Seven Recommendations for Improving Science in Secondary Schools

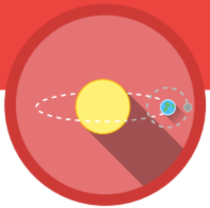
Andrew Bailey

Improving Secondary Science

Education
Endowment
Foundation

1

Preconceptions: Build on the ideas that pupils bring to lessons



2

Self-regulation: Help pupils direct their own learning

3

Modelling: Use models to support understanding

https://educationendowmentfoundation.org.uk/tools/guidance-reports/improving-secondary-science/

IOP Institute of Physics
Scotland

Improving Secondary Science

Education
Endowment
Foundation

4

Memory: Support pupils to retain and retrieve knowledge

5

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

6

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

7

Feedback: Use structured feedback to move on pupils' thinking

IOP Institute of Physics
Scotland

EEF ISS Example Toolkit

RECOMMENDATION 5
Practical Work

	Ineffective	Intermediate	Exemplary
Using practical work purposefully	Teachers use practical work as a lesson activity rather than thinking about the reason that they are using it.	Teachers understand the different purposes that practical work can have. They consider why they are doing a particular activity and make this clear to pupils.	Teachers carefully select practical activities to support the aims of the lesson. They are clear about the purpose of the practical activity and make this explicit to pupils. Teachers use a range of practical activity types according to the purpose, this includes virtual experiments and open-ended investigations.
Linking practical work with other learning	Practical work is seen as a stand alone activity and is not clearly linked to the rest of the lesson. Teachers expect pupils to learn scientific concepts through practical activities alone.	Teachers link the practical activity to the aims of the lesson. They remind pupils through the activity what they should be observing and the ideas they should be using.	Teachers link the practical activity to the aims of the lesson. They remind pupils through the activity what they should be observing and the ideas they should be using. After the activity teachers discuss with pupils what was observed and how this adds to their understanding of the ideas being taught.
Using practical work to develop scientific reasoning	Limited opportunities for scientific inquiry are provided.	Opportunities for scientific inquiry are provided but these could be unfocused or are often pupil-lead.	Opportunities for scientific inquiry are frequent. These are teacher-lead and focus on skills which develop science specific reasoning skills.

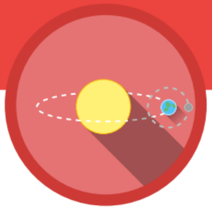
https://educationendowmentfoundation.org.uk/public/files/EEF_secondary_science_audit_tool.pdf

Preconceptions

Education
Endowment
Foundation

1

Preconceptions: Build on the ideas that pupils bring to lessons



- 1a: Understand the preconceptions that pupils bring to science lessons
- 1b: Develop pupils' thinking through cognitive conflict and discussion
- 1c: Allow enough time to challenge misconceptions and change thinking

IOP Institute of Physics
Scotland

Preconceptions / Misconceptions

- Pupils construct their own explanations these may differ from scientific explanations.
- Learning is more effective when preconceptions are considered.
- There are common misconceptions and research to suggest what these are.

Review & Misconceptions

- Experience of colleagues
- EEF Research & Anticipate, Diagnose & Address, Assess & Review , RADAAR
  https://educationendowmentfoundation.org.uk/public/files/Publications/Science/RADAAR_Planning_Logic_diagram.pdf
- Best Evidence Science Teaching
  https://www.stem.org.uk/best-evidence-science-teaching
- IoP Spark
  https://spark.iop.org/misconceptions-blogs
- American Association for the Advancement of Science
  http://assessment.aaas.org/topics

IOP Institute of Physics
Scotland

IMPROVING SECONDARY SCIENCE
RADAAR Planning Logic diagram

Education Endowment Foundation

Research **A**nticipate | **D**iagnose **A**ddress | **A**ssess **R**eview

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, past examiner reports, 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?

Uncover and diagnose

- How will you uncover the misconceptions that pupils 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 keep talk focused and productive?

Activities

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

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 pupils 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?

You can find the full report here: eef.li/science-ks3-ks4/

https://educationendowmentfoundation.org.uk/public/files/Publications/Science/RADAAR_Planning_Logic_diagram.pdf

IOP Institute of Physics Scotland

Self-regulation

Education
Endowment
Foundation

2

Self-regulation: Help pupils direct their own learning

- 2a: Explicitly teach pupils how to plan, monitor, and evaluate their learning
- 2b: Model your own thinking to help pupils develop their metacognitive and cognitive knowledge
- 2c: Promote metacognitive talk and dialogue in the classroom

Metacognition & Self-regulated learning

Education
Endowment
Foundation

1. Teachers should acquire the professional understanding and skills to develop their pupils' metacognitive knowledge
2. Explicitly teach pupils metacognitive strategies, including how to plan, monitor, and evaluate their learning
3. Model your own thinking to help pupils develop their metacognitive and cognitive skills

https://educationendowmentfoundation.org.uk/tools/guidance-reports/metacognition-and-self-regulated-learning

Metacognition & Self-regulated learning

Education
Endowment
Foundation

https://educationendowmentfoundation.org.uk/tools/guidance-reports/metacognition-and-self-regulated-learning

Teacher Modelling

Teachers should verbalise their metacognitive thinking, as they approach and work through a task.

“What do I know about problems like this?”

“What ways of solving them have I used before?”

EEF report on Metacognition and Self Regulation

https://educationendowmentfoundation.org.uk/tools/guidance-reports/metacognition-and-self-regulated-learning

Teacher Modelling

Experts in a topic/procedure forget easily how difficult it was to learn something.

"The curse of knowledge"

Teacher Modelling

Teachers need to make their thinking visible explicitly so a novice can understand the process.

Novice learners are not good at absorbing knowledge by ‘osmosis’.

Teacher Modelling

A charge of 15 C passes through a resistor in 12 s. The potential difference across the resistor is 6 V.

The power developed by the resistor is

A 4·8 W

B 7·5 W

C 9·4 W

D 30 W

E 1080 W.

$P = \frac{E}{t}$

$P = IV$

$P = \frac{V^2}{R}$

$P = ?$
$t = 12\,s$
$Q = 15\,C$
$V = 6\,V$

$Q = It$

$Q = It$
$15 = I \times 12$
$I = \frac{15}{12} = 1.25\,A$

$P = IV$
$= 1.25 \times 6$
$= 7.5\,W$

Modelled in real time

$$8 = 2y$$

$$\frac{8}{2} = \frac{2}{2}y$$

$$\frac{8}{2} = 1y$$

$$\frac{8}{2} = y$$

$$4 = y$$

$$\mathrm{v} = f\lambda$$

$$\frac{v}{f} = \frac{f}{f}\lambda$$

$$\frac{v}{f} = 1\lambda$$

$$\frac{v}{f} = \lambda$$

Progressive problems, appropriate challenge

Set progressive problems that increase in complexity and challenge .

Setting an appropriate level of challenge helps to develop pupils' self-regulation and metacognition

Progressive problems

1. Calculate the speed of water waves which have a frequency of 2 hertz and a wavelength of 5 metres.

2. Calculate the speed of sound waves in air which have a frequency of 500 hertz and a wavelength of 0·34 metres.

3. A submarine sends a pulse of sound through the sea. Determine the speed of the sound pulse if it has a frequency of 7 500 hertz and a wavelength of 0·2 metres.

4. Every second, 2 waves are produced on a bath of water by water dripping from a tap. If these waves have a wavelength of 0·05 metres, calculate their speed.

5. Water waves in a swimming pool are travelling with a speed of 2 m/s and have a wavelength of 0·8 m. What is their frequency?

6. A wave generator in a ripple tank creates waves which have a wavelength of 0·02 m. If the speed of these waves is 1·2 m/s what is their frequency?

7. Sound travels through steel at 5200 metres per second. In the steel, sound waves have a wavelength of 2 metres. Calculate their frequency.

Q1 Simple numbers

Q2 Decimals

Q3 Determine not calculate

Q4 Different order

Q5 to Q8 Different subject

Q10 Onwards some prefixes

Q14 Onwards, pictures and text

Worked examples

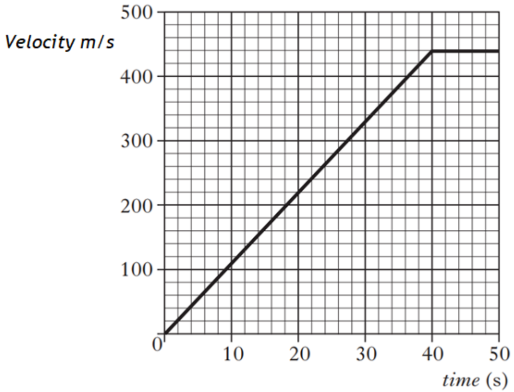
Scaffolded tasks, like worked examples, allow pupils to develop their metacognitive and cognitive skills without placing too many demands on their mental resources.

EEF report on Metacognition and Self Regulation

https://educationendowmentfoundation.org.uk/tools/guidance-reports/metacognition-and-self-regulated-learning

Example problem pairs

A car fitted with a jet engine is used in a land speed record attempt. The graph shows the velocity of the car for the first 50 seconds of a test



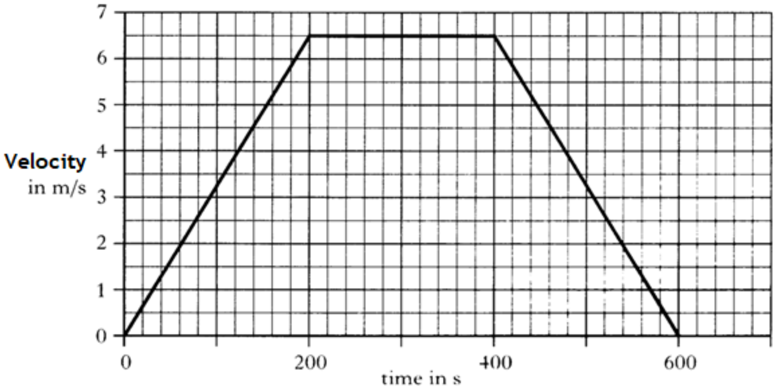
a= ?
u= 0 m/s
v= 440 m/s
t = 40s

a) Calculate the acceleration of the car during the first 40 s

$$a = \frac{v - u}{t}$$

$$a = \frac{440 - 0}{40} = 11\, ms^{-2}$$

A train carries people up a mountain. The graph shows how the speed of the train varies with time for the journey.



a= ?
u=
v=
t =

a= ?
u= 0 m/s
v= 6.5 m/s
t = 200 s

a) Calculate the acceleration of the train during the first 200 s

$$a = \frac{v - u}{t}$$

$$a = \frac{6.5 - 0}{200} = 0.0325\, ms^{-2}$$

Cognitive Load Theory

Dylan Wiliam
@dylanwiliam

I've come to the conclusion Sweller's Cognitive Load Theory is the single most important thing for teachers to know bit.ly/2kouLOq

6:16 PM · Jan 26, 2017 · Twitter Web Client

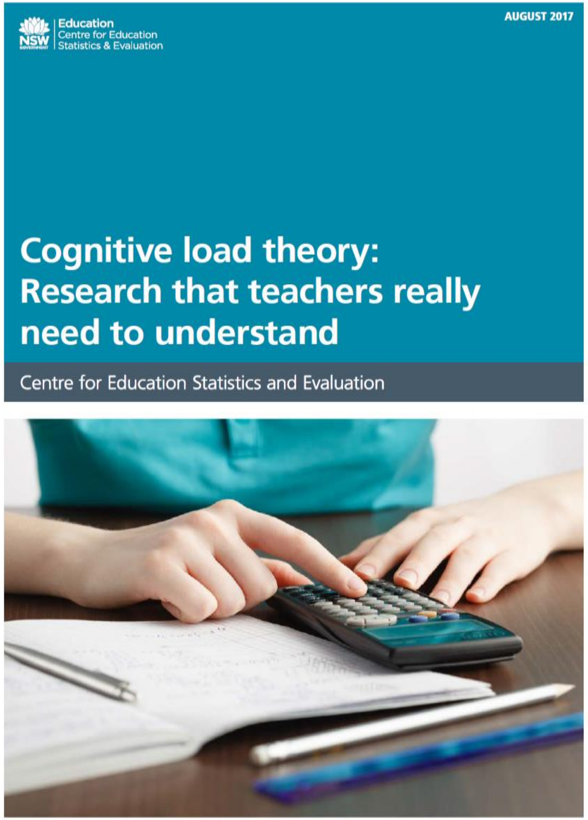
409 Retweets **74** Quote Tweets **662** Likes

Worked example effect

“the quickest way to get any well-organised knowledge into long-term memory is to borrow it from an expert” (p118)

(Lovell, O. (2020) Cognitive Load Theory in Action. John Catt: Woodbridge)

Cognitive load theory



Excellent summary report

https://www.cese.nsw.gov.au/publications-filter/cognitive-load-theory-research-that-teachers-really-need-to-understand

Modelling

Education
Endowment
Foundation

3

Modelling: Use models to support understanding

- 3a: Use models to help pupils develop a deeper understanding of scientific concepts
- 3b: Select the models you use with care
- 3c: Explicitly teach pupils about models and encourage pupils to critique them

Parallel session on visualising electric circuits,
Session 5 Modelling the Expanding Universe

IOP Institute of Physics
Scotland

Memory

Education
Endowment
Foundation

4

Memory: Support pupils to retain and retrieve knowledge

- 4a: Pay attention to cognitive load—structure tasks to limit the amount of new information pupils need to process
- 4b: Revisit knowledge after a gap to help pupils retain it in their long-term memory
- 4c: Provide opportunities for pupils to retrieve the knowledge that they have previously learnt
- 4d: Encourage pupils to elaborate on what they have learnt

Retrieval practice

Quick Quiz

1. What is meant by ultrasound? — Question 1&2 from last lesson
2. Name two uses of ultrasound? — Question 3 from last week
3. What is meant by frequency? — Question 4 from last month
4. Draw a transverse wave and label the wavelength and amplitude

Retrieval practice: Brain dump

- Retrieval practice, “Brain dump”
- Blank piece of paper
- Recall what you know about a topic without books
- Check for accuracy
- Add omissions
- Repeat at a later time

How to Study Effectively for School or College [Top 6 Science-Based Study Skills]

https://www.youtube.com/watch?v=CPxSzxylRCI

Review

- Retrieval practice
- Spaced learning
- Interleaving

https://www.learningscientists.org/

IOP Institute of Physics
Scotland

Practical Work

Education
Endowment
Foundation

5

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

- 5a: Know the purpose of each practical activity
- 5b: Sequence practical activities with other learning
- 5c: Use practical work to develop scientific reasoning
- 5d: Use a variety of approaches to practical science

IOP Institute of Physics
Scotland

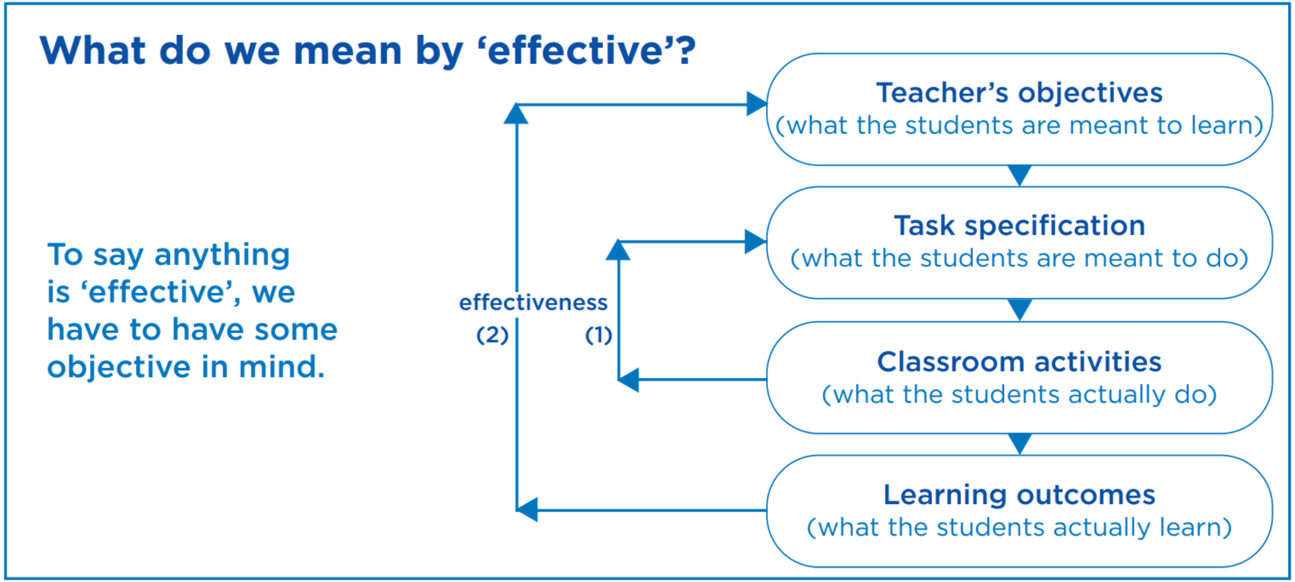
Practical work

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 pupils.

Purpose of practical work



"Hands on" or "Minds On"

Millar, R. and Abrahams, I. (2009) 'Practical work: making it more effective', School Science Review, 91 (334), pp. 59–64.

IOP Institute of Physics
Scotland

Planned practical science

Good Practical Science – making it happen (2019) ASE

Written policy, why, how, age, stage, support needs.

Process of producing the policy, discussions as important as policy.

https://www.ase.org.uk/resources/good-practical-science-making-it-happen

IOP Institute of Physics
Scotland

Practical work

Holman J (2017) Good Practical Science, Gatsby Foundation, London.
https://www.gatsby.org.uk/education/programmes/support-for-practical-science-in-schools

GATSBY

Planned practical work

Purposeful practical work

Expert teachers (Subject specialists)

Frequent and varied practical work

Laboratory facilities and equipment

Technical Support / Technicians

Real experiments, virtual enhancements

Investigative projects

Balanced risk (unnecessary risk aversion)

Assessment fit for purpose

(include practical and formatively assess)

Reducing cognitive load in practical work

Students have a limited working memory.

Demonstrate / Visualise each step of the practical to students.

Use visual instructions to minimise cognitive load of complex tasks.

Use narrative to remember concepts via stories.

Make practical work hypothesis driven to enable thinking about what results they might get.

Reducing cognitive load in practical work

3a. Make students think about why they are making a given Hypothesis.

e.g. Use two part MCQs.

Question:

What is the relationship between the force of friction and the mass of an object?

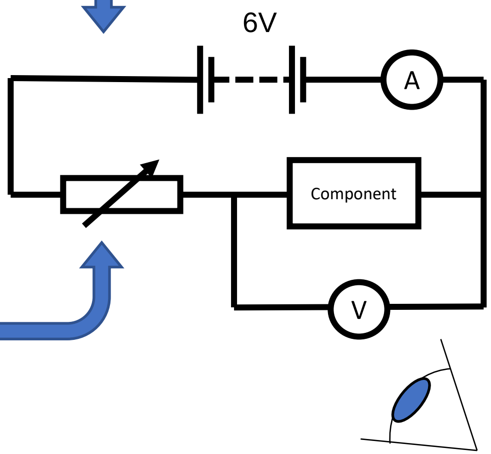
A. As mass increases, friction stays the same

B. As mass increases, friction decreases

C. As mass increases, friction increases

- because the roughness of the surface is always the same regardless of the mass
- because the roughness is smoothed out by increased mass pushing down
- because the roughness is more difficult to overcome when increased mass pushes down

❶ Set up circuit
component = ⊗
component = ▭



❷ Adjust variable resistor to give different voltage reading

❸ Measure voltage and current

❹ Repeat ❷ & ❸ five times

❺ Reverse the battery wires. Repeat ❷ & ❸ & ❹

Language of Science

Education
Endowment
Foundation

6

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

- 6a: Carefully select the vocabulary to teach and focus on the most tricky words
- 6b: Show the links between words and their composite parts
- 6c: Use activities to engage pupils with reading scientific text and help them to comprehend it
- 6d: Support pupils to develop their scientific writing skills

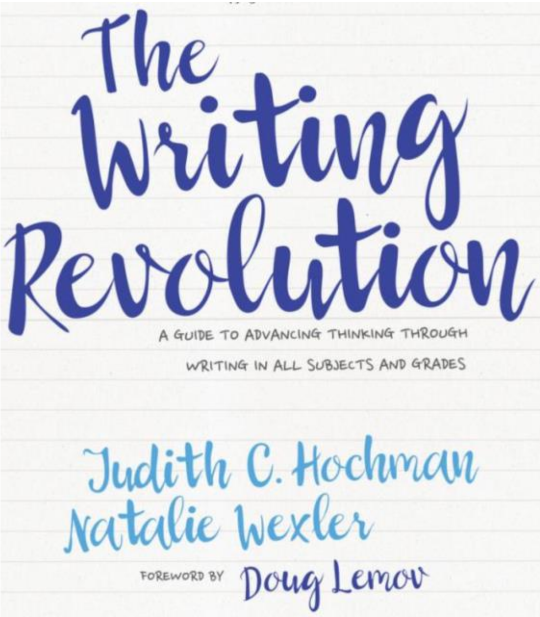
Key words: Etymology

Photovoltaic

Light   Voltage

Scientific writing

- Based upon techniques discussed in "The Writing Revolution" by Hochman & Wexler



Because, but, so

The teacher gives students a sentence stem, an independent clause ending with because, but, so, to encourage extended responses.

Because: explains why something is true = reason

But: indicates a change in direction = contrast

So: what happens as a result of something else = consequence

Because, but, so

In a gas, the particles move about the container, but in a solid, they can only vibrate.

In a gas, the particles move about the container, because they are not attracted to each other.

In a gas, the particles move about the container, so they collide with the walls and exert pressure.

Because, but, so

Fission and Fusion
Refraction and diffraction

but

because

so

My details

Andrew Bailey
Teacher of physics and science
Grove Academy, Dundee
Institute of Physics teacher coach

Twitter:	@andrewkbailey13
Email:	andrewkbailey@gmail.com
Glow:	ddabailey980

Other research to improve learning

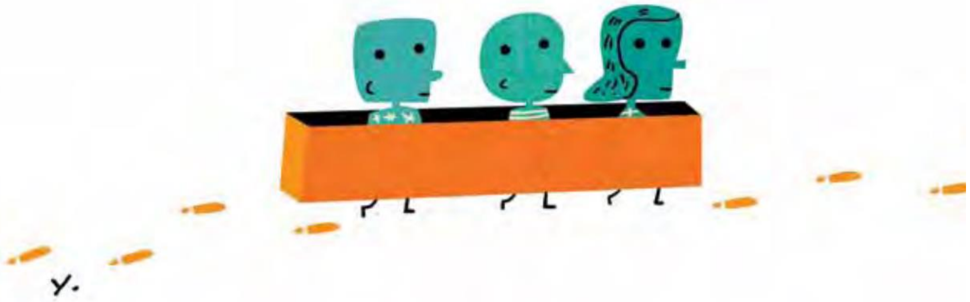
- Rosenshine: Principles of Instruction
- Sweller: Cognitive Load Theory
- Coe: What makes great teaching?
- The Learning Scientists

Rosenshine

Principles of Instruction

Research-Based Strategies That All Teachers Should Know

1. Review of prior learning
2. Present material in small steps, practice after each step.
3. Ask lots of questions and check responses
4. Provide models
5. Guide student practice
6. Check for student understanding
7. Obtain a high success rate
8. Scaffold difficult tasks
9. Require and monitor independent practice
10. Review weekly and monthly



[Principles of Instruction: Research-Based Strategies That All Teachers Should Know, by Barak Rosenshine; American Educator Vol. 36, No. 1, Spring 2012, AFT]()

References

1. Millar, R. and Abrahams, I. (2009) 'Practical work: making it more effective', *School Science Review*, 91(337), pp. 59–65.
2. Rogers, B. (2017a) *Integrating Questions and Diagrams to Reduce Cognitive Load for Novice Physicists – Reading for Learning*. Available at: https://readingforlearning.org/2017/05/01/integrating-questions-and-diagrams-to-reduce-cognitive-load-for-novice-physicists/ (Accessed: 14 May 2023).
3. Rogers, B. (2017b) *When knowledge is wrong… – Reading for Learning*. Available at: https://readingforlearning.org/2017/05/29/when-knowledge-is-wrong/ (Accessed: 12 March 2021).
4. Rogers, B. (2018) *The big ideas in physics and how to teach them: Teaching physics 11-18*, *The Big Ideas in Physics and How to Teach Them: Teaching Physics 11-18*. doi: 10.4324/9781315305431.
5. Rosenshine, B. (2012) 'Principles of Instruction: Research-based strategies that all teachers should know', *American Educator*, pp. 12–20. doi: 10.1111/j.1467-8535.2005.00507.x.

References

6. Sweller, J. *et al.* (2011) 'Cognitive Load Theory in Perspective', in *Cognitive Load Theory*. doi: 10.1007/978-1-4419-8126-4_18.
7. (Centre for Education Statistics and Evaluation/NSW Education Department) (2017) *Cognitive load theory: Research that teachers really need to understand.* Available at: https://www.cese.nsw.gov.au//images/stories/PDF/cognitive_load_theory_report_AA1.pdf (Accessed: 14 May 2023).
8. Coe, R. *et al.* (2014) 'What makes great teaching? A framework for professional learning Question 1: "What makes great teaching?"; Available at: https://headguruteacher.files.wordpress.com/2017/06/what-makes-great-teaching-report-2.pdf (Accessed: 14 May 2023).
9. Deans for Impact (2015) 'The Science of Learning', *Deans for Impact*, p. 9. Available at: www.deansforimpact.org. (Accessed 14 May 2023)

References

10. EEF (2018) ‘Metacognition and Self-regulated Learning: Guidance Report’, *The Sutton Trust-Education Endowment Foundation Teaching and Learning Toolkit*, pp. 1–30. Available at: https://educationendowmentfoundation.org.uk/public/files/Publications/Metacognition/EEF_Metacognition_and_self-regulated_learning.pdf (Accessed: 14 May 2023).
11. Holman, J. and Yeomans, E. (2018) ‘Improving Secondary Science’, *Education Endowment Foundation*. London, p. 48. Available at: https://educationendowmentfoundation.org.uk/tools/guidance-reports/improving-secondary-science/ (Accessed: 14 May 2023).
12. Jenkins, R. (2017) ‘Using educational neuroscience and psychology to teach science. Part 1.: A case study review of Cognitive Load Theory (CLT) and Cognitive Acceleration through Science Education (CASE)’, *The School Science Review*, 99(367), pp. 93–103. Available at: www.kcl.ac.uk/sspp/departments/ (Accessed: 14 May 2023).
13. Lovell, O. (2020) *Sweller’s Cognitive Load Theory in Action*. John Catt. Available at: https://www.johncattbookshop.com/sweller-s-cognitive-load-theory-in-action (Accessed: 14 May 2023).

References

14. Paterson, D (2017) Making Practical work more effective, Education in Chemistry. Available at: https://edu.rsc.org/feature/making-practical-work-more-effective/3008027.article (Accessed: 14 May 2023)
15. Boxer, A (2017) Cognitive Load in Chemistry Practicals. Available at: https://achemicalorthodoxy.wordpress.com/2017/10/23/cognitive-load-in-chemistry-practicals/ (Accessed: 14 May 2023)
16. Holman, J (2017) Good Practical Science, Gatsby Foundation London. Available at: https://www.gatsby.org.uk/education/programmes/support-for-practical-science-in-schools (Accessed: 14 May 2023)
17. Wilkinson B (2019), Applying Cognitive principles to practical work, ASE West 2019. Available at https://twitter.com/DrWilkinsonSci/status/1195674063399784449 (Accessed: 14 May 2023)
18. Hochman J & Wexler N (2017) One Sentence at a time. The need for Explicit Instruction in Teaching Students to Write Well. Available at https://www.aft.org/sites/default/files/ae_summer2017_hochman_and_wexler.pdf (Accessed: 14 May 2023)

References

19. Chillimamp T (2019) The Writing (In Science) Revolution. Available at: https://tomchillimamp.medium.com/the-writing-in-science-revolution-a10b2d0bc811 (Accessed 14 May 2023)
20. Raichura, P (2018) Writing in Science: A Symposium. Available at https://bunsenblue.wordpress.com/2018/10/03/writing-in-science-a-symposium/ (Accessed 14 May 2023)