of a substance and the temperature identifies which substance. The ‘basic’ particle model can then be introduced to explain melting and why different substances have different melting points. Once established for the solid and liquid states, the model is used to predict the gas state (and boiling). This approach recognises that students will not know what a gas is and, importantly, demonstrates the predictive function of scientific models.

The basic model is then used to explain dissolving, which includes looking at diffusion within the liquid state. To account for evaporation into and condensation from the air below boiling point, ideas of energy distribution are introduced. In terms of understanding the nature of models, this illustrates development of the model to accommodate further phenomena without undoing the main ideas. To tidy up we return to the gas state and consider pressure and weight and some well known diffusion experiments for illustrating intrinsic motion which draw on other ideas to differing degrees. Finally, we consider the advantages of introducing particles within a substance-based framework over a ‘solids, liquids and gases’ framework.

To a large extent, the sequence is governed by the logical structure of the content. However, the basic model could be consolidated for the solid and liquid states in the context of dissolving before moving on to the gas state. Each stage is now considered in more detail.

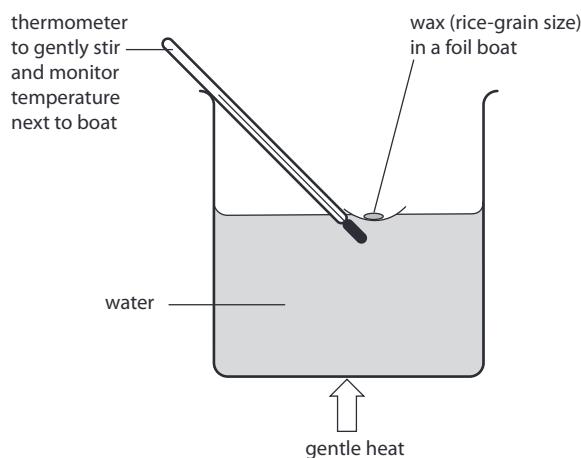
2.1 Melting and solidifying

Melting points

There are many aspects to melting, at varying depths of understanding. To begin with, introduce the idea of a melting point as when something is 'hot enough to melt'. As a class experiment, students could be challenged to find the melting point of candle wax by the method shown in Figure 2.1. (Note that a sample of candle wax is not just one substance but, within the limits of the experiment, there is a precise enough melting point. Candle wax has the advantages of being familiar and readily cut to convenient size. Octadecanoic acid (stearic acid, melting point 70 °C) or 1-hexadecanol (cetyl alcohol, melting point 56 °C) are alternatives.)

Discussion should draw attention to the independence from sample size – if melting temperature depended on amount, the experiment would not be worth doing. (Of course, the time it takes for a sample to melt does depend on amount, for example snowflake versus iceberg.)

Figure 2.1 Finding the melting point of candle wax



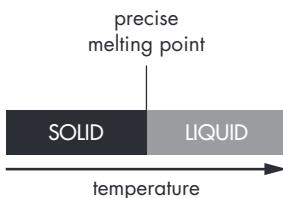
Demonstrations of melting lead (melting point 328 °C) and sodium chloride (melting point 801 °C) can follow. (For the latter use large crystals from rock salt and three Bunsen flames.) The temperatures cannot be measured, but draw attention to the distinct change from solid to runny liquid which is characteristic of a precise melting point.

Defining a substance

A sample of a substance can now be defined as something which has a precise melting point, and solid and liquid can be defined as

two of the states a substance can be in. Figure 2.2 highlights melting point as a ‘switching’ temperature. On heating, a substance melts when it reaches this temperature. On cooling, a substance solidifies on falling to this temperature.

Figure 2.2 A substance has a precise melting point.



Many students think the temperature needs to fall well below melting point before solidifying occurs; perhaps the result of an association of ‘freezing’ with 0 °C. (This is why the word ‘solidify’ is preferred to the term ‘freeze’ in the language of chemistry.) More of the story is revealed in heating/cooling curve experiments and their interpretation in terms of latent heats. However these are difficult ideas going well beyond requirements at this stage. Thinking that solidifying takes place at just below melting point represents significant progress for most students and is a position to build on later. Other points for later are the absence of a precise melting point for mixtures (such as chocolate) and, after chemical change, the decomposition of some substances before melting (such as calcium carbonate).

2.2 A ‘basic’ particle model

Particle theory involves a number of ideas which work together to form a model. The minimum core for a ‘basic’ particle model is:

- A sample of a substance is a collection of identical particles; the particles are the substance.
- The particles hold on to each other; the ‘holding power’ is different for different substances.
- The particles are always moving in some way – they have energy of movement. Heating gives the particles more energy of movement – they are more energetic.

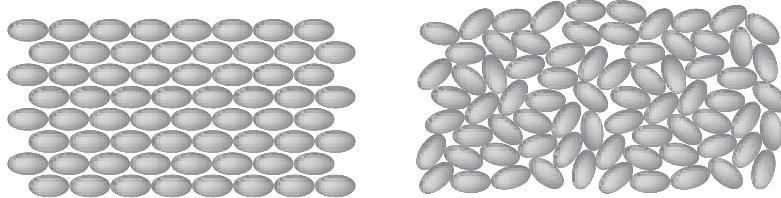
‘Holding power’ is preferred to talk of forces since the strengths of forces depend on the distances between particles, and distances change. Holding power belongs to the particle and does not change. However, holding power applies only to particles of the same substance – it cannot be used to predict the strength of hold between particles of different substances.

The solid and liquid states

The state of a substance depends on the balance between holding power and energy of movement (which depends on the temperature of the sample). For the solid state, the holding power can keep the particles close together in fixed places and the particles can only vibrate. For the liquid state, the holding power keeps the particles close together but not in fixed places. The particles move around from place to place. The melting point of a substance depends on the holding power – the stronger the hold, the higher it is.

In diagrams, we recommend using shapes other than circles for substance particles. This has the advantage of making it easier to show the disorder of the liquid state. With circles there is a tendency to move particles too far apart. Furthermore, if circles are reserved for atoms, the distinction between the substance and sub-substance levels of theory is emphasised.

Figure 2.3 The same substance in the solid and liquid states



Solid state

The particles hold themselves close together.
Each particle is in a fixed position.
The particles are vibrating.
There is an ordered arrangement.

Liquid state

The particles hold themselves close together.
The particles move around from place to place, randomly.

Introducing the basic particle model

With respect to understanding the nature of models it should be noted that the phenomenon of melting of itself is not direct evidence for the existence of particles. The model can be presented as a useful way of thinking. As noted in Chapter 1, everyday discourse often uses ‘particle’ to describe small yet visible pieces of material and it is important to emphasise the special scientific meaning within the particle theory. A small drop of water (0.05 cm^3) contains the order of 1.7×10^{21} water particles (molecules). Employing terms such as ‘grains’, ‘pieces’, ‘bits’, ‘lumps’, ‘specks’, ‘droplets’ and ‘globules’ in other contexts helps to make the distinction. Appreciating the absolute scale of particle size is a challenge to all of us. However, a sense of being extremely small is good enough to operate with the model.

The change in movement – from fixed places to moving around – is the key point in explaining the change from solid to liquid. To counter notions of individual particles having a state, emphasise that the particles themselves do not change – individual particles do not melt. Point out that we have not said what individual particles are like, physically. All we can say is they are not like anything we know. They behave like rubber balls but they are not made of rubber! It is also worth noting that the distances between the particles hardly changes. For melting ice, the particles actually move closer together. Moving further apart does not explain the change from solid to liquid. In considering the balance between ‘hold’ and ‘energy’, students have a tendency to think of the hold weakening rather than increased energy overcoming the hold enabling the particles to move around. (The change in average distance apart is very small and hence the average strength of forces changes little. At times, moving particles will be very close and if not energetic enough will be held in place.)

■ Limitations of an energy-only explanation

An energy explanation of melting is a limited view which does not account for ice melting at temperatures down to -12°C in the presence of salt. Like all changes, a more complete explanation of melting concerns entropy which considers the arrangement of energy and particles. At melting point, the decrease in entropy of the surroundings (due to loss of energy supplied for the melting) is equal to the increase in entropy associated with the change from solid to liquid situation. However, ice in the presence of salt melts to form a solution, and solutions have higher entropy than pure liquid. Therefore, the increase in entropy from ice to salt solution is greater than the increase for ice to water. The greater increase compensates a greater decrease in entropy of the surroundings and so ice melts at a temperature below 0°C (a lower temperature means a bigger change in entropy for a given change in energy). Of course, this treatment is very advanced, but students will know about salt on icy roads and may well ask. We need to acknowledge that there is more to understand about melting. For now one could say that it is easier for ice to melt to form part of a solution than a pure liquid. When measuring melting points it is important to have pure samples of substances.

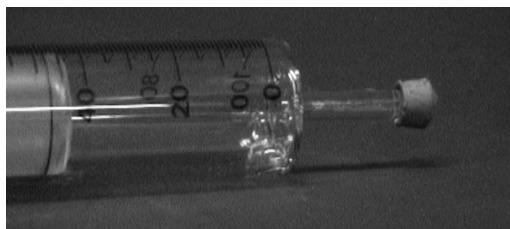
2.3 Boiling and condensing

Predicting the gas state

Having established the basic particle model for the solid and liquid states, students could be invited to speculate about the continued heating of substances in the liquid state. Imagine heating a drop of water in a sealed plastic bag (with all air excluded) to higher and higher temperatures. What might happen to the particles? With little or no prompting some students will suggest that the particles could move apart because they have too much energy for the hold to keep them together. Objects held together by Velcro® can be used in an analogy. The ability to hold – the Velcro – does not go away but with enough energy the objects will separate. Students could imagine themselves wearing suits made from the two sides of Velcro arranged in a chequered pattern. They would stick together as opposite patches matched up, but with enough energy they could move apart. On losing energy, the Velcro would be able to keep them together again. (Patches of Velcro glued to polystyrene or wooden balls make an effective model.)

What is observed if the particles move apart? Students may not be so sure about this but here is an experiment worth trying! Since heating water in a plastic bag is not so easy, inject a small volume of water (0.05 cm^3) into a sealed gas syringe preheated to around 150°C instead. On the bench out of its oven, the syringe retains a high enough temperature long enough to give satisfactory results. Explain that the small amount of water will quickly heat up on contact with the hot glass. The plunger moves out quickly, the liquid water disappears (some bubbling may be seen) and inside the syringe is clear (Figure 2.4). Practice is recommended since the volume of gas is very sensitive to the volume of liquid water, and speed is of the essence. Reasonably consistent volumes around the 100 cm^3 mark are achievable, but back-up syringes are advisable in case another go is necessary. On cooling, condensation appears as the plunger moves in. (The plunger might not go right back in because some air may intrude through the pierced seal.)

Figure 2.4 Water changing to the gas state

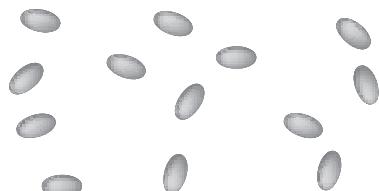


There are many important points to discuss. When particles move apart the gas state is created (Figure 2.5). The particles are still water particles so this is water in the gas state. Draw attention to the huge change in volume. If the particles close together only take up 0.05 cm^3 , what is between the particles when they are apart in the gas state? Many students will want to say air (it looks like air inside the syringe), but remind them that there is only water in the syringe – where could air have come from? We are forced to conclude there is nothing between the particles – empty space. Some students may suggest that the particles expand. This is consistent with the observations but point out that we would have to explain why particles can expand. It is simpler to say the particles do not change and scientists always prefer the simplest model that works. For solid to liquid the key change is a change in movement (fixed positions to moving around); for liquid to gas the key change is a change in spacing (from close together to apart). Ideally, students will not have heard about water being made of hydrogen and oxygen since this can be a source of confusion. If they have, some will say the gas is oxygen and/or hydrogen, because these are known to be ‘gases’. Again, point out that we do not need a more complicated explanation (and tests show it is still water).

Figure 2.5 The gas state

Gas state

The particles do not hold themselves together.
Particles are apart, moving freely in all directions.
There is a lot of empty space (nothing) between the particles.



Boiling water

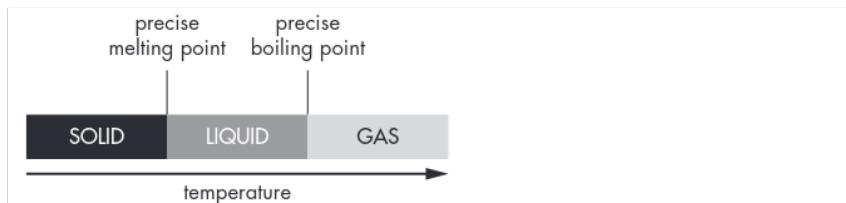
The syringe experiment helps students to understand the more complex event of a beaker of boiling water. What are the big bubbles? Previously, most will have said ‘air’ but now they know water in the gas state looks like air. The parallel with the syringe experiment can be made. At the bottom of the beaker, a small amount of liquid water changes to the gas state (some particles move apart) to form a bubble. Draw attention to the mist above the boiling water. Is this water in the gas state? No! Water in the gas state cannot be seen. The mist is where the gaseous water has condensed to form small droplets of liquid water. To corroborate, generate another syringe of clear gaseous water, remove the cap and expel the gas to give a small puff of mist on cooling in the air.

Boiling points



Students could measure the boiling point of water; the boiling points of other substances such as ethanol (79°C) and propanone (56°C) could be demonstrated (avoid naked flames, heat on a hot plate in a fume cupboard). As with melting, place the initial focus on the idea of boiling point as a ‘switching’ temperature. On heating, a substance changes from the liquid to the gas state when it reaches this temperature. On cooling, a substance changes from the gas to the liquid state when it falls to this temperature (it condenses). Again, full discussion of temperature–time graphs associated with the change of state could be left for later. However, the steady temperature during boiling is very noticeable and could be explained in terms of needing energy to change from liquid to gas. This is why the liquid does not change to gas all at once (and a parallel could be drawn with melting). The substance and its states chart can now be completed as in Figure 2.6.

Figure 2.6 A substance and its three states



‘Gases’

Students are now in a position to understand what ‘gases’ are. These are substances with boiling points below room temperature and therefore in the gas state at room temperature. In effect, they have already boiled to the gas state. Boiling points of these substances are low because the holding powers of their particles are very weak. At room temperature, the particles are energetic enough to be apart. Like water in the gas state, nearly all gases are clear and colourless. Looking the same hardly helps with the notion of being so many different substances. Putting a burning splint to samples of nitrogen (splint goes out), oxygen (splint burns brighter) and methane (catches alight) shows they are very different. Introducing a jar of chlorine shows that the gas state can have colour, but is still clear. It is worth stressing the clarity of the gas state to counter any confusion about mists and smokes being gases. The gas state is clear because particles are separate from each other and we cannot see individual particles.

■ Air

Air can now be understood as a mixture of substances that are all above their boiling points. Translating the percentage composition into particles is a useful consolidation exercise. Out of every 10 000 particles, 7800 are nitrogen, 2100 are oxygen, 93 are argon, four are carbon dioxide and three are various others. Given all the discussion in the media about carbon dioxide, students will be surprised to find out there are so few particles of it. However, proportionality is the point. Putting more carbon dioxide into the atmosphere makes a significant increase because there is not much to start with.

2.4 Dissolving

Dissolving provides a context to strengthen and develop students' understanding of the basic particle model, but also to recognise its limitations.

Recognising and explaining dissolving

For a focal event, students could watch a single, large crystal of common salt (sodium chloride) dissolve in water on gentle stirring. The crystal's gradual disappearance is explained by salt particles mixing in with water particles. We can see a crystal because there are lots of particles together in a lump. We cannot see individual salt particles dispersed among the water particles so the solution looks clear (nor can we see individual water particles, just the water as a whole). The crystal has dissolved but the salt particles are still there. Suspensions of fine powders are more challenging. Many students will say powdered chalk (calcium carbonate) dissolves on stirring because it spreads throughout the water turning it white. For some students it is worth spending time on what a powder is – they could make one by grinding a lump of chalk in a pestle and mortar. Emphasise that each tiny piece of chalk is still made of billions and billions of particles. On close inspection of the suspension, the tiny pieces of chalk are visible and eventually settle to the bottom. The pieces of chalk have not dissolved. From this, clearness emerges as the key criterion for recognising dissolving (as with the gas state). Copper sulfate could be introduced to show a clear but coloured solution. Comparing the results of passing solutions and suspensions through filter paper reinforces their difference and provides another opportunity to apply the particle model. (Make sure the filter paper grade is fine enough.)

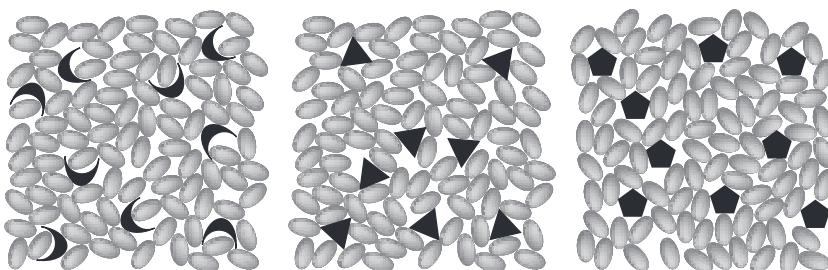
Solutes in the liquid and gas states

Lest students think dissolving only applies to solutes in the solid state, those in the liquid and gas states (at room temperature) should be included. For the liquid state, ethanol, glycerine, olive oil and volasil are suitable examples to test in water. The first two dissolve readily, the last two do not – all can be used by students. (Although olive oil is a mixture, it all behaves in the same way.)

For a solute in the gas state, injecting 1 cm³ of water into a gas syringe of ammonia (100 cm³) is an effective demonstration. The plunger moves in quickly at first, slowing until all of the ammonia has dissolved in the water. Explaining these observations tests students' understanding of the gas state. How can 100 cm³ of ammonia dissolve in only 1 cm³ of water? The key point is that most of the 100 cm³ is nothing – empty space. We know that the particles of 100 cm³ of water in the gas state make a small drop when together in the liquid state. So, 100 cm³ of ammonia in the gas state is equivalent in amount to a drop or a small crystal. A drop or small crystal dissolving in 1 cm³ of water is not such a surprise.

It is worth emphasising that the original state of a solute has no bearing on the nature of the solution. Particle diagrams for solutions of sugar, ethanol and ammonia look the same save the different solute particle shapes (Figure 2.7). A dissolved substance does not have a state as such.

Figure 2.7 Particle diagrams of sugar, ethanol and ammonia solutions



Empty space in the liquid and solid states

Volume and empty space can be covered in the context of liquid state solutes. When 50 cm³ of ethanol and 50 cm³ of water are mixed, the total volume is around 96 cm³. Even though particles in the liquid state are close together, there will be pockets of space where the shapes do not fit together snugly, especially since they are moving around. The particles of another substance could go into some of this space and vice versa. Mixing pasta shells and lentils

makes a good analogy. By the same argument, there will be pockets of empty space between particles in the solid state too. Students could be challenged to find out if volume is ‘lost’ with solid solutes.

Intrinsic motion and the liquid state

To target the idea of intrinsic motion, students could be asked to predict and then observe whether a crystal of salt dissolves without stirring. This also moves thinking on to the mechanism of the change. Even for still water, individually, the particles are moving around. Bombarding water particles knock salt particles out of the crystal, gradually dismantling it. Using a coloured crystal like copper sulfate or potassium manganate(VII) shows how the particles of the dissolved substance spread out due to the intrinsic random motion of the liquid state (a classic diffusion practical).

■ Why does stirring speed up dissolving?

Stirring has a big effect on the rate of dissolving. Why? Most students will suggest that stirring gives the particles more energy. This is a plausible explanation. However, more energetic particles would mean a higher temperature and stirring does not increase the temperature of the water measurably. Stirring moves batches or swathes of particles around but it does not increase their individual, random movement. So, why does stirring speed up dissolving? The diffusion experiment with a coloured crystal gives a clue. Without stirring, a high concentration of solute particles builds up next to the crystal. Through random collisions, some particles are knocked back to the crystal and rejoin. Therefore, the rate at which the crystal actually disappears depends on the difference between the rate of particles ‘leaving’ and rate of particles ‘rejoining’. Stirring moves ‘dissolved’ particles away from the crystal and hence reduces the rate of rejoining (so long as the incoming solution has a lower concentration). Using hypothetical numbers can help to make the point. For example, if the rate of leaving is 100 particles per second and the rate of rejoining without stirring is 60 particles per second, the rate of dissolving is 40 particles per second. On stirring, the rate of leaving will still be 100 but the rate of joining will reduce to, say, 20. The rate of dissolving will be 80 particles per second. You may feel this is too advanced for your students. However, the idea of rejoining is not so difficult. Importantly, it counters the teleological thinking that tends to creep into explanations: particles have no intentions. Furthermore, the notion of a two-way process lays important groundwork for understanding dynamic equilibrium at a later stage.

Solubility

The basic model explains dissolving but it cannot deal with solubility. There is no simple explanation for why up to 203 g of sucrose will dissolve in 100 cm³ of water, compared to 36 g of sodium chloride and only 0.1 g of calcium hydroxide (all at room temperature). All are saturated solutions but saturation has got nothing to do with filling up spaces. Similarly, there is no simple explanation for the different effects of temperature on the solubility of different substances, with some increasing (such as potassium nitrate), some decreasing (carbon dioxide) and some almost unaffected (sodium chloride). Entropy is needed to understand solubility. However, solubility is a topic that cannot be ignored in early secondary school chemistry and this is a case where the limitations of our model should be openly acknowledged. Our model is not wrong, but other ideas are needed to tell the whole story of dissolving and this will have to wait. Meanwhile, viewing saturation in terms of equal rates of 'leaving' and 'rejoining' does accommodate the wide range in solubilities but does not explain why this arises at such different concentrations (down to effectively zero) and the differential effect of temperature.

Another aspect of solubility is the use of different solvents. For example, why will sodium chloride dissolve in water but not in propanone, whereas olive oil will dissolve in propanone but not in water? Developing the basic model with notions of different ways of holding and compatibility between ways gives some account. So, sodium chloride particles hold on to sodium chloride particles and propanone particles hold on to propanone particles, but sodium chloride and propanone particles do not have a good hold for each other and will not mix. On the other hand, sodium chloride and water particles do have a hold for each other. A general idea of types of hold prepares the ground for the more detailed look at structure and bonding covered in Chapter 3.

2.5 Evaporation into and condensation from the air

Evaporation and boiling

From everyday experience, students will know that water evaporates at temperatures well below boiling point. The basic particle model can deal with the overall disappearance – water particles become mixed in among air particles – but it cannot explain how this can happen. Moreover, to explain boiling we said particles were

energetic enough to overcome the hold and move apart. If water must be at 100°C to boil, how can particles escape from each other when less energetic at much lower temperatures? There seems to be a serious contradiction here which undermines our model rather than merely exposing its limitations as was the case with solubility. Bringing in ideas of energy distribution resolves the problem.

Temperature and energy

The idea of energy distribution is best introduced with the gas state. Without going into details of momentum, students can appreciate that energy is exchanged in collisions (snooker is a useful analogy). The total amount of energy within the sample stays the same but individual particles at any one time have different amounts of energy. We can say that temperature relates to the *average* energy of the particles. Much can be done with a simplified idea of low-, medium- and high-energy particles. At higher temperatures there are more high-energy particles and fewer low-energy particles. The same arguments apply to the liquid and solid states (energy is exchanged between neighbouring vibrating particles). It is worth emphasising that individual particles do not have a temperature in the same way that they do not have a state.

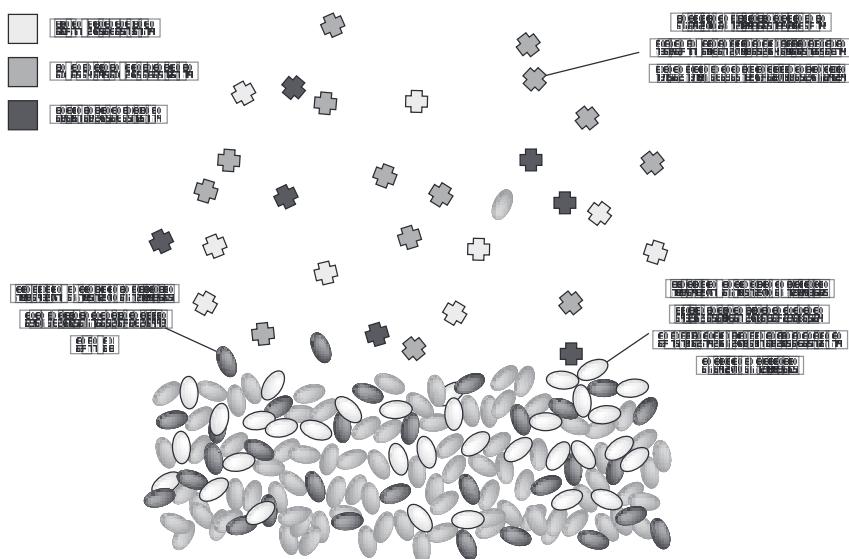
Explaining evaporation below boiling point

Evaporation is explained as follows (Figure 2.8). High-energy water particles that happen to be at the surface of the sample, and that happen to be moving in an outward direction, will be able to overcome the hold and move into the air. The escaped water particles mix with the air particles (here, we will not distinguish air itself as a mixture of substances). At the same time, high-energy air particles collide with other water particles (those of medium and low energy) at the surface. Energy is transferred in the collisions so the water particles gain enough energy to escape. In effect, the water particles are ‘knocked out’. In this way all of the water particles will eventually escape from the saucer and mix in with the air particles.

Viewing the event in terms of energy and temperature, the initial loss of high-energy water particles (that can leave on their own) will cause the temperature of the remaining sample to drop (the average energy will be lower). Energy will then transfer from the room to the remaining water in the saucer (through collisions with high-energy air particles). This helps to maintain the number of particles with enough energy to escape, and so the particles of the sample gradually disperse among the air particles. Although not as obvious as heating with a Bunsen, the room is providing the energy to maintain the evaporation of the water.

2.5 Evaporation into and condensation from the air

Figure 2.8 A particle explanation for evaporation below boiling point



Factors affecting the rate of evaporation

The model easily accounts for the effects of surface area, temperature and a breeze on the rate of evaporation. The action takes place at the surface and so with a larger surface area, more can happen at once. At higher temperatures there are more high-energy particles about. The effect of a breeze parallels the effect of stirring on dissolving. In the random movement, water particles could return. The actual rate of evaporation is the difference between the rate of leaving and rate of rejoining. A breeze sweeps away water particles, thus reducing the rate of rejoining. (Note that applying ideas of energy distribution refines our previous explanation of dissolving. Only the high-energy solvent particles 'knock' particles away from a crystal (and higher-energy crystal particles are more easily knocked out). Rate of dissolving increases with temperature because more particles have high energy.)

Reconciling boiling and evaporation

Having explained evaporation below boiling point with our developed model, we should reconsider boiling. It is worth highlighting the differences. Evaporation takes place at any temperature (between melting and boiling) and there are no bubbles. Boiling takes place at a particular temperature and there are bubbles of water in the gas state. For evaporation, the particles leave one by one from the surface to form a mixture with air particles. We

cannot see individual particles leaving and at any temperature there will be some high-energy particles for this to happen. For boiling, a bubble is a pure sample of water in the gas state that forms inside the liquid water (where it is being heated). It takes more than one particle to form a bubble. This means there have to be enough high-energy water particles able to overcome the hold at the same time. There are only enough high-energy water particles when the temperature reaches 100 °C. Our improved model gives a better account of why boiling takes place at a particular temperature and can also explain why boiling point depends on external pressure. This will be covered later in the chapter.

Condensation from a water–air mixture

The appearance of condensation on a cold object is a perplexing event for many students. They know the liquid is water, but are not sure where it comes from. Many students think the water goes straight up to the clouds after evaporating rather than occupying the air all over (most water cycle diagrams do depict it going straight up). Our explanation of evaporation shows how water particles can mix into the air and this opens up the possibility of some water particles being a normal part of air. However, a little more thinking with the model is required.

Although escaping water particles have high energy, all will not retain this status. On mixing and colliding with air particles, a distribution of energies among the water particles will re-establish. The distribution will match that of the air particles since the whole collection of particles is at one temperature. In that case, when low- and medium-energy water particles meet up (as they will through random movement) one could ask why they do not cluster together to form a droplet of water in the liquid state (they will not have enough energy to escape their hold). This could happen, but a high-energy particle (water or air – most likely air because there are more air particles than water particles) could also knock the water particles apart (as with evaporation). The outcome will depend on the relative rates or chances of the two competing processes. The chances of water droplets being broken apart will depend on the number of high-energy particles, which depends on the temperature. The chances of water particles joining will largely depend on the concentration of water, and also the temperature since this affects the proportion of low- and medium-energy particles within the concentration. In a clear air–water mixture, like normal room temperature air, the rate of breaking apart is greater than the rate of clustering and so droplets do not form. On cooling the mixture, the rate of breaking apart decreases. When the rate of

breaking goes below the rate of clustering, droplets of water will form. The temperature at which this happens will depend on the concentration of water.

In explaining the appearance of condensation, the emphasis is usually on temperature but concentration is an equally important factor. For example, when a jar is placed over a lighted candle, condensation forms despite the glass being warmed. This is because the flame gives out water and the concentration inside becomes very high. On lifting the jar the condensation quickly evaporates because the concentration falls – there is no change in temperature.

■ Could evaporation and condensation be explained without ideas of energy distribution?

If ideas of energy distribution are felt to be too intricate for some students, a simpler treatment of water–air mixtures could be given. Evaporation could be explained in terms of bombarding air particles knocking out water particles. Importantly, this explains why evaporation happens below boiling point. Water particles then become mixed with air particles, with the air particles keeping them apart. The more energy the air particles have, the better they are at keeping the water particles apart. Therefore, on cooling there comes a point when the water particles cannot be kept apart and condensation forms. How cold the mixture has to be for condensation to form depends on the concentration of water in the air: the more water, the less cold it needs to be.

2.6 More on the gas state: pressure, weight and diffusion

Our arguments for water–air mixtures also apply to pure samples of substances in the gas state. Higher-energy particles prevent lower-energy particles from clustering. Where the holding power is very weak, only the very lowest-energy particles would cluster and these are far outnumbered by the rest.

The gas state and pressure

Gas state pressure is readily tackled by the basic particle model. Bombarding particles exert a force on the walls of their container. The total force on an area depends on how strong the collisions are and the number of collisions at any one time. For a given sample of

gas, the average strength of collisions depends on the average speed, in other words, temperature. The number of collisions will depend partly on the average speed but also on the number of particles in a given volume (concentration). Therefore pressure increases by either raising the temperature or squashing to a smaller volume.

Pressure considerations could be addressed in some of the events we have looked at. For the ‘drop of water in hot syringe’ experiment, one could ask why the plunger stops moving and explain that this is when the pressure of gaseous water inside equals atmospheric pressure outside. For a beaker of boiling water, the bubbles form when there are enough high-energy particles to give a pocket of gas with a pressure equal to atmospheric pressure. From this we can predict that water will boil at a lower temperature if the external pressure is reduced. On injecting water into a syringe of ammonia, the plunger is pushed in by atmospheric pressure since the pressure inside falls as the ammonia dissolves. The classic ‘fountain experiment’ makes a suitably spectacular follow-up demonstration. (This can be found as no. 79 in *Classic Chemistry Demonstrations*, Royal Society of Chemistry, 1998.)

Mass and weight of the gas state

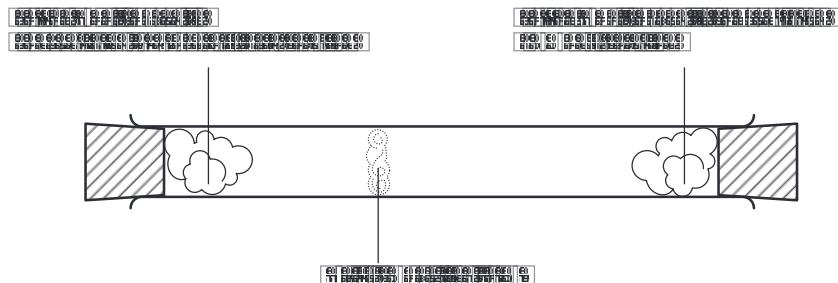
The gas state presents many challenges, not least the idea that a sample of gas has a mass and therefore a weight due to gravity. Understanding that gases are substances ought to help with the idea of having mass. The particles of a substance have mass and this does not change with a change of state. However, understanding how a sample of gas exerts a weight is not at all straightforward. Consider an absolutely empty container (strong enough to resist atmospheric pressure) standing on a balance. If air is let into the container, the balance reading increases to show the weight of the air. However, since most of the air particles are not in contact with the bottom of the container, how can this be? The explanation lies with the concentration and hence pressure gradient caused by gravity acting on the sample. The pressure acting downwards on the bottom is greater than the pressure acting upwards on the top, which gives an overall downwards force. This so happens to equal the weight of all particles. Such arguments must wait for later (perhaps in physics). We raise the issue to point out that it is not at all obvious why a sample of gas has a weight. The increase in weight when particles from the gas state end up combined in the solid state is less problematic (such as oxygen in magnesium oxide).

Diffusion involving the gas state

■ Ammonia and hydrogen chloride

Perhaps the best known diffusion experiment is that shown in Figure 2.9.

Figure 2.9
Diffusion of
ammonia and
hydrogen chloride
in air



Once solutions of gaseous solutes have been addressed, students will be in the position to appreciate that some ammonia particles escape from concentrated ammonia solution and likewise for hydrogen chloride. The appearance of the white rings shows that the respective substance particles have met and have therefore moved by themselves (making their way in among air particles). The faster progress of the ammonia particles is also evident and this could just be left as an observation. Explaining the faster movement will draw on ideas of kinetic energy ($\frac{1}{2}mv^2$). Assuming the same average kinetic energy, ammonia particles have a higher speed to compensate their smaller mass.

■ Perfume

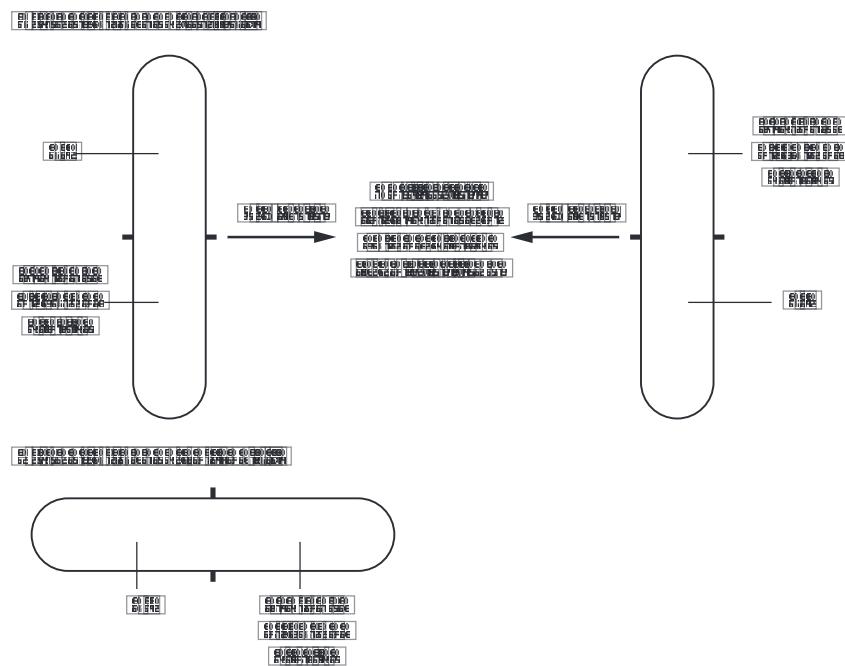
Pouring perfume or a smelly substance like propanone into a dish involves evaporation and mixing into the air. Some students think ‘smell’ is something else infusing the substance so it is important to establish smell as an interaction between particles and nose receptors which leads to a stimulation in the brain (theories suggest either through shape or vibrational frequency). Interestingly, some animals can smell carbon dioxide which enables them to catch prey in the dark. Also be aware that this demonstration gives a false impression of the rate of diffusion. Most of the spreading out is due to particles being carried by air currents rather than their individual random motion.

■ Samples of substances in the gas state

The simplest way to demonstrate diffusion in the gas state is to use substances in the gas state. Traditionally, samples are positioned in alternate vertical arrangements (Figure 2.10a). However, this adds the complication of weight and different densities. Arranging the tubes horizontally avoids the issue (Figure 2.10b).

Figure 2.10

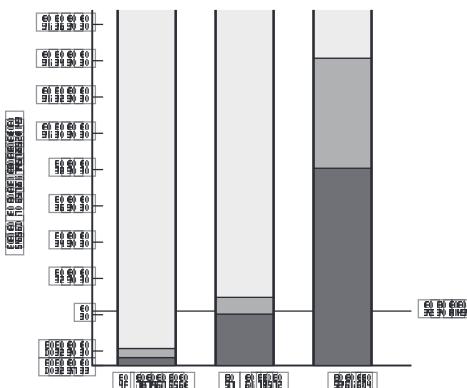
Diffusion using substances in the gas state



2.7 What, no 'solids, liquids and gases'?

Most likely, you will have been expecting to read about 'solids', 'liquids' and 'gases' in a chapter on introducing particle theory. This is the conventional approach. In fact, we have avoided all reference to 'solids', 'liquids' and 'gases' because fundamentally there are no such things. For the chemist, there are only substances and their states. The room temperature state is quite arbitrary and has no fundamental significance (Figure 2.11).

Figure 2.11
Substances and
their room
temperature states



Three types of matter?

At first sight, basing our teaching on ‘solids, liquids and gases’ seems appropriate since this reflects direct experience and is more user friendly. Classifying materials into the three categories makes a nice activity. However, this carries the danger of promoting the idea that ‘solids’, ‘liquids’ and ‘gases’ are three separate kinds of matter, akin to different species. Students could come out thinking something is either ‘a solid’, ‘a liquid’ or ‘a gas’: many do. Changes of state are then viewed as the anomalous and somewhat confusing behaviour of some substances (for example, is wax ‘a solid’ or ‘a liquid’?). Thinking of ‘gases’ as a third kind of matter preserves their mystery and inhibits the idea that gases are substances just as much as anything else.

The concept of a substance is important

By focusing on the states generically, the ‘solids, liquids and gases’ approach also ignores the concept of a substance. States do not have an identity and therefore the particles lack identity – the talk is in terms of ‘solid particles’, ‘liquid particles’ and ‘gas particles’. This suggests different types of particle, which reinforces the idea of three different kinds of matter and that particles carry the macroscopic properties – the very common misconception noted earlier.

Ignoring the concept of a substance precludes the important distinction between pure samples of substances and mixtures of substances. All ‘solids’ are treated as one and similarly ‘liquids’ and ‘gases’. In classification activities, this can lead to the very unsatisfactory situation where difficulties associated with

classifying gels and pastes are seen as limitations of the framework rather than their nature as mixtures. Strictly speaking, the idea of a state only applies to pure samples of substances and in these cases deciding which state is relatively unproblematic. Students should not be asked to do the impossible as if it were possible. The first thing a chemist wants to know about a sample of stuff is whether it is a pure sample of a substance or not. Separation techniques are so important because pure samples are wanted (well, pure enough).

Distinguishing between mixtures and substances helps explain the difference between melting and dissolving. Otherwise, if sugar solution is just ‘a liquid’, why has the sugar not melted? Similarly, there would be no differentiation between boiling and evaporation below boiling point. In the ‘solids, liquids and gases’ approach, both are treated as a change of state. However, as noted earlier, it makes no sense to say that water changes to the gas state under such different conditions. Evaporation into the air below boiling point is better viewed as a mixing phenomenon akin to dissolving.

Another limitation of the ‘solids, liquids and gases’ approach is the way it ties the strengths of forces to the state. Thus ‘solids’ have strong forces, ‘liquids’ medium forces and ‘gases’ very weak forces. Of course, this pertains if comparing different substances at, say, room temperature. However, it does not deal well with changes of state. On melting there is not a significant weakening of forces since the average distance changes little. Furthermore, oxygen in the solid state does not have stronger forces than iron in the liquid state. More insidious is encouragement of the idea that force strength is a consequence of the state (because X is a solid etc.) rather than a factor in determining the state along with particle energy. Again, ideas of three types of matter are boosted.

Introducing a ‘basic’ particle model through substances covers everything the ‘solids, liquids and gases’ approach seeks to do but avoids the problems. Scientifically, it is more accurate and coherent. As noted earlier, the concept of substance is not obvious and needs to be taught alongside particle theory in mutual support.

Identifying basic particles with the substance also lays a secure foundation for ideas of atoms. For example, when there is talk of ‘oxygen’, students must be able to distinguish between oxygen atoms and the substance oxygen (O_2) – they are quite different. (This was covered in greater depth in Chapter 1.)

Other resources



Stuff and Substance is a multimedia package developed by the Gatsby Science Enhancement Programme (SEP) which provides teaching materials to support a substance-based approach to introducing the particle theory. *Stuff and Substance: Ten Key Practicals in Chemistry* is a booklet which complements the multimedia package. It looks at how practical work can be used to support the development of key ideas. The *Stuff and Substance* materials are available online in the National STEM Centre elibrary (www.nationalstemcentre.org.uk/). Registered users of the National STEM Centre can also download the individual videos and animations.

Some articles describing the research background are:

Johnson (1998). Progression in children's understanding of a 'basic' particle theory: A longitudinal study. *International Journal of Science Education*, **20** (4), 393–412.

Johnson & Papageorgiou (2010). Rethinking the introduction of particle theory: a substance-based framework. *Journal of Research in Science Teaching*, **47** (2), 130–150.

Johnson & Tymms (2011). The emergence of a learning progression in middle school chemistry relating to the concept of a substance. *Journal of Research in Science Teaching*, **48** (8), 849–984.