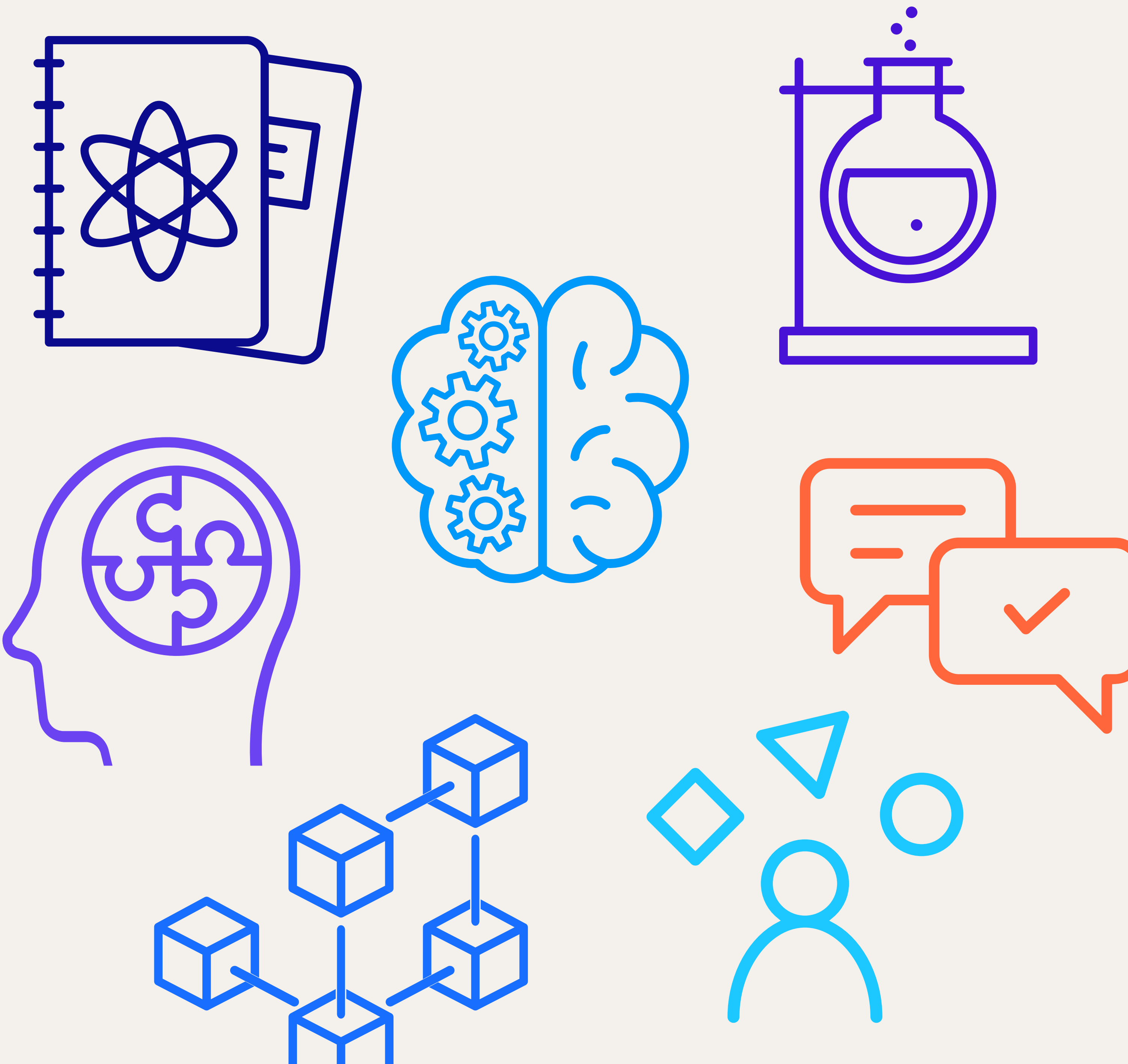
EVIDENCE FOR LEARNING

Guidance Report

Secondary

Improving secondary science



This Guidance Report is based on a report of the same name produced by the Education Endowment Foundation (EEF). The original content has been modified where appropriate for Australian context.

The authors of the original Guidance Report are Sir John Holman (University of York) and Emily Yeomans (EEF).

Australian content for this Evidence for Learning (E4L) Guidance Report was provided by Michael Rosenbrock, Susannah Schoeffel, Danielle Toon and Hannah Matthews.

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Contents

Foreword

Building a qualified Science, Technology, Engineering and Mathematics (STEM) workforce has been a priority for the Australian Government for more than ten years.[1] With globalisation and technological advances changing the nature of work, the number and variety of STEM occupations is increasing, and these skills are becoming more important to the Australian economy.

Science is a powerful lens for all students for understanding the world – from the knowledge developed by First Nations peoples for thousands of years to recent discoveries about health, wellbeing, the environment, and interconnectedness of ecosystems. But many Australian students are not confident, capable, or enthusiastic about engaging with science.

The achievement gap in science may not be as well-documented as the gap in English and maths, but it is also pervasive. International research has shown that students experiencing disadvantage start to fall behind in science in early primary school, and the gap only gets wider throughout primary and secondary school. In Australia, the science achievement level for a 15-year-old from a low socio-economic background is an average of three years below that of their classmates from more advantaged backgrounds.[2]

We've produced this Guidance Report to help science teachers and leaders to access, understand and apply the most rigorous and relevant evidence on effective science teaching. Helping schools to use evidence and to better understand the most effective ways to improve student learning in science is one of the best ways to tackle the science achievement gap.

Developed by our UK partner, the Education Endowment Foundation (EEF) and updated for Australian audiences, this report offers seven practical evidence-based recommendations that are relevant to all students, but particularly to those struggling with science. The recommendations are based on the best available international research and informed by experts in secondary science teaching.

Much of what we have to say — about literacy, memory, and feedback, for example — is applicable to teaching in many subjects. But in this report, we have set the guidance in the context of secondary science and drawn all our examples from it.

Of course, this guide on its own will not create better outcomes for students in science. It is only when the research knowledge summarised in this guide is combined with local data on students' needs and teachers' professional expertise that students in classrooms will benefit.

We hope that you will appreciate our contribution to the shared endeavour of improving student outcomes in science throughout Australia.

The Evidence for Learning team

Introduction

Who is this guide for?

This Guidance Report is for secondary science teachers, heads of science departments, and senior leaders. The recommendations are designed to be actionable by classroom teachers, but there is benefit in teachers coming together as a department to think about how it applies in their context.

What does this guide cover?

This report is relevant to the teaching of science in secondary school. We have focussed on the seven areas where the evidence provides the strongest steer about how to enhance the teaching of science to students in this age group and have provided examples of how to apply the recommendations in practice. Each recommendation provides a 'first stop for further reading' for teachers who want to find out more about the evidence underpinning the recommendations. In addition to the seven areas, we provide guidance on the overarching theme of teaching for engagement, something which is particularly important for science education.

Research in science education has a strong history in areas such as teaching difficult ideas in science, language in science lessons, how students represent their scientific understanding, and ways of engaging students with what they are learning in their lessons. However, there are also important messages from research about learning more generally, such as in the area of memory and strategies for improving metacognition and self-regulated learning.

Evidence-informed science teaching is not about fitting more into a tight timetable: it's about using limited time and resources as smartly as possible, by focusing on what is most likely to have a positive impact. Many of the suggestions in this guidance report will be familiar to you from your own experience and practice.

We have used the research evidence to show how some of the things you already do can be as effective as possible, as well as some ideas which may be new to your practice. Take practical work, for example. Many of your lessons will involve practicals: in this report we summarise what the research says about how to get the most out of your lab time by being clear about its purpose and sequencing it with other learning activities.

This resource can be used to support educators to develop aspects of their practice that relate to the following **Australian Professional Standards for Teachers**[3]:

2. Know the content and how to teach it
3. Plan for and implement effective teaching and learning
5. Assess, provide feedback and report on student learning

Teaching for engagement

Good teaching begins with gaining students' engagement and winning their commitment to learn. Science teaching is not just about getting good results in senior secondary sciences, important though that is; every secondary teacher knows the deep satisfaction that comes from lighting the fires of interest in young people and stimulating them to take a particular subject further. A considerable body of evidence now identifies the quality of teaching as a major determinant of student engagement and success.[4] Effective science teaching improves both achievement and engagement, and all the recommendations in this report should therefore support positive attitudes to science.

But there is an engagement problem in science – many students feel that science is 'important, but not for me'.[5,6] They know science is powerful, but they do not see its relevance to their lives, and they don't believe that 'people like them' go on to study science. This is an issue that starts young and worsens through schooling, with attitudes declining from the age of five onwards;[7] interest in pursuing further study in science is largely formed by the age of 14.[8]

A major study of attitudes towards science (ASPIRES) has shown that students who aspire to study science subjects are more likely to have high levels of 'science capital'.[9] There are eight key dimensions of science capital—these include a student's science-related attitudes, their knowledge about the transferability of science, their participation in out-of-school science contexts, and the science skills and qualifications of their family.[10] Knowledge about the features that lead to high engagement with science has led to the development of a 'Science Capital Teaching Approach'.[11] This approach has promising evidence suggesting it leads to more students being interested in studying science at senior secondary levels.[12]

So an important part of science teaching is to make students feel that science is something they can achieve in, whatever their background. As a science teacher, you have two big advantages. The first is that science is a practical subject. When students are asked what made school science enjoyable, the leading reasons turned out to be having a good teacher and enjoying practical work.[13]

The second advantage is the ease with which you can make links to issues that matter, and are of interest, to students. A major international review of research evidence showed that school science courses that emphasise links between science and everyday life foster more positive attitudes to the subject and to school science.[14]

Science is often perceived to be harder than other subjects and this perception has been found to be a determinant of subject choice,[15] but science qualifications open the door to many rewarding careers, which can be motivating for students. Science lessons are the starting point for making links between what is being taught and future careers—the examples are numerous: radiography technician (physics), food analyst (chemistry), conservationist (biology), and so on. There is evidence from the US that this approach can impact on academic outcomes.[16]

Science teachers can be powerful role models too, attracting students towards their subject and the careers that flow from it. Providing role models of people studying science[17] or working in science[18] enables students to develop a 'science identity' and to see themselves as possibly studying STEM subjects at university or following a different technical route to a career. Creating excitement, motivation, and better career pathways for STEM is a national priority. In 2015, all Australian education ministers agreed to the National STEM School Education Strategy 2016–2026, which aims to coordinate current activities, and improve STEM education.[19]

> *"Science qualifications open the door to many rewarding careers and this can be motivating for students"*

Incorporating First Nations scientific knowledge

First Nations Peoples have worked scientifically for millennia and continue to contribute to contemporary science.

The Australian Professional Standards for Teachers and the Australian Curriculum expect that Australian teachers support First Nations students so that they are able to see themselves, their identities and their cultures reflected in the curriculum, and are able to and incorporate Aboriginal and Torres Strait Islander Histories and Cultures as a cross-curriculum priority for all students.[3,20]

The Australian Institute of Aboriginal and Torres Strait Islander Studies (AIATSIS) has developed a Guide to evaluating and selecting education resources[21] that supports educators to make conscious and critical decisions when selecting curriculum resources, to ensure they reflect all children, including First Nations students, and cause no harm.[22]

A number of organisations provide guidance and resources to assist in incorporating Indigenous perspectives into the science curriculum, including:

- The Australian Curriculum Assessment and Reporting Authority (ACARA) Australian Curriculum resources include Aboriginal and Torres Strait Islander Histories and Cultures[23] and Illustrations of practice[24]
- Melbourne University's Indigenous Knowledge Institute[25]
- The Australian Council of Deans of Science (ACDS) Indigenous Science resource[26]
- Narragunnawali Subject Guides[27]
- CSIRO's Indigenous STEM Education Project focussed on the link between the traditional ecological knowledge of Australia's First Nations Peoples and the science curriculum and how it can be taught[28] and includes stories of those impacted by the project[29] as well as Science Pathways for Indigenous Communities resources.[30]

If you are working with First Nations people and organisations on science curriculum and projects, you may wish to refer to Social Ventures Australia's First Nations Practice Principles to ensure the collaboration supports self-determination, diversity, real partnership and is trauma-aware.[31]

Summary of recommendations

1
Preconceptions:
Build on the ideas that students bring to lessons

- Understand the preconceptions that students bring to science lessons
- Develop students' thinking through cognitive conflict and discussion
- Allow enough time to challenge misconceptions and change thinking

See page 8

2
Self-regulation:
Help students direct their own learning

- Explicitly teach students how to plan, monitor, and evaluate their learning
- Model your own thinking to help students develop their metacognitive and cognitive knowledge
- Promote metacognitive talk and dialogue in the classroom

See page 14

3
Modelling:
Use models to support understanding

- Use models to help students develop a deeper understanding of scientific concepts
- Select the models you use with care
- Explicitly teach students about models and encourage students to critique them

See page 20

See also: Teaching

4

Memory: Support students to retain and retrieve knowledge

- Pay attention to cognitive load—structure tasks to limit the amount of new information students need to process
- Revisit knowledge after a gap to help students retain it in their long-term memory
- Provide opportunities for students to retrieve the knowledge that they have previously learnt
- Encourage students to elaborate on what they have learnt

See page 25

5

Practical Work: Use practical work purposefully and as part of a learning sequence

- Know the purpose of each practical activity
- Sequence practical activities with other learning
- Use practical work to develop scientific reasoning
- Use a variety of approaches to practical science

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6

Language of Science: Develop scientific vocabulary and support students to read and write about science

- Carefully select the vocabulary to teach and focus on the most challenging words
- Show the links between words and their composite parts
- Use activities to engage students with reading scientific text and help them to comprehend it
- Support students to develop their scientific writing skills

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7

Feedback: Use structured feedback to move on students' thinking

- Find out what your students understand
- Think about what you're providing feedback on
- Provide feedback as comments rather than marks
- Make sure students can respond to your feedback

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g for engagement

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1 Preconceptions: Build on the ideas that students bring to lessons

Evidence summary

This is a well-researched field and there is strong evidence that learning is more effective when students' prior knowledge is taken into account. In particular, evidence suggests that:

- students construct their own explanations for phenomena and these ideas may differ from scientific explanations—there are common misconceptions in science and there is research to suggest what these are;
- cognitive conflict is an effective way of moving on students' thinking, helping them to reconstruct their existing ideas; and
- misconceptions can be difficult to shift, but doing so can lead to big gains in learning, particularly for threshold concepts.

Science is about how the world works and long before children start a formal education in science, they build their own understanding about the phenomena that they meet on a daily basis. These **preconceptions** are built through sensory experiences and social interaction.[32] These self-constructed ideas may or may not align with scientific understanding and, if they do not, are called misconceptions or alternative conceptions.* Students usually need to go through a process of adjusting their ideas, or even replacing them with more scientifically correct ones.

> *"Students usually need to go through a process of adjusting their ideas, or even replacing them with more scientifically correct ones"*

The process of students adapting and refining their theories is akin to the process of scientific discovery itself. Think of how the theory of relativity built on and refined Newton's classical mechanics. There is much that we can learn from the process of scientific discovery when dealing with students' preconceptions:

- Preconceptions are part of the history of science, and we all have them. The key thing is to be aware of the preconceptions that your students are likely to hold and to know how to build on them.
- To adjust their misconceptions, students need to see compelling evidence that helps them to change their thinking and accept the new conception.
- Changing thinking takes time and students need to revisit ideas and be shown different examples to develop their thinking.

It is common for adults to hold misconceptions, as well as children and young people. Students need to feel comfortable to share their ideas so you can build on their thinking. Creating an environment where ideas can be openly shared fosters inclusion, relevance, and models for students the nature of science – whereby knowledge is developed from evidence and can change over time in response to new evidence or more effective explanations.

*The terms 'alternative conceptions' or 'alternate conceptions' are emerging language used in place of the term 'misconceptions'. However, as the term 'misconceptions' is most familiar to teachers and is widely used in existing resources it will be used throughout this report.

Box 1: Online sources of information on common misconceptions

- STEM Learning's Understanding misconceptions[33]
- The Royal Society of Chemistry's Chemistry Misconceptions website[34]
- The Institute of Physics IOPSpark: Misconceptions website[35]
- American Association for the Advancement of Science Project 2061 Project 2061: Some Things Middle and High School Students Know and Misconceptions They Hold[36]
- Harvard-Smithsonian Center for Astrophysics MOSART: Student Misconceptions[37]
- Deakin University's Ideas for Teaching Science: Years 5-10[38] includes details of common alternate conceptions for a range of topics

Understand the preconceptions that students bring to science lessons

First, find out what your students' preconceptions are. Well known misconceptions are a useful place to start; Box 1 contains some places that you can find information on common misconceptions. However, they may not be the preconceptions held by your class and it is important to get students' ideas into the open quickly at the start of a topic. You can then use the information to judge how best to approach the topic. It is useful for your students themselves to be aware of the ideas they hold so they can compare them with the scientific explanations you are teaching.

There are different ways to make students' thinking explicit and two routes are explored in Box 2.

Box 2: Helping students to make their thinking explicit

Diagnostic questions

These are multiple choice questions with the incorrect options (the distractors) carefully designed to uncover common misconceptions. Below is an example question from the U.S. AAAS Assessment bank[39]

> *Which of the following parts of an animal's body are made of cells?*
>
> A. *The muscles, but not the brain*
>
> B. *The brain, but not the muscles*
>
> C. *Both the muscles and brain*
>
> D. *Neither the brain nor the muscles*

The correct answer to this question is C: the other answers demonstrate the misconception that some living parts of organisms are not made of cells.

Such questions can be usefully employed at 'hinge points' in your teaching, helping to inform where teaching should go next.[40] A good source of diagnostic questions is Best Evidence Science Teaching (BEST) [41]

Class and small group discussions

Misconceptions can be uncovered through dialogue, and it is often useful to use concept cartoons as a basis for discussion (more information on these can be found in the self-regulation section of this report – see recommendation 2). Another approach is to get students in groups to write down, draw or discuss what they know about a topic. At the start of the topic study, all answers are acceptable. A list of their ideas can be kept throughout the topic and revisited to show students how their thinking has changed over the course of several lessons.

Develop students' thinking through cognitive conflict and discussion

Once you have identified their preconceptions, you can begin to help students develop their thinking. A useful way to develop thinking is to provide evidence that may conflict with students' currently held ideas.[42]

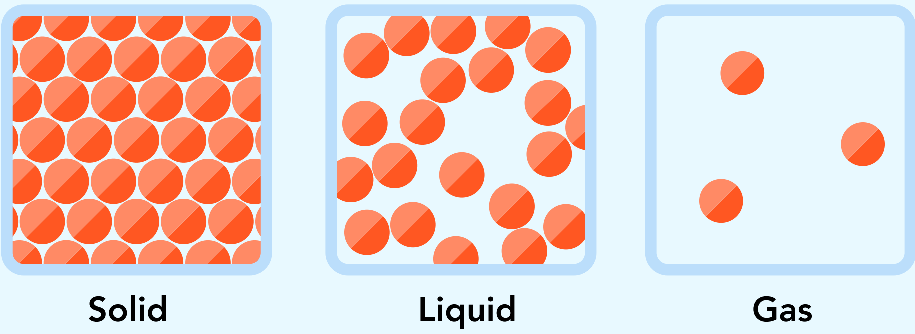
One way of achieving this is to introduce cognitive conflict into lessons.[43,44] This has been widely tested as part of the Cognitive Acceleration through Science Education (CASE) program.[45, 46] As part of CASE lessons, students make unexpected observations which challenge their misconceptions and require them to restructure their way of thinking to accommodate this new evidence. They are then supported, by the teacher and their peers, to work through the problem and resolve the cognitive conflict. By doing this, students develop new learning strategies and knowledge that they can then apply to other contexts.

An example of cognitive conflict may be found in Box 3.

Box 3: Example of cognitive conflict

Teaching about the particle model of gases

Adapted from Burrows et al., (2017 p. 47)[47]



One of the key things that students need to know about gases is that there is empty space (a vacuum) between the particles.

These ideas can, however, conflict with students' preconceptions. Even if students know that the particles in a gas have gaps between them, they often think that the space between them is full of other things such as bacteria, pollutants, or oxygen.

One way to create cognitive conflict in this case is to show that air in a blocked syringe can be compressed into a smaller volume (for example using a 100cm^3 syringe and showing that the air can be compressed to 50cm^3), but that a liquid and a solid cannot. This provides students with a situation that cannot be explained without a vacuum between particles and means that they will need to adjust their ideas to accommodate this new situation.

Students can work in groups to come up with models of how the particles in air are arranged to allow this compression to happen. This could be done through drawing, allowing a class discussion about the different models proposed by students. The understanding can be extended by asking if they think a gas could ever be compressed to zero volume.

Allow enough time to challenge misconceptions and change thinking

Throughout teaching sequences, it is useful to revisit misconceptions and remind students of what they thought at the beginning, getting them to revisit these early ideas and acknowledge any changes in their thinking. Some misconceptions can take time to shift, so it is important to use formative assessment to check that thinking has changed in the long-term.

Many misconceptions link to **threshold concepts**. These are transformative to the way students think and, although they are difficult,[48] once you have mastered them you are unlikely to go back. Evolution is an example of a threshold concept; as is the particle theory of matter, which opens the door to all of chemistry. It is worth persevering with threshold concepts because they are so fundamental to other understanding.

Meyer and Land offer a number of characteristics of threshold concepts.[49] They are likely to be:

- *transformative* – they result in a change in perception of a subject and may involve a shift in values or attitudes;
- *irreversible* – the resulting change is unlikely to be forgotten;
- *integrative* – they 'expose a previously hidden interrelatedness' between other concepts within the discipline, as evolution does for biology;
- *potentially troublesome* – students may have difficulty coping with the new perspective that is offered; and
- *bounded* – once learnt, students identify these concepts as specific to a particular discipline (evolution to biology, particle theory to chemistry).

Turn on the RADAAR for misconceptions[50]

The RADAAR planning framework is designed to help teachers to plan around misconceptions, based around a 3-step (cyclical) process.

It prompts us to **Research** and **Anticipate** misconceptions before teaching a topic. What are the key ideas and misconceptions, what language do we need to be careful about, and what have students learned about previously that will help them build their understanding in this topic?

The next stage is to **Diagnose** and **Address** those misconceptions that our students hold. This is the bread-and-butter of teaching: finding out what our students think, then building on these ideas.

Finally, we need to **Assess** and **Review** ideas later. We can't assume that ideas will 'stick' forever, or that our students will understand how they link to other things they learn. We need to help students to review their understanding of key concepts, and explicitly prompt them to make links between ideas.

The process repeats and is cyclical. The ideas from this topic will be the building blocks for others in the future. As teachers, we have an overview of our subjects, and can take this into account as we plan.

Research Anticipate

Key concepts and common misconceptions

- What are the prerequisite ideas that must be understood to access this topic?
- What are the most common misconceptions for this topic?
- Can you consult collections of common misconceptions or draw on your own, or colleagues' experience?

Language and vocabulary

- What is the key vocabulary for this unit?
- Is there any potentially confusing language you should avoid, such as key words that are also used in a non-scientific context?
- Which words do you have to be particularly precise about, because they're commonly misused, or used in the wrong context?

Links to previous topics

- Which ideas from previous topics link directly to this one, and how will you explicitly link to them?
- Have you encountered any common misconceptions from this topic in previous ones? How will you revisit and build on this?
- How will you activate prior knowledge?

Diagnose Address

Uncover and diagnose

- How will you uncover the misconceptions that students hold?
- Which plausible answers and misconceptions could you use as distractors in diagnostic questions?
- Could you use prompts, such as concept cartoons, to stimulate discussion, and how will you keep talk focussed and productive?

Activities

- How can you build on the ideas that students bring with them?
- How might you help students confront their misunderstandings and misconceptions?
- When might you simply present correct ideas alongside wrong ones, and when could you stimulate cognitive conflict?

Assess Review

Assess and review

- When and how will you revisit the key concepts and misconceptions from this topic?
- Where can concepts and ideas from this topic be reviewed and referred to in future topics?
- How could you assess understanding of the most common misconceptions in future assessments?

Links to future topics

- Which ideas from future topics relate directly to this one, and how will you explicitly link to them?
- Which future concepts build on those from this topic, and how will you help students to understand these connections?
- Which future ideas would be directly affected by misconceptions from this topic, and when will you review them?

- Do you need to re- teach anything?
- Is there any key vocabulary you need to revisit and reinforce?
- Are there any concepts that haven't quite stuck?

First stop for further reading

Dawson, V. Venville, G. and Donovan, J. (2019) .The Art of Teaching Science. London: Routledge[51]

Treagust, D.F. (2012). Diagnostic assessment in science as a means to improving teaching, learning and retention[52]

Driver, R., Squires, A., Rushworth, P. and Wood-Robinson, V. (2014). Making sense of Secondary Science: Research Into Children's Ideas. London: Routledge.[32]

2 Self-regulation: Help students direct their own learning

Evidence summary

Several large correlational studies show strong links between self-regulation and achievement in science. In addition, there are intervention studies, testing the impact of programs aimed at improving self-regulation, which show improvements in science outcomes. Evidence also suggests that:

- students with low prior achievement benefit more than those with high prior achievement, so explicitly teaching these strategies may help to close the achievement gap;
- self-regulation skills need to be developed within the context of learning a subject; and
- specific strategies to develop these skills in science lessons include modelling your own thinking to students and engaging students in metacognitive talk.

The ability of students to direct their own learning is often called 'self-regulation' and includes three parts:

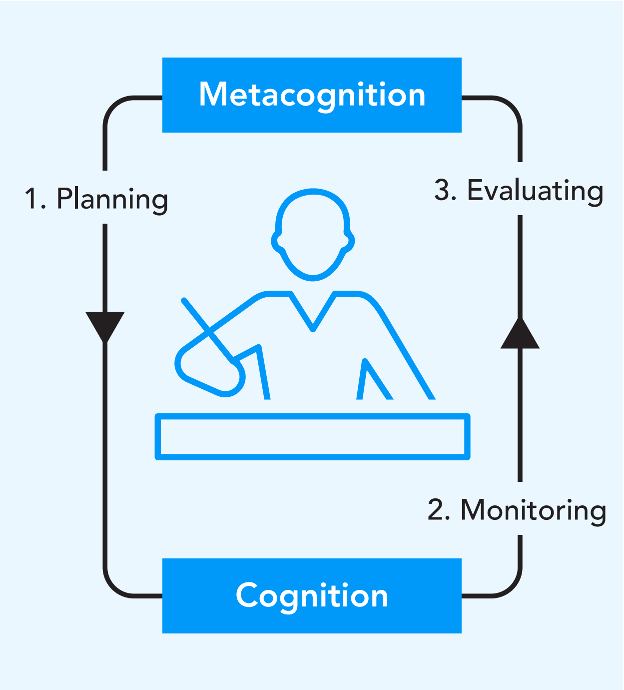
- **cognition**–students' understanding about strategies they can use to learn, for example, strategies for solving equations or planning controlled experiments;
- **metacognition**–students being able to monitor and purposefully direct their learning, for example, checking that the cognitive strategies they have chosen for solving an equation are helping; and
- **motivation**–students' motivation to learn, including their self-beliefs and interest in topics; for example, students motivating themselves to undertake a challenging task for homework.

Although skills such as monitoring learning may seem like generic skills, it is important to develop them within the context of learning a specific subject. It is often supposed that these skills will be naturally developed by students, but the reality is that explicit instruction is needed and that this may be particularly beneficial for low-achieving students. This section contains specific pedagogies that will help to develop metacognitive skills within science lessons.

Explicitly teach students how to plan, monitor, and evaluate their learning

Metacognition is not just 'thinking about one's thinking', but also monitoring one's learning and, importantly, making changes to one's approach to a task as a result of the monitoring. Encourage students to engage in the Planning-Monitoring-Evaluation cycle (Figure 1) as part of science lessons.

Figure 1: The metacognitive regulation cycle



This is a cycle rather than a one-off process. As students progress through a task, they may need to go through the cycle more than once to complete the task fully. In expert learners, these processes become unconscious and automatic. In novice learners, however, it is valuable to make them explicit.

Metacognition needs to be embedded within a specific task rather than addressed in abstract. The task starts with students accessing their existing metacognitive knowledge, including about their own abilities, the strategies they could use, and their knowledge about this type of task. During the task itself they engage in the planning, monitoring, and evaluation cycle, which then updates their metacognitive knowledge for tackling similar tasks in the future.

> *"Metacognition is not just 'thinking about one's thinking', but also monitoring one's learning and, importantly, making changes"*

Take as an example the task in Box 4. The teacher has set a clear learning goal. Students then begin the planning phase to decide how they will achieve the goal. At this stage it is helpful for teachers to encourage students to ask questions that activate their prior knowledge of plant growth as well as the process of designing a successful experiment such as, *'Are there any strategies that I have used before that might be useful?'*, or *'How will I ensure that I only change one factor at a time?'*. Depending on the ability of students to work in this way, these questions may have to be approached as a class or in groups, with teachers suggesting suitable strategies that may be helpful.

During the monitoring phase of the cycle, students will be following their plans: *'Are the strategies I've chosen working?'*; *'Am I really only changing one thing at a time?'*. They will also monitor and update their prior knowledge of plant growth. If students are not practised in this approach you may have to prompt them to monitor and provide dedicated breaks in activity to ensure monitoring happens.

During the evaluation phase, students determine how successful the strategy they used was in helping them to achieve the learning goal. *'What went well?', 'What didn't go well?', 'What could I do differently next time I have to plan an experiment?', 'What have I learnt about plant growth?'*. Again, students less practised in the approach may need your guidance.

Box 4: Using a task to develop metacognition

Design an experiment to find out the effect of an abiotic factor on plant growth.

You will be given some seedlings. Choose a factor to test on the growth of the seedlings (for example, amount of sunlight, amount of water, or different mineral solutions added to the soil). Design an experiment to find out the effect that the factor has on plant growth.

Model your thinking to help students develop metacognitive and cognitive knowledge

Show your students how you think. You can provide a useful example for students by making your thinking processes explicit.[44] You can do this by working through problems in front of a class, talking through how you are approaching the problem, the kinds of strategies you are trying and why you've chosen them, and how you are monitoring if they are successful. You can do this with problems that you have seen before, but it is often useful to do it with problems you haven't seen, to provide students with a live example of how to approach a new problem.

This approach is particularly useful when students first approach a new problem or way of thinking, however it is important to encourage students to become increasingly independent over time. Introduce some 'deliberate difficulty'[53] so that students must think for themselves at points and reflect on their learning.

The ‘FAME’ approach to maximising the effectiveness of worked examples.[54]

Worked examples can help students develop confidence, knowledge and understanding[55] in the science classroom. They are a form of modelling, providing students with a step-by-step demonstration that makes clear the required solution and the process of completing the task. Research suggests that (when the strategy is new to students) two or three worked examples often provide a greater benefit than one alone.[56] There are a few simple strategies that can be used to help optimise the effectiveness of worked examples, which can be remembered using the handy acronym FAME.

Fading: Once students have experienced complete worked examples, scaffolding can be reduced as they move towards independence. Research suggests that removing the steps in the solution in reverse order provides greater support for novice learners.[57]

Alternating: Alternate worked examples with opportunities for learners to complete a similar problem using an ‘I do, you do’ approach. This allows students to develop expertise before a new process or variation is introduced.

Mistakes: Including mistakes in worked examples can provide further challenge. Supporting learners to explain why incorrect solutions are wrong can help students to develop deeper understanding than if they solely consider correct solutions. Wrong worked examples should clearly be signposted as such and should only be used once students have developed competence.

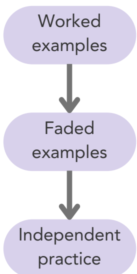
Explanation: To help learners understand how and why the worked example has been used, teachers should model their thinking using a ‘Think Aloud’ process.[58] Make your thoughts and procedures clear; what is the question asking? What are you doing? How are you doing it? Why that way? Have you experienced similar problems before? How is this different? Learners should also be encouraged to reflect on the worked example and explain to themselves why each step has been used, helping them make sense of the modelled solution.

F FADING

Fading describes the process of gradually reducing and removing elements of full worked examples.

Research suggests that removing the steps in the solution in reverse order (backwards fading) provides greater support for novice students.

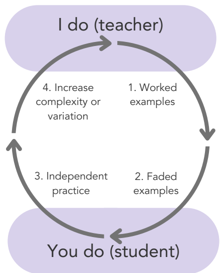
An awareness of the prior knowledge of your students is vital; removing the scaffold too quickly or providing it when it’s no longer needed, can hinder learning.



A ALTERNATION

Rather than using a collection of worked examples together at the beginning of a lesson, alternate these with opportunities for students to complete a similar problem using an ‘I do, you do’ format.

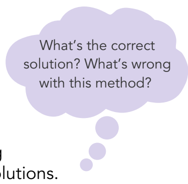
Once they have developed confidence, add variation or additional complexity to the examples, then repeat the cycle.



M MISTAKES

Once students have developed a good understanding of the topic, including mistakes in the worked examples can provide further challenge.

Supporting students to explain why incorrect solutions are wrong can help them to develop a deeper understanding than when they solely consider correct solutions.

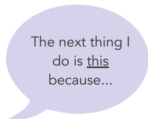


An awareness of the confidence and competency of your students is vital. Introducing incorrect worked examples too early can embed misconceptions.

E EXPLANATION

To help students understand how and why the worked example has been used, initially, teachers should model their thinking using a ‘Think Aloud’ process.

This can involve completing the worked example verbally, describing how and why they are tackling each stage of the problem.



Students should also be encouraged to reflect on the worked example and explain to themselves why each step has been used, helping them make sense of the modelled solution. Explanation prompts or peer-to-peer explanation can facilitate this.

Promote metacognitive talk and dialogue in the classroom

Discussion requires careful structuring and students need explicit instruction on how to have effective group discussions.[59] One way of doing this is to set out ground rules for the group. The example in Box 5 has rules that have been found to impact positively on reasoned argument.

Argumentation is a specific form of dialogue that can help students make reasoned claims that are backed by evidence.[60] This helps them to understand the power and limitation of scientific knowledge, showing not only *what* we know but *how* we know.

One way to promote argumentation is to help students to move from weaker arguments—which use minimal data and warrants (statements that link data to claims)—to stronger arguments that include greater use of data and rebuttals of counter arguments (see Box 6 for examples of weak and strong arguments).

It is helpful to discuss wrong ideas and why they're wrong, as well as why the right idea is right, and this helps students to examine their preconceptions – see also recommendation 1.

Evidence also suggests that group discussions work better when a stimulus is used to present a diversity of views.[59] One way of stimulating students to explore different ideas is to use 'talking heads' items (see Figure 2). The groups can use the 'talking heads' to answer a variety of questions, including:

- who has the right idea, who has the wrong idea?
- who gives the best scientific explanation?
- who is talking about data, who is giving an explanation?
- who is using evidence, who is expressing an opinion?

Box 5: Group rules

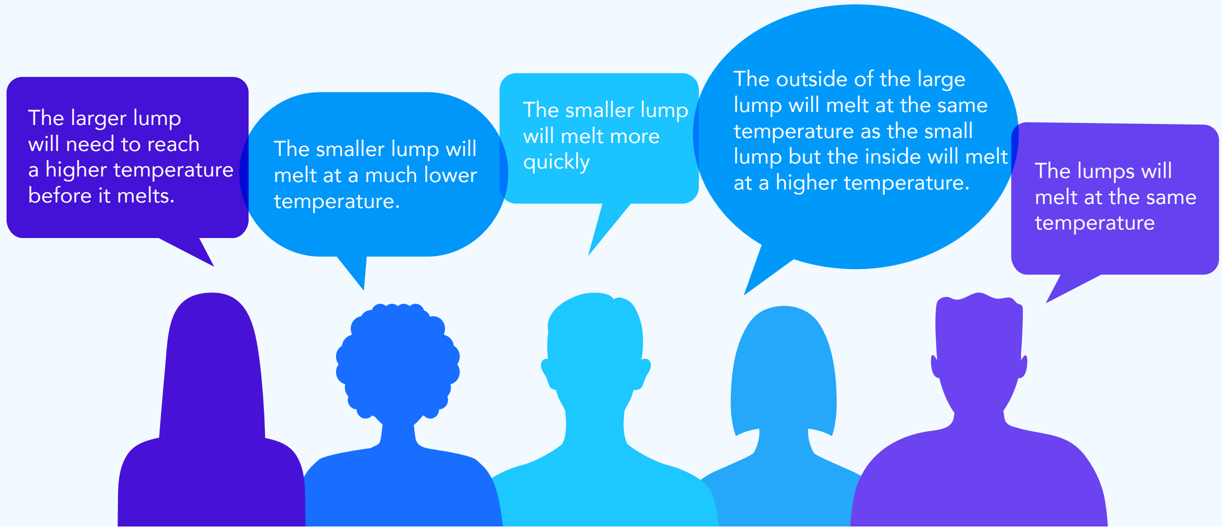
Adapted from Mercer et al., 2004.[61]

- All group members must contribute; no one member should say too much or too little. Team members should encourage those who are saying less;
- Every contribution should be treated with respect, listened to thoughtfully, and allowed to finish;
- Each group much achieve consensus by the end of the activity, and you may need to resolve differences; and
- Every suggestion a member makes has to be justified—say what you think and why you think it.

Figure 2: 'Talking heads' to encourage exploratory talk

Adapted from BEST science project[41]

Question: What do you think will happen when two pieces of differently sized wax are melted?



Box 6: Weak and strong arguments

Adapted from Osborne et al., 2004.[60]

Weak argument

We must see because light enters the eye [claim]. You need light to see [data]. After all, otherwise we would be able to see in the dark [warrant].

Stronger argument

Seeing because light enters the eye makes more sense [claim]. We can't see when there is no light at all [data]. If something was coming out of our eyes, we should always be able to see even in the pitch dark [rebuttal]. Sunglasses stop something coming in, not something going out [data]. The only reason you have to look towards something to see it is because you need to catch the light coming from that direction [rebuttal]. The eye is rather like a camera with a light-sensitive coating at the back, which picks up light coming in, not something going out [warrant].

First stop for further reading

Evidence for Learning's Metacognition and self-regulated learning guidance report[58]

Science of Learning Research Centre (SLRC) PEN Principles[62] provide resources drawing together research from psychology, education and neuroscience that are designed to help teachers use the science of learning to inform their practice.

3 Modelling: Use models to support understanding

Evidence summary

Research shows that modelling is widespread in science teaching. The focus of studies tends to be on how to optimise the use of models rather than on the value of models themselves. Evidence suggests that:

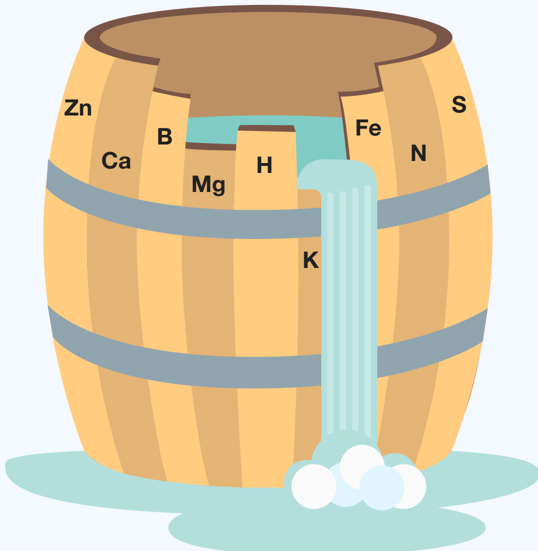
- the ideas that models are based on should be familiar to students, as otherwise this can confuse them further; and
- it is important that students understand how models differ from the idea being taught and learn the underlying idea rather than the model.

Models are an essential part of developing and sharing scientific knowledge and they have been around for as long as scientists have been explaining their ideas to one another (Figure 3). Models are critical as science often involves working with phenomena and concepts that are inaccessible to our everyday senses. Reality is complicated and models can help to simplify things and make them easier to manage and understand.

Effective teachers use models all the time to provide a bridge between students' current ideas and new understanding. Models are ways of thinking about the 'real thing', and there are many kinds (see Box 7). By being explicit about models, you can help your students understand their own thinking. By inviting them to comment on and identify the limitations of models they can gain extra insights.

Figure 3: The barrel analogy for limiting factors

Justus von Leibig (1803–1873) used the barrel analogy to explain the effect of limiting nutrients on plant growth. The height of the water represents plant growth and each of the wooden staves represents one of the nutrients that the plant needs to grow. In this example, the growth rate is being limited by potassium, K.



Box 7: Models that teachers often use

Models that teachers often use include:

- *three dimensional models* – for example, a plastic ball-and-stick model of an organic molecule, or a coloured plastic model of the human circulatory system;
- *verbal and written models* – for example, analogies such as the water flow analogy for electric current;
- *mathematical models* – for example, equations of motion and chemical formulae;
- *visuals* – such as graphs, diagrams, and animations; and
- *computer models* – such as simulations of population growth.

Use models to help students develop a deeper understanding of scientific concepts

Scientific knowledge is difficult to learn because we are constantly moving between observations we can make with our senses, the explanations for observations, and the symbolic representation of these explanations. You can use models to link observations to explanations and representations.

The idea of three levels of scientific knowledge was first developed by Alex Johnstone,[63,64] who initially used it to explain the three levels of chemical knowledge. Figure 4 shows Johnstone's Triangle.

Johnstone's Triangle can be expanded to include all science learning. In physics, the three levels might be 'the macro' (for example, physical objects), 'the invisible' (such as forces, reactions, and electrons), and 'the symbolic' (formulae). In biology the three levels might be 'the macro' (for example, plants or animals), 'the micro' (such as cells), and 'the biochemical' (for example, DNA).

Each of these levels helps create an individual's understanding of a phenomenon, and expert scientists will build understanding that blends the three levels. Students, however, often operate at the macroscopic level and find it hard to relate their experiences of the phenomenon to the sub-microscopic and symbolic levels – particularly as they can't observe these two levels. Models help students to link observations to the sub-microscopic and symbolic levels and to build a richer understanding.

Figure 4: Johnstone's Triangle – for the three levels of chemistry knowledge

The three levels of description are:

- the **macroscopic** – including descriptive knowledge as acquired through experience, either directly (through our senses) or indirectly (through measurement), for example:

  Natural gas burns in the presence of air and can be used to warm things up;

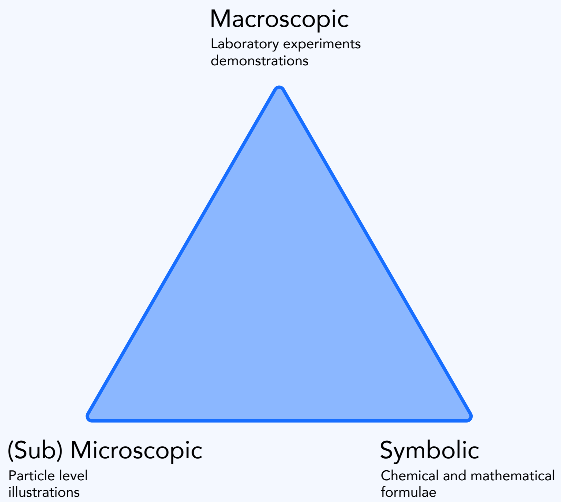
- the **sub-microscopic** – including the explanatory models that scientists have developed to make sense of observations at the macroscopic level; we can't directly observe things at this level. For example:

  Natural gas is mainly composed of methane, a chemical compound that undergoes a combustion reaction with oxygen in the air, producing two new substances, carbon dioxide and water, and releasing energy as heat and light;

  and

- the **symbolic** – including chemical symbols, formulas, and mathematical equations:

  CH4 + 2O2 à CO2 + 2H2O + energy



Select the models you use with care

As a science teacher you have many models in your repertoire. Models should only be used if they aid understanding—and there are plenty of concepts that can be taught without the use of models.

Think about the models that you are going to use before, during, and following lessons. A useful way of doing this is the Focus, Action and Reflection (FAR) approach (Box 8).

Make sure students are familiar with the underlying idea that the intended model is based on. If the model is just as unfamiliar as the new concept being taught, the model may hinder rather than help teaching.

Box 8: The FAR approach to using models

Focus (before lesson)	
Concept that will be taught during the lesson	Is it a difficult, unfamiliar, or abstract concept or process?
Students	What ideas do students already know about the concept or process that the model will be describing?
Model	Is the model itself something that students are familiar with? (For example, if using water flow to model electric current, do students know about turbines and water pumps?).

Action (during lesson)	
Discuss	Discuss the features of the science concept and the model.
Likes	Draw similarities between the concept and the model. (For example, the atom is like the solar system model in that the nucleus and the sun are both at the centre).
Unlikes	Discuss where the model is different from the concept. (For example, the atom is unlike the solar system model in that electrons are all the same size and planets differ in size).

Reflection (after lesson)	
Conclusions	Was the model clear and useful, or confusing?
Improvements	How could the model be improved for future use? Does the class need to revisit the idea?

Adapted from Treagust et al., 1998[65] and Harrison & Treagust, 2000[66]

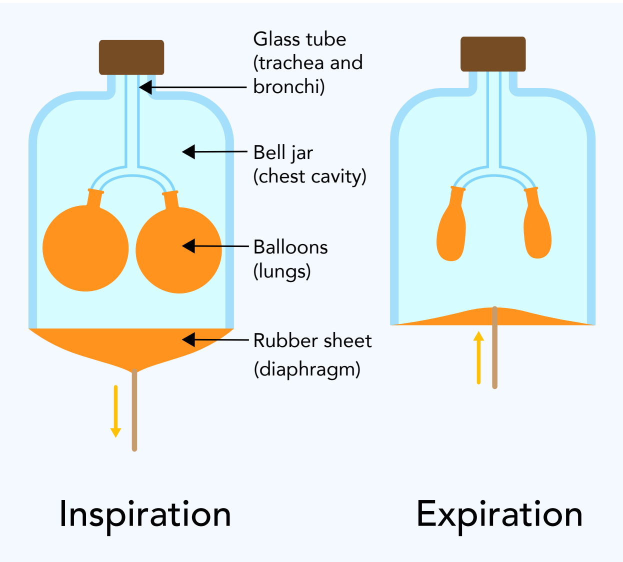
Explicitly teach students about models and encourage students to critique them

For students to get the most out of models they need to understand how models relate to reality and why they are used. This is an important step in developing their ability to 'reason like a scientist'. Three levels for understanding the 'nature of models'[67] are:

- **beginner** – 'I think that models are a direct copy of reality and don't see how they differ from reality';
- **intermediate** – 'I understand that models are not direct copies of reality and I understand that models are used to help me develop my scientific understanding'; and
- **expert** – 'I know that several different models can be used to explain different aspects of an idea; I understand that models have strengths and weaknesses and that existing models can be changed and improved; I know that models can be used to test ideas and are created for specific purposes'.

Most models are limited. For example, a physical model of the lungs showing balloons inflating inside an evacuated glass bell-jar is useful (Figure 5)—but it is limited because the chest wall is not rigid like a glass jar and the role of the ribs and intercostal muscles are not explained by that model. Be careful that models do not lead to students being confused or developing misconceptions.

Figure 5: The bell jar model of the lungs



Avoid students learning the model rather than the concept it is meant to explain. You can do this by explicitly directing students to the similarities and differences between the model and the concept. One way to do this is to give them first-hand experience with a wide range of model types, then challenge them to compare existing models. For example, they could compare the three different models to represent electric current (Box 9).

> *"Avoid students learning the model rather than the concept it is meant to explain."*

The point here is not to pick one model but to use the comparison between models to help students develop an understanding of both the concept and the nature of models.

When discussing the different models, typical discussion questions might be:

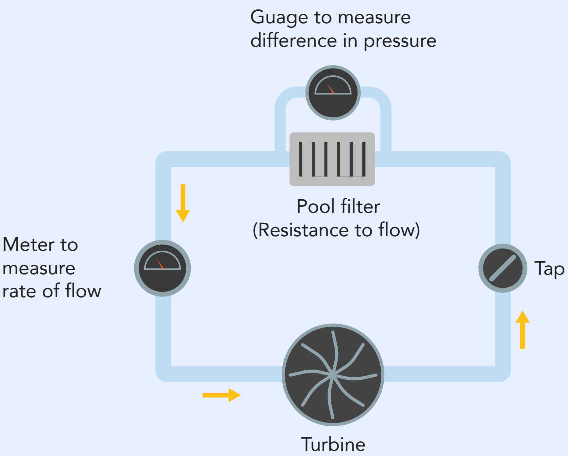
- In each model, how would you represent:
  - increasing the current?
  - increasing the voltage?
- Which model do you find most helpful? Why?
- How could you improve the models?
- How would you develop each model to deal with alternating current?

Box 9: Different models for electric current and the limitations of each

There are three commonly used models for electric current—the water circuit model, the rope model, and the delivery van model.

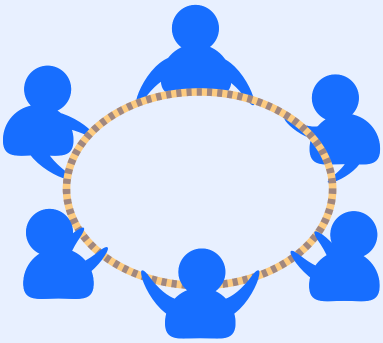
The water circuit model

The water circuit model is one that students can easily relate to. However, they need to be aware of the differences from their everyday experiences with water in pipes. For example, unlike water leaving the plumbing through taps, electricity cannot leave the circuit.



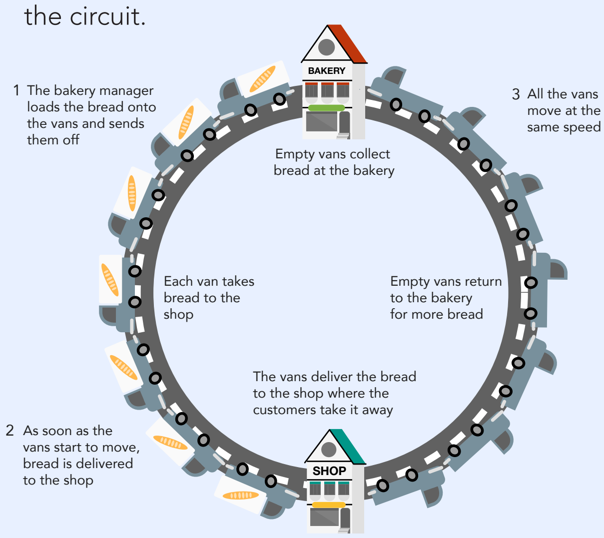
The rope model

The rope model is useful for developing the idea of energy flow and for showing the constancy of current in a circuit. However, this model does have limited use as there is not a component in the circuit that is performing energy transfer. It is tangible: students can stand in a circle and hold and feel the rope and it can demonstrate heating in an electric circuit.



The delivery van model and jellybean model

The delivery van model is useful for showing that the movement of electrons in a circuit is accompanied by a transfer of energy. The limitation here is that energy is seen as a substance rather than a concept. It is also important that the delivery vans are seen as being in a continuous line rather than with gaps between them as otherwise the model does not depict how electrons move around the circuit.



The jellybean model is very similar in how the concepts are represented and its limitations. It can be used as a role play during a lesson. A path within the classroom is used to represent the circuit. Students act in the roles of battery, light bulb and moveable charged particles, with jellybeans representing the energy.[68]

First stop for further reading

Gilbert, J. K. and Justi, R. (2016). Modelling-based Teaching in Science Education. Switzerland: Springer International.[69] This book provides detail on the research in this area and how to best use models as part of science teaching.

4

Memory:
Support students to retain and retrieve knowledge

Evidence summary

Cognitive science has recently led to significant breakthroughs in understanding the different functions and processes of the brain, but applying laboratory data to classroom practice is not straightforward. Research does support:

- cognitive load theory, although it is less clear how much information students can hold in their working memory;
- spaced review, which has the most evidence from classroom studies of the strategies discussed in this section, with effects noted across different contexts; and
- retrieval practice and elaborative interrogation, which have a number of studies with positive effects.

You cannot do science without knowledge. Students must learn new concepts and vocabulary and apply this learning in new contexts. So being able to remember information is important for success in school science.

This is not about rote learning: knowledge is an important step in progressing to more complex understanding.

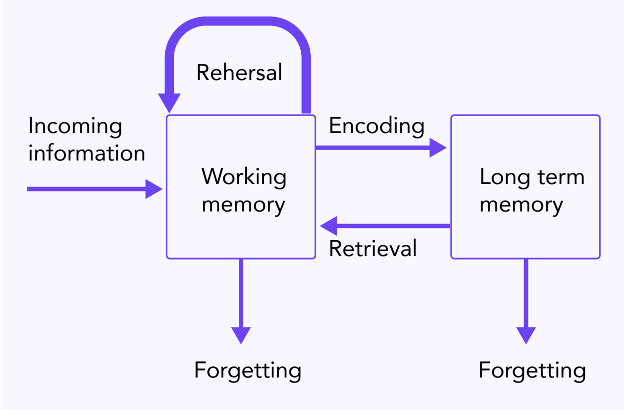
There are two important components of memory—long-term memory and working memory. **Long-term** memory can be considered as a 'store of knowledge'. **Working memory** is where information that is being actively processed is held—it is where 'thinking' happens (see Figure 6). Long term memory, however, should not be thought of as a static store of knowledge; it is constantly updating and evolving.

> *"Long-term memory should not be thought of as a static store of knowledge; it is constantly updating and evolving."*

The important thing to appreciate is that working memory is limited in how much information it can hold at any one time. On average, your working memory can hold around seven 'bits' of information and only keeps them for about 20 seconds unless they are refreshed by rehearsal.

These capacity limits apply to new information, but working memory does not have this limitation when dealing with information retrieved from your long-term memory. Information in your long-term memory is stored in schemas: a schema is a pattern of thought that organises categories of information, and the links between them. The working memory deals with each schema as a single element of information so the load on the working memory is reduced because even complex schema can be dealt with as a single element.

Figure 6: Working memory and long-term memory



Pay attention to cognitive load

The limit of the working memory means that it can quickly become overloaded when dealing with a new task. Any task that exceeds the limit of the working memory will result in cognitive overload and this increases the possibility that the content may be misunderstood and not effectively encoded in the long-term memory.

> *"Any task that exceeds the limit of the working memory will result in cognitive overload and this increases the possibility that the content may be misunderstood"*

Here is an example from chemistry of a task that may require lots of information to be held in the working memory. When students learn about titrations, there are many new concepts and practical skills to learn, as well as new equipment to get to grips with. If all of this is introduced simultaneously, students are likely to find it difficult to process.

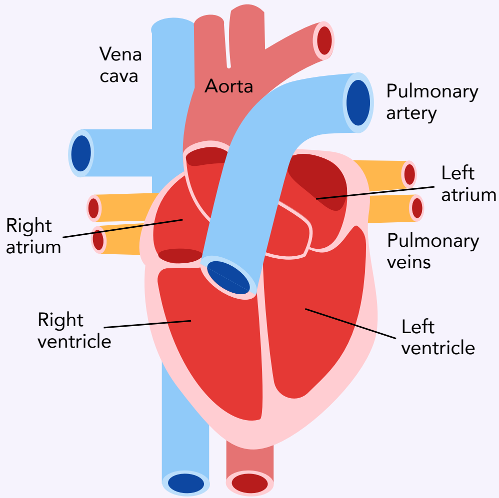
You can structure complex tasks, so that working memories are not overloaded, by limiting the amount of new information students need to process. Here are some approaches:

- Plan lesson sequences so that any necessary background knowledge is covered in advance, including revisiting previously taught ideas that a complex task relies on;
- Avoid split attention by ensuring students do not need to refer to multiple sources to complete a task. For example, split attention occurs when students have to move between a diagram and a written explanation (see Figure 7);
- Use worked examples or partially solved examples that take students through each step of a process—this is particularly useful when first learning a problem-solving strategy—but reduce the use of examples as students' expertise increases; and
- Break down a task so that students tackle it step-by-step, writing down what they know at each step, before tackling the next step.

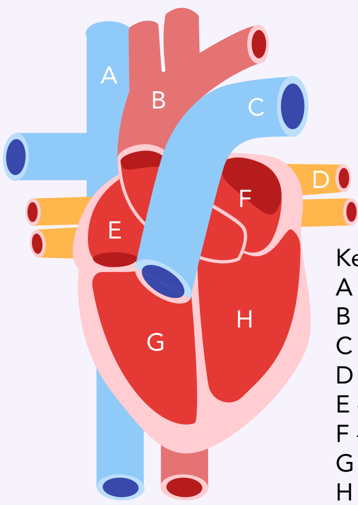
A key way of preventing cognitive overload is to help students commit important and frequently used pieces of information to their long-term memory.

Figure 7: Avoiding split attention

a) This diagram prevents split attention and reduces cognitive load by integrating the labels with the visual



b) This diagram requires students' attention to move between the visual and the list of labels, splitting their attention and increasing cognitive load.[70]



Key
A - Vena cava
B - Aorta
C - Pulmonary artery
D - Pulmonary veins
E - Right atrium
F - Left atrium
G - Right ventricle
H - Left ventricle

Revisit knowledge after a gap to help students retain it in their long-term memory

Learning everything to do with a topic during a single time period is not as effective as distributed learning.[71,72] **Spaced review** involves revisiting a topic after a 'forgetting gap' and strengthens long-term memory. A simple way to manage this is to build in review time, including reviewing learning from the previous lesson at the start of the next one or over longer periods (at the end of each week, month, or topic). This also links with retrieval practice: combining spaced review and retrieval practice can lead to great benefits in retention in the long-term.

Provide opportunities for students to retrieve knowledge they previously learnt

Repeatedly re-reading a text is not an effective way of learning. It is much more effective for students to try to retrieve what they already know about a topic,[73] or what they have recently read about it, from memory. **Retrieval practice** involves retrieving something you have learnt in the past and bringing it back to mind. You can use retrieval to review past learning before introducing new related learning. For example, you might ask students to recall group one of the periodic table before introducing group seven, showing its similarities and differences.

Students are using retrieval practice every time you administer a test. Using frequent (for example, weekly instead of termly), short, and, importantly, low-stakes tests causes students to retrieve knowledge on a regular basis. *Any* activity that requires students to draw on past knowledge can have the same effect, including activities such as the use of flashcards, completing practice questions, or writing a concept map. The key is that students are drawing on their long-term memory as much as possible, although they can look at sources afterwards to help them fill in any gaps and to give themselves feedback.

Retrieval practice needs to occur a reasonable time after the topic has been initially taught. Research shows that longer (at least a week) intervals are more effective. What makes retrieval practice really interesting for education is the durability of the effect, with impacts being seen sometimes years after the approach has been used.[74]

> *"What makes retrieval practice really interesting for education is the durability of the effect, with impacts being seen sometimes years after the approach has been used."*

Encourage students to elaborate on what they have learnt

Elaboration involves describing and explaining in detail something you have learnt. This approach supports learning by integrating new information with existing prior knowledge, helping to embed it in the long-term memory. This is useful as students progress in their understanding of a concept.

A well-studied form of elaboration is **elaborative interrogation**, which involves prompting students to generate an explanation for an idea that they have learnt. Prompt them to ask and answer 'Why?' and 'How?' questions about the topics that they are learning (for example, 'Tell me how an electric motor works'; 'Why does it turn faster when the current is higher?'; 'How does the electric current get into the coil?'). Studies show that learning effects are larger when students generate answers to these questions themselves rather than being provided with the explanations.[59]

First stop for further reading

Science of Learning Research Centre (SLRC) PEN Principles[62] provide resources drawing together research from psychology, education and neuroscience that are designed to help teachers use the science of learning to inform their practice.

The Learning Scientists website[75] has more information on the areas covered in this section and examples of how to apply these techniques in the classroom.

Horvath, J., Lodge, J., & Hattie, J. (2016). From the Laboratory to the Classroom: Translating Science of Learning for Teachers. pp 139-154. Oxon: Routledge[76]

5 Practical Work: Use practical work purposefully and as part of a learning sequence

Evidence summary

Different studies on practical work tend to focus on different purposes which makes reaching a consensus view about the impact of practical work difficult and there are few studies that compare the effectiveness of different types of practical activity. However, evidence suggests that:

- practical science engages students;
- due to the wide variety of aims and purposes of practical work, it is important to be clear about your purpose for choosing a particular activity as different types of practical work are needed to achieve different aims;
- practical work has positive impacts on the development of specific practical skills;
- there are benefits of developing scientific reasoning skills through practical work and this can impact on student achievement; and
- open ended research projects can have impacts on skill development, student attitudes, and outcomes.

Seeing is believing. As well as being intrinsic to science, experiments help students to root scientific theory and knowledge in reality.

Our definition of 'practical science' includes a wide variety of activities in which students manipulate and observe real objects and materials in laboratories and field studies.

Gatsby Charitable Foundation's international study[77] found science educators are broadly agreed on five purposes for practical science, shown in Box 10.

Know the purpose of each practical activity

It is important that you are clear about the skills or knowledge that you are trying to develop in your students with a particular practical activity. Think through the best approach to developing these things and plan how to sequence it with other learning.

'Are we doing an experiment today?' You know the cry. Practical work engages students.[78] But keeping students happy is not enough of a reason on its own for using valuable time. Look at the purposes in Box 10. Are you doing the experiment to introduce a new phenomenon such as electromagnetism, engaging students' interest so they will be more receptive to learning? Are you teaching them a new skill, such as using a microscope, so that when you want them to look at plant cells they can do so without the distraction of working out how to focus? Be clear in your own mind about the purpose and the outcomes you are looking for from the experiment—and make sure your students know them too. Students should know why they are doing an experiment, but young people often report 'just following the instructions' without understanding the purpose of practical work.[78]

Box 10: Purposes of practical science

(Not in any order of priority.)

- to teach the principles of scientific enquiry;
- to improve understanding of theory through practical experience;
- to teach specific practical skills, such as measurement and observation, that may be useful in future study or employment;
- to develop higher level skills and attributes such as communication, teamwork and perseverance; and
- to motivate and engage students.

Sequence practical activities with other learning

It is unreasonable to expect lasting learning of a scientific concept from a single, relatively brief practical activity. Practical work is an important string to your bow, but as an effective science teacher you will use it alongside a range of other activities. An experiment may be the centre-piece of a lesson, but don't forget the activities that go with it.

Think about how the practical activity sequences with other work on the topic, before and after. What knowledge and skills will students need before they can get the most out of the practical? Will the practical introduce a new idea, or will it reinforce ideas students have already met? You need to plan how their practical skills develop in the same way as you plan the development of their knowledge.

For practical activities that aim to improve understanding of scientific theory, you may have to help students to make links between the practical activity and the underlying scientific ideas. Students need to be 'minds on' as well as 'hands on'.[79] Table 1 shows how to assess whether a practical activity is effective in being both.

Table 1: Assessing effectiveness of a practical in terms of whether it is 'hands on' or 'minds on'

Adapted from Millar and Abrahams, 2009.[79]

	Assessing if a practical activity is 'hands on'	Assessing if a practical activity is 'minds on'
Do the students do what is intended?	Students do what was intended with the objects and materials provided, and make the intended observations.	During the activity, students think about what they are doing and observing, using the ideas intended in the activity.
Do the students learn what is intended?	Students can later recall and describe what they did in the activity and what they observed.	Students can later discuss the activity using the ideas it was aiming to develop.

Use practical work to develop scientific reasoning

Science, for humans, is a powerful way of exploring the nature of the world around us and the greater Universe we are a part of. A scientific attitude is an attribute that can serve students well in life.

Every time you do an experiment, you can model some aspect of scientific reasoning. Even if the main purpose of the experiment is to develop a particular scientific theory or a scientific skill, you can point out how you are using scientific methodology.

One of the fundamentals of scientific reasoning is the control of variables.

Indeed, performance on 'control of variables' tasks predicts students' outcomes on tests of scientific knowledge.[80] Discuss the control of variables explicitly when you introduce an experiment such as the factors affecting reaction rates, or the limiting factors for photosynthesis. It is also beneficial for students to practice controlling variables when designing their own experiments.[81] An example of the type of thinking it is helpful to take students through can be found in the self-regulation section of this report– recommendation 2.

Experiments sometimes go wrong; think of this as an opportunity as well as a problem. Use scientific reasoning to explain the unexpected.

> *"Experiments sometimes go wrong; think of this as an opportunity as well as a problem."*

Use a variety of approaches to practical science

There are different ways to expose students to the processes of practical science, from virtual experiments to open-ended projects. Virtual experiments, such as the PhET simulations from the University of Colorado[82] at Boulder, allow students to quickly change variables, see patterns in data, and understand relationships. Virtual experiments should not replace the real thing, but they can support it. A computer simulation of an experiment can allow students to go through the process of a particular practical activity so that when they do it in the classroom they are already familiar with the steps they need to take and can concentrate on the learning that it is aimed at developing. This is consistent with the cognitive science of memory as outlined in recommendation 4.

An approach to practical work that requires more time involves open-ended projects, with students pursuing a project of their own choosing over an extended period of time. Providing project opportunities within the constraints of the applicable curriculum, especially at senior secondary, is challenging. But there can be opportunities for project work outside the timetable and through other programs such as STEM clubs[83] A synthesis of the international evidence of the impact of open-ended projects in science showed several benefits for these types of projects, including learning science ideas, attitudes towards pursuing science careers, and skill development. There were also interesting attitudinal outcomes for groups typically under-represented in science.

First stop for further reading

Hackling, M. (2005). Working Scientifically. Western Australia Department of Education and Training.[84]

Holman, J. (2017). Good Practical Science. London: Gatsby Foundation.[77] This report is the result of an international study. It includes a useful literature review of available evidence and examples of good international practice.

Abrahams, I. and Reiss, M. J. (2016). Enhancing learning with effective practical science 11–16. London: Bloomsbury.[85] This book provides a summary of research as well as example lesson plans for how to make practical work effective.

University of California Understanding Science 101: A blueprint for scientific investigations unpacks the process of investigation in science[86]

6 Language of Science: Develop scientific vocabulary and support students to read and write about science

Evidence summary

The research literature shows consistent and strong correlations between students' literacy skills and their success in learning science, and literacy interventions have shown impacts on science outcomes. Evidence suggests that:

- students need to be explicitly taught new scientific vocabulary and this can be challenging; however, it is familiar words used in unfamiliar contexts that cause most difficulty;
- showing the links between words is an efficient way of teaching vocabulary and aids understanding;
- extended reading rarely happens in science lessons but reading authentic texts is a good way of exposing students to scientific writing; and
- science writing can help develop students' understanding and writing frames can provide helpful scaffolds.

Learning science involves learning a whole new language and it is important that you develop students' fluency in that language.

To become competent in the language of science students need to be able to comprehend, analyse, and interpret texts and use the language of science to explain ideas and construct evidence-based explanations. This may seem like something that needs extra time and work, but it is really the core of learning and teaching science.

> *"To become competent in the language of science students need to be able to comprehend, analyse, and interpret texts and use the language of science to explain ideas and construct evidence-based explanations."*

Science requires a breadth of literacy skills, but this section deals specifically with teaching scientific vocabulary and supporting students to read and write about science. More information on the types of talk that are helpful in developing thinking can be found in the self-regulation section of this report – recommendation 2.

Carefully select the vocabulary to teach and focus on the most challenging words

Be aware of the vocabulary demands of a topic and make a conscious choice about the words that you are going to teach and when to introduce them. Focus on the words that students really need to understand and make sure they understand them well. Less is more: a deep understanding of fewer words is better than understanding lots of words at a surface level.[87]

Remember that some familiar words, such as 'field', have a different meaning in science from everyday life, and several studies have shown that these words often cause more problems for students than words we might normally consider to be technical language.[88,89]

Discussing how the meaning of such words differs in science should be a key part of teaching the word. Even though they are not 'new' words they should be a focus of vocabulary teaching. Box 11 shows examples of these words.

Box 11: Example words in science with alternative everyday meanings

- Incident
- Complex
- Spontaneous
- Relevant
- Valid
- Composition
- Emit
- Random

For more examples of words that students often have alternative conceptions of, see Vocabulary mix-ups from the University of California Understanding Science 101: Correcting misconceptions[90]

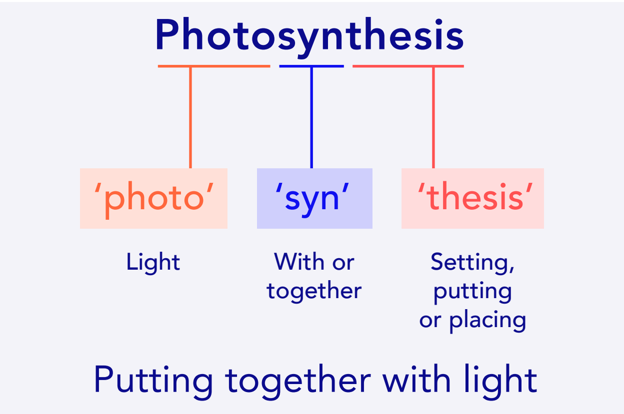
Show the links between words and their composite parts

Teach new scientific vocabulary explicitly. Direct instruction is a good way of doing this.[91] You also need to show students how words are linked and how to use them in a range of contexts.

Support students to understand the meaning of root words and how to use prefixes and suffixes to change the meaning of root words. This helps them to learn new words and make connections between different words.[92] This approach also helps students to see the differences between words with the same root but with different meanings such as 'compress', 'compression', and 'compressional', which can often be challenging.

Teach students to segment and manipulate words according to their morphemes (unit parts) so that new words with similar morphemes are more easily recognised and understood; this is also an efficient way of expanding students' vocabulary. Figure 8 shows how the word 'photosynthesis' breaks down, so students will more easily recognise words with these morphemes in the future.

Figure 8: Teaching the morphemes that make up the word 'photosynthesis'



Another way of demonstrating links between words is through the use of knowledge organisers. These act as a taxonomy of words and display how words are linked together across topics. You can give them to students as reference material or get students to generate them as they meet new words and ideas. You can display a class knowledge organiser during lessons and add to it as new terminology is learnt across a topic.[93]

Once you have introduced a new scientific word, it is important to reinforce it by encouraging students to use it as much as possible in your lessons. For example, get students using the word in different contexts ('give me a sentence that has both "photosynthesis" and "night" in it').

Use activities to engage students with reading scientific text & help them to comprehend it

It is important that the texts students are reading are at an appropriate level, but challenging and interesting; students should have the opportunity to engage with authentic scientific books and texts.[94]

The use of authentic texts does not mean that all students need to be reading journal articles, but they should have access to quality texts from a range of sources, including news articles and parts of popular science books.

Support students to read science. Teach them the necessary vocabulary and use structured activities to help them comprehend text. DARTS (Directed Activities Related to Text) can help with this. See Box 12 for a summary of types of DARTs and the types of learning they can support.

Box 12: Summary of types of DART

Adapted from Osborne and Dillon, 2010.[95]

Reconstruction DARTs	Analysis DARTs
Completing text, diagrams, or tables Completing phrases or sentences Labelling diagrams using text Using text to complete a table	**Marking and labelling** Underlining (students search for specified parts of a text) Labelling (students label text according to labels given to them) Segmenting (students break the text down and label the different parts)
Ordering or classifying text Students put segments of text into a logical order Students classify segments of text according to set categories (e.g., 'instruction', 'explanation', 'evidence')	**Recording and constructing** Constructing diagrams to show the content and flow of text Students make up their own tables from information in the text Students use the text to answer questions or to create their own questions Students list the key points made in a text
Predicting Students write the next part of the text	

Support students to develop their scientific writing skills

Writing about science is more than communication alone; it supports students in their learning because when they write about science they reflect on their understanding, formulate their own ideas, and combine ideas in new ways.

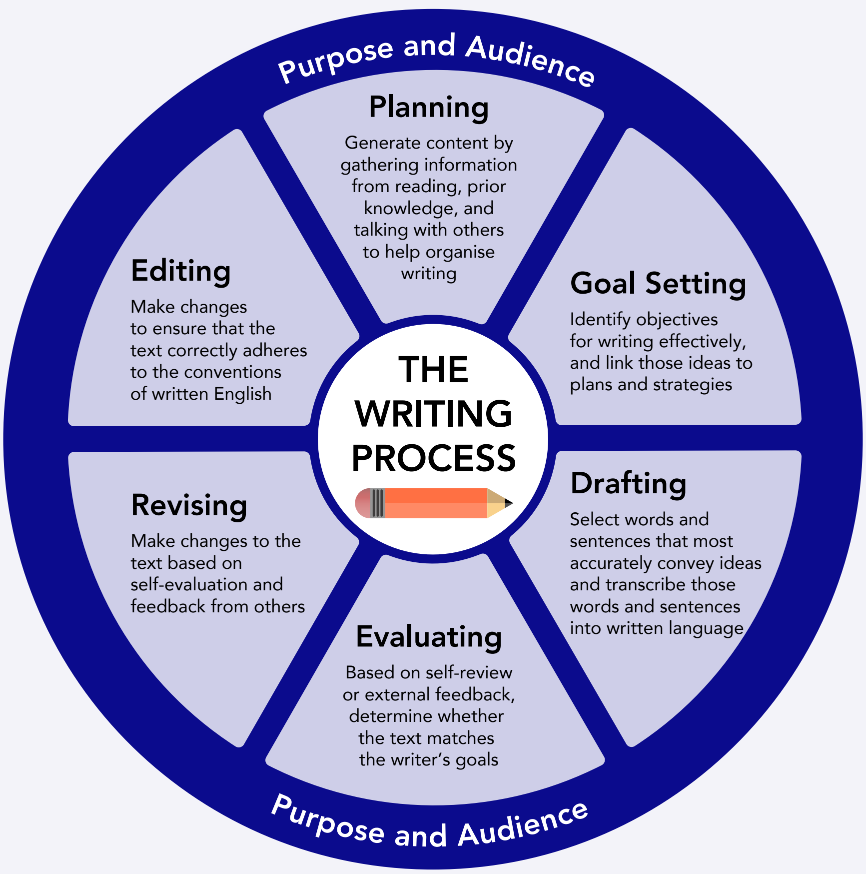
The Process Approach to Writing (Figure 9—see the What Works Clearinghouse *Teaching secondary students to write effectively*[96] for more information on this) is an effective way of developing students' writing skills. Good writing needs a strong sense of purpose and audience: 'Why am I writing this, and who is it for?' Thinking about purpose and audience helps students to evaluate their own writing and increases students' motivation and interest.[97]

Frameworks can be helpful to support early writing and to teach students strategies they can use over time: the frameworks can be withdrawn as students become more confident writers. A useful frame is the Science Writing Heuristic[98] which aims to support students in developing scientific arguments and planning how to present these. The framework has both a template for students (Box 13) and a template for teachers with activities to promote understanding.

Figure 9: The writing process

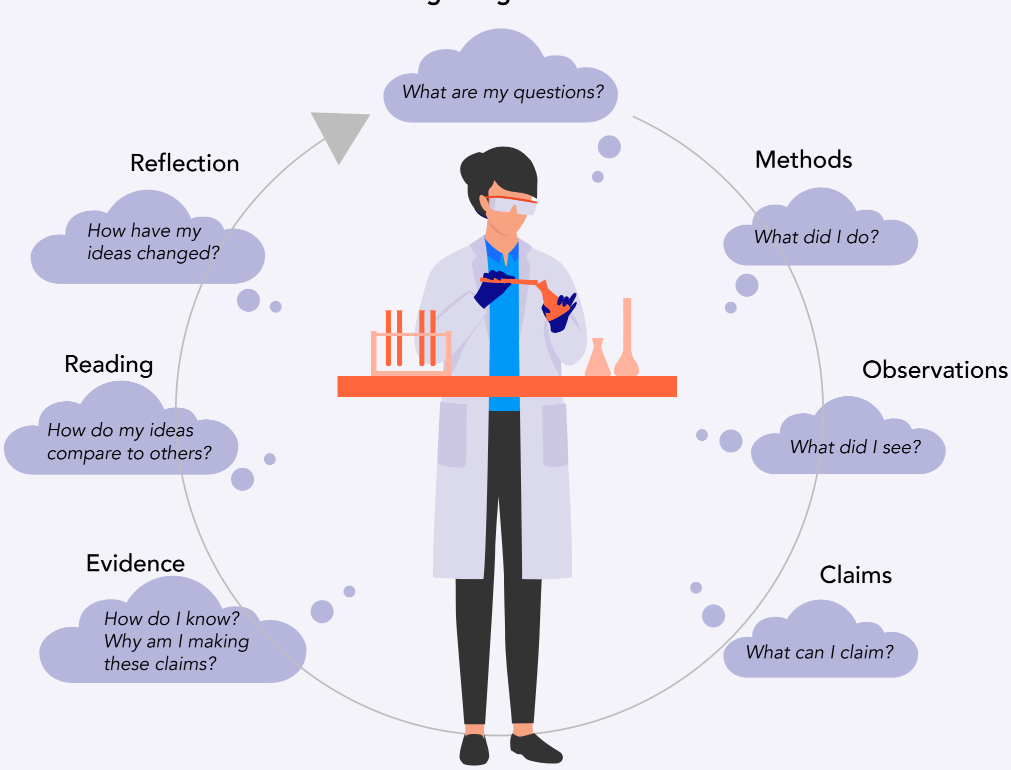
Adapted from What Works Clearinghouse Teaching secondary students to write effectively[96]

The writing process involves several components and is iterative. Students may implement these components in a different order or implement some of the components simultaneously. Purpose and audience are kept in mind throughout the process.



Box 13: Science writing heuristic – template for students

Adapted from Hand et al., 2016.[99]



First stop for further reading

Wellington, J. and Osborne, J. (2001). Language and literacy in science education (2011 ed.), Buckingham, Philadelphia: Open University Press.[57] A useful overview of language in science with examples for applying in the classroom.

What Works Clearinghouse practice guide Teaching secondary students to write effectively[96]

Kok-Sing Tang (2016). Constructing scientific explanations through premise–reasoning–outcome (PRO): an exploratory study to scaffold students in structuring written explanations. International Journal of Science Education, 38:9, pp.1415-1440

7 Feedback: Use structured feedback to move on students' thinking

Evidence summary

There are many meta-analyses pointing to feedback having a very high effect on student outcomes. However, simply providing more feedback will not necessarily lead to better outcomes as it is the type of feedback that is critical. The evidence shows:

- different methods of feedback delivery can be effective and feedback should not be limited exclusively to written marking, with studies of verbal feedback showing slightly higher impacts overall[100]
- teachers should use a range of strategies to find out what students understand, not just formal assessments;
- feedback should help students develop as learners, not just improve performance on a specific task;
- student performance improves when feedback is in the form of constructive comments, and there are ways of doing this that minimise workload; and
- feedback is most effective when students know how to respond to it and are given time to do so.

Find out what your students understand

Students can have strengths in one area and weaknesses in another. So it is important that you build up an accurate picture of the current understanding of all your students. One way to get this is through the use of formal tests. Less formally, you can use frequent low-stakes class assessments, informal observations of students, whole-class or group discussions, and peer- and self- assessment.

Peer assessment is useful as students are often more receptive to feedback on their work from their peers than from their teacher.[99] A useful way to structure peer assessment is to get a group to look at the responses of each member and assess the strength and weaknesses of each. By doing this they can start to objectively understand how their work compares to the work of their peers.[101] Students can do this with a marking scheme or can develop their own criteria for quality which may help them to self-assess their own work in the future.

Think about what you're providing feedback on

Feedback should help the student develop as a learner, not just improve on the specific task that you are providing feedback on—and teachers can provide feedback at different levels (see Figure 10). Feedback at the task level is likely to be difficult for students to transfer, although it is useful for correcting errors, whilst feedback at the level of 'self-evaluation' may lead students to think that their abilities are fixed, which could limit their willingness to try difficult things in the future. The most useful feedback is therefore at the 'subject' and 'self-regulation' levels, although it may sometimes be appropriate to give feedback at the other two levels.

> *"Feedback should help the student develop as a learner, not just improve on the specific task that you are providing feedback on"*

Figure 10: The four types of feedback that teachers can give

Adapted from Fletcher-Wood, 2018[102]

Level of feedback		Type of feedback	The questions it helps students to answer	Examples in science
Specific ↑	*Concrete*	The task	How can I get this done? How can I make this better?	Your understanding of Ohm's Law is good, but be careful to use the correct units.'
	Reflective	The subject	How can I do better in tasks like this? What does it mean to be good in this subject?	'Next time you do a calculation like this, try to set it out the way I showed you.'
		Self-regulation	How can I manage myself to learn better? How can I motivate myself?	'Are you happy that you understand photosynthesis now? What could you do to extend your understanding further?'
General ↓	*Existential*	Self-evaluation	How good am I?	'Well done, you've worked really hard this week.'

Provide feedback as comments rather than marks

Black and Harrison[103] found that feedback from science teachers was mainly through marks rather than comments. However, marks can demotivate low achieving students and can make high achieving students complacent; in contrast, comments show both how they can do better: 'You understand about homeostasis, but try to find some examples from plants as well as animals.'

Remember that comments do not necessarily need to be written: effective feedback can be given orally to individuals or groups of students during lesson time. While you are looking at students' work, try to find common mistakes which lots of students make, then provide feedback on these to the whole class. This approach can reassure students when they realise they have the same misunderstandings as many of their peers. Try to make quality, not quantity, the watchword when it comes to looking at students' work: a smaller quantity of rich feedback is likely to do more good than a larger quantity of superficial marking.

Make sure students can respond to your feedback

Several studies report that students do not always understand feedback, or they misunderstand it. Try to make the feedback clear and easy to act on, as well as appropriate for the student concerned. Feedback can vary in quality (Box 14 outlines some features of quality feedback) and in the ease it can be acted on.

It is helpful to frame feedback as a question. Black and Harrison[103] compare 'Add notes on seed dispersal' with 'Can you suggest how the plant might disperse its seeds? Could this be an advantage?'. Feedback can also usefully direct students where to go for help: 'Go back to your notes from last week and check where chlorophyll is in the leaf and the reasons why leaves are good photosynthetic structures.'

It is important to ensure that students have enough time to respond to feedback, in lesson or homework time.

Box 14: Features of quality feedback

Quality feedback:

- is specific, accurate, and clear;
- makes connections with prior performance, or to students' success or failure on another part of the task;
- is encouraging, helping students to identify things that are hard and require extra attention;
- provides guidance to students on how to respond to their teacher's comments; and
- provides concrete suggestions for improvement.

First stop for further reading

Evidence for Learning's Guidance for educators on Assessment and feedback in schools[104]

Australian Institute of Teaching and School Leadership's Feedback resources[105]

Black, P. and Harrison, C. (2004). Science Inside the Black Box: Assessment for Learning in the Science Classroom. London: NfER Nelson.[103] This provides a good overview of how to apply formative assessment in science.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Acting on the evidence

These recommendations do not provide a 'one size fits all' solution. It is important to consider the delicate balance between implementing the recommendations faithfully and applying them appropriately to your school's particular context. Implementing the recommendations effectively will require careful consideration of how they fit your school's context, including your current practices, what your data is showing about your students' needs and the application of sound professional judgement.

It is important to consider the precise detail provided beneath the headline recommendations. Evidence for Learning has produced a Red-Amber-Green self-assessment tool that can be useful for unpacking the recommendations, reflecting on current practice and exploring opportunities for improvement.[106]

Inevitably, change takes time, and we recommend taking at least two terms to plan, develop, and pilot strategies on a small scale before rolling out new practices across the school. Gather support for change across the school and set aside regular time throughout the year to focus on this project and review progress.

Evidence for Learning has produced Putting evidence to work: a school's guide to implementation, a Guidance Report which could be used as a guide as you make changes[107]. Figure 11 provides an overview of the implementation process which schools can apply to any implementation challenge.

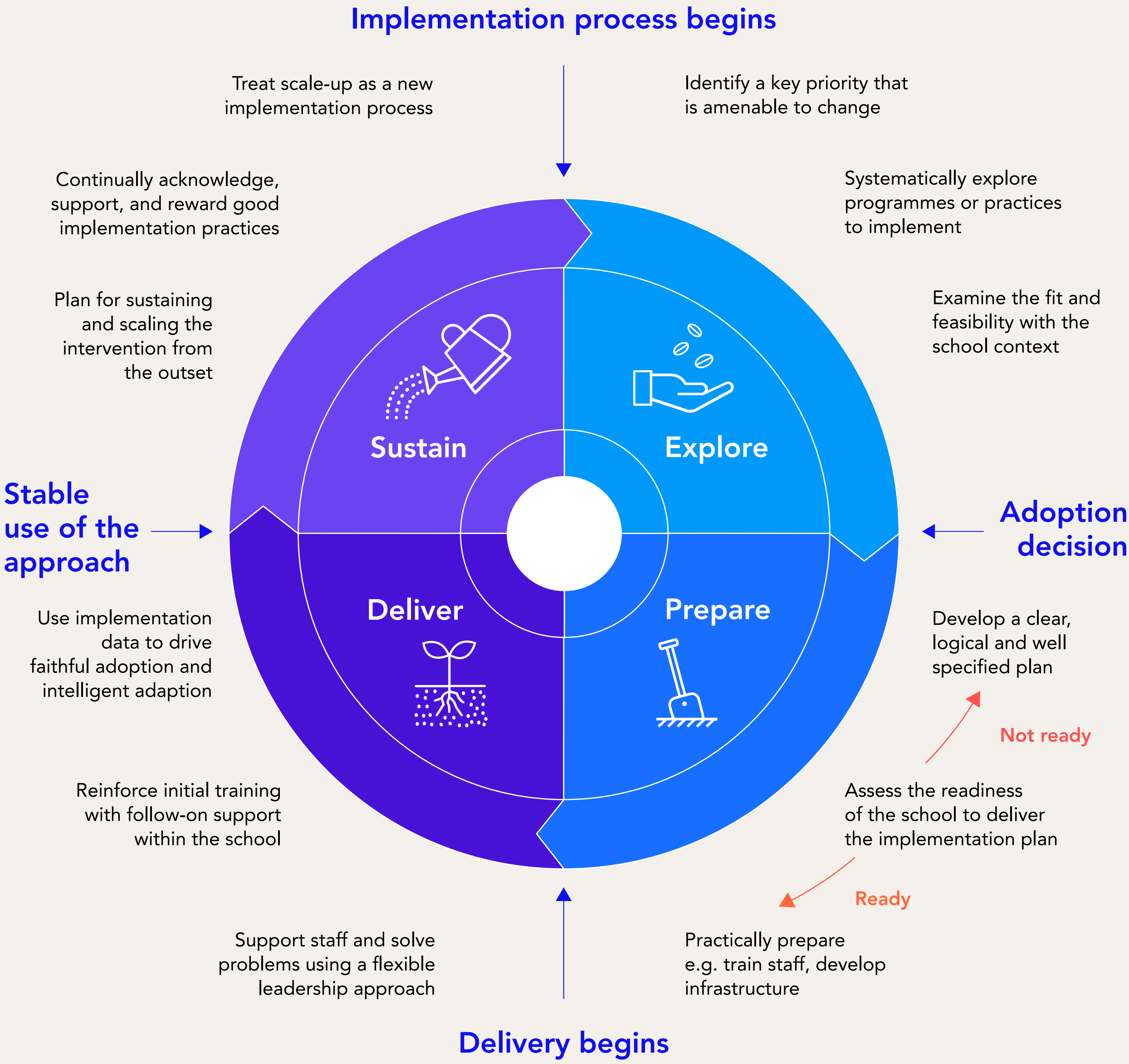
The stages of implementation

Foundations for good implementation

- ✓ Treat implementation as a process, not an event. Plan and execute it in stages.
- ✓ Create a leadership environment and school climate that is conducive to good implementation.

Implementation can be described as a series of stages relating to thinking about, preparing for, delivering, and sustaining change.

Figure 11: The stages of implementation



Australian resources

Evidence for Learning's suite of Guidance Reports contain recommendations for school leaders on a range of priority topics, including:

- Improving literacy in secondary schools
- Improving mathematics in upper primary and lower secondary
- Metacognition and self-regulated learning

Evidence for Learning highlights the international research within the Teaching & Learning Toolkit. The following strands are of particular relevance to the recommendations in this guidance report:

- Metacognition and self-regulation
- Feedback

The **Science of Learning Research Centre** (SLRC) brings together neuroscientists, psychologists and education researchers from across the country with the vision to improve learning outcomes at pre-school, primary, secondary and tertiary levels through scientifically validated learning tools and strategies. The SLRC have developed the PEN Principles – Psychology, Education and Neuroscience – that are designed to help teachers use the science of learning to inform their practice:

1. Written Text and Spoken Word Don't Mix
2. Visual Images and Spoken Word Mix Well
3. Spatial Predictability Guides Attention
4. Spacing-Out Practice Enhances Memory
5. Leverage Context according to Outcome
6. Multitasking Impairs Memory & Learning
7. Mix-Up Practice Tasks to Boost Performance
8. Embrace Error to Improve Learning
9. Active Recall Trumps Passive Review
10. First Impressions Colour Future Judgement
11. Find the Story Behind the Fact
12. Pre-Activate Strategies to Guide Learning

The **Australian Institute of Teaching and School Leadership** (AITSL) has a comprehensive set of resources related to feedback developed in conjunction with Evidence for Learning.

The **Australian Curriculum, Assessment and Reporting Authority** (ACARA) has further resources on its website to support the Australian Curriculum, specifically:

- Aboriginal and Torres Strait Islander Histories and Cultures
- STEM Resources
- Science Work Samples

How was this guide compiled?

This guidance report draws on the best available evidence regarding the teaching of secondary science. The primary source of evidence for the recommendations was a series of evidence reviews conducted by Professor Marcus Grace and his team at Southampton University. We also often drew on an earlier review commissioned by the EEF and the Royal Society and led by Professor Terezinha Nunes and Professor Peter Bryant at Oxford University.

The guidance report was created over four stages.

1. **Scoping.** The process began with a consultation with teachers, academics, and other experts. The EEF team selected the area of interest, appointed an Advisory Panel and evidence review team, and agreed research questions for the evidence review. The Advisory Panel consisted of both expert teachers and academics.
2. **Evidence review.** The evidence review team conducted searches for the best available international evidence about approaches to science teaching.
3. **Writing recommendations.** The EEF worked with the support of the Advisory Panel to draft the recommendations. Academic and teaching experts were consulted on drafts of the report.
4. **Adapting for Australian educators.** Evidence for Learning consulted with Australian experts and practitioners to translate the findings and recommendations to be relevant and useful for Australian school leaders, teachers and those who support them.

The evidence review was conducted by Dr Andri Christodoulou, Professor Marcus Grace, Professor Janice Griffiths, Dr Carys Hughes, and Willeke Rietdijk (all University of Southampton).

The peer review was conducted by Professor Michael J Reiss (UCL Institute of Education), and Professor Ian Abrahams (University of Lincoln).

The advisory panel included Professor Judith Bennett (University of York), Lia Commissar (Wellcome Trust), Professor Harrie Eijkelhof (Universiteit Utrecht), Dr Niki Kaiser (Norwich Research School, Notre Dame High School), and Lauren Stephenson (Blackpool Research School, St. Mary's Catholic Academy).

Evidence for Learning would like to thank the researchers and practitioners who were involved in providing support and feedback on drafts of this Guidance Report in both the UK and in Australia.

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