Talking science pedagogy
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How to use this study unit

As well as background theory this study unit offers practical strategies for you to use in the classroom. All the strategies suggested have been tried and tested by teachers in their own classrooms. They draw on both academic research and the experience of practising teachers. You may have looked at *Teaching and learning in secondary school materials* (DfES 0423-2004); although there are similarities with these materials, you will find that this unit gives specific advice that will be immediately relevant for use in your classroom.

Your science consultant can help you work through this unit on your own but it would be better to pair with a colleague who also wishes to enhance the progress of the pupils.

The unit is structured so that the activities listed towards the beginning are simple and quick to implement; more challenging activities come towards the end. It contains case studies and tasks for you to undertake, and ‘reflection’ activities which will help you revisit an idea or consider your own practice. Practical tips and tasks allow you to consider the advice or try out new techniques in the classroom. The final page invites you to reflect on the experience of having tried out new materials and set some personal targets for the future. You can work through the materials in a number of ways.

- Start small – choose one class to work with. Ask another teacher or your subject leader to help by providing a sounding board for your ideas.

- Work with your science consultant on developing and planning your approach to creating a progress culture. After three weeks, meet together to review how it is going. Discuss which strategies have been most effective with one class and plan how to use this with other classes.

- Find another science teacher to pair with and team teach. Design the activities together and divide the teacher’s role between you.

- Work with a group of teachers in the department. Use the unit as a focus for joint working, meet regularly to share ideas and then review progress after a few weeks.

- Identify the sections of the unit that are most appropriate for you and focus on those.

You may find it helpful to keep a journal of events. For some tasks you may want to make a video recording of yourself in action so you can make a realistic appraisal of your performance. You could add this, along with any other notes and planning that you do as you work your way through the unit, to your continuing professional development (CPD) portfolio.
Talking science pedagogy

Introduction

We all know that some lessons are more successful at delivering the intended learning outcomes than others. In order to improve our practice, and achieve better outcomes for pupils, it is vital that as a profession we can explore why certain approaches are more effective in a given context than another. Why are some lessons successful? Why don’t others turn out as we had hoped?

You may also have noticed that you can look at a lesson plan in a scheme of work and have a sense of whether that lesson is likely to be successful even though you have never taught it. Have you ever wondered what the basis is for this ‘intuition’? What is it about the lesson plan that clues you in to its likely success?

Reflection

- Think about some lessons that you have taught recently that you felt were particularly successful or did not go as well as you had hoped.
- Did you discuss the reasons behind the success/disappointment with colleagues afterwards?
- How much of the discussion focused on the behaviour of pupils and how much on the design of the lesson itself?
- Do you have opportunities to review how you teach particular ideas or areas of science as a department? Do you have a rolling review of the lessons that make up your schemes of work?

If you have tried any of the things suggested in the reflection activity you may have noticed that one of the obstacles to discussing the successful/less successful features of given lessons is the absence of a shared vocabulary with which to talk about aspects of teaching and learning. Research suggests that establishing a common vocabulary is an important step towards enabling improvement.

‘I can go into a classroom and see an outstanding teacher and feel guilty that I am not as good as that. But we have not developed the language or way of working that allows teachers to take that good practice and use it to develop themselves.’

Professor David Hopkins, reported by TES 10 June 2005
The aim of this study pack is to help you and your colleagues to begin to develop such a vocabulary.

The new programme of study for Key Stage 4 science from September 2006 and the new Key Stage 3 from September 2008 have a much greater emphasis on ‘How science works’. At Key Stage 4 many teachers have found that in order to teach ‘How science works’ effectively they need to use teaching approaches that are new or infrequently used in previous GCSE science teaching.

There is a fundamental shift of emphasis in the new courses with the objective of teaching ‘How science works’ being that pupils develop an understanding of how science and scientists work rather than gain a body of knowledge.

The demands of the new Key Stage 4 courses provide fertile ground for exploring again with colleagues which teaching approaches are most successful and more importantly, why.

### Starter: Stop and think

- Think back to how you were taught science at school.
- What were lessons like?
- What did the teacher do?
- What did you do?
- What worked best for your learning?
- Discuss your experiences with a colleague. Record your thoughts for use later in this unit.

### Talking science pedagogy

This study unit explores the idea of ‘teaching models’ as a fourth dimension to a teacher’s professional knowledge. It focuses on opportunities to improve the learning and engagement of pupils at Key Stage 3 and Key Stage 4 science.

This unit is one of four self-study packs that are provided as part of a suite of materials designed to increase the number of pupils who reach L6+ at Key Stage 3 and achieve A*/B at Key Stage 4. The four booklets are:

- Talking science pedagogy
- Creating a progress culture
- Going for gold: securing attainment
- Developing critical and creative thinking: in science

You should use this unit in conjunction with the five other self-study units in the Strengthening teaching and learning in science through using different pedagogies (DfES 0703-2004G) materials, each of which covers different aspects of science teaching.
The challenge of the new programmes of study

There is a fundamental shift of emphasis in the new programmes of study. The objective of teaching ‘How science works’ is that pupils develop critical and creative thinking skills and become flexible problem solvers by exploring how science and scientists work.

Pupils should not just be acquiring a body of knowledge (‘learning about science’) and neither should ‘How science works’ be a ‘bolt on’ extra to lessons.

‘How science works’ should be central to pupils’ learning. For many, embracing this change has been and still is the greatest challenge of the new science curriculum.

How much do you know about the reasons behind the changes at Key Stage 4 from September 2006 and the nature of ‘How science works’?

Pre-task: An exploration of the demands of the new Key Stage 4 specifications

The activities in the table below (taken from the spring term 2007 science subject leader development meeting materials) are designed to develop your understanding of several key aspects of the new specifications.

You need to look at only the activities which relate to aspects you are unsure about.

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Supporting activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Why was the programme of study for KS4 science changed and what do these changes aim to achieve?</td>
<td>Presentation Why GCSE 2006?</td>
</tr>
<tr>
<td>The progression between scientific enquiry in KS3 and ‘How science works’ at GCSE</td>
<td>Activity P1 Matching the PoS for KS3 scientific enquiry to the PoS for GCSE ‘How science works’</td>
</tr>
<tr>
<td>The ‘How science works’ dimension of the grade criteria for the new GCSEs</td>
<td>Activity P2 Highlighting the ‘How science works’ aspects in the new GCSE grade criteria</td>
</tr>
<tr>
<td>The concepts and terminology of ‘How science works’</td>
<td>Activity P3 Developing a shared understanding by matching terminology and definitions from GCSE ‘How science works’</td>
</tr>
</tbody>
</table>
### Supporting activities

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Supporting activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Using approaches such as group work and discussion in lessons</td>
<td>Strengthening teaching and learning in science through the use of different pedagogies: Unit 1 Using group talk and argument (DfES 0703-2004-G)</td>
</tr>
<tr>
<td>Using contemporary science issues in science lessons</td>
<td>Strengthening teaching and learning in science through the use of different pedagogies: Unit 5 Teaching the science of contemporary issues (DfES 0703-2004-G)</td>
</tr>
</tbody>
</table>

## Task 1: ‘How science works’ in your specification

Think about your Key Stage 4 specification. To what extent are the following aspects a requirement and to what extent are they explicit in your scheme of work?

<table>
<thead>
<tr>
<th>Learning demands</th>
<th>Requirement of specification?</th>
<th>Explicit in the scheme of work?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enquiry skills particularly data handling and the interpreting graphs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group work, debate and argument</td>
<td></td>
<td></td>
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<tr>
<td>Research opportunities</td>
<td></td>
<td></td>
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<tr>
<td>Critical evaluation of evidence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extended writing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Learning demands | Requirement of specification? | Explicit in the scheme of work?
--- | --- | ---
How the scientific community works |  |  
The tentative nature of scientific knowledge |  |  

So, how does science work?

Much has been written about the nature of the scientific method ([see resource 9.1](#) for a brief history of the scientific method). Click on the following link to hear leading scientist Lewis Wolpert talking about this subject.

Lewis Wolpert on the scientific method

But what about school science?

For a long time the message to pupils about how science was done was dominated by the rigid dogma of *method, results, conclusion*. Then, almost as a reaction against this, an era of ‘egg racing’ was ushered in. The ‘method’ in school science became a matter of starting with a blank sheet of paper and ‘playing around’ with apparatus in the hope of finding out something interesting – fine as an approach if you have 400 years to re-invent the wheel!

In more recent times GCSE science has presented a view of the scientific method based around POAE (planning, obtaining evidence, analysing/drawing conclusions and evaluating). The assessment of a pupil’s ability to ‘do science’ gradually reduced to a measure of their ability to jump through a series of pre-determined hoops and to do so in an ever narrowing range of contexts. A whole generation of pupils became masters at ‘investigating the rate of reaction between marble chips and acid’ or ‘investigating the resistance of wires’.
The POAE model of the scientific method raised the idea of a fair test to undue prominence. For many pupils and their teachers fair testing has become the only method of scientific investigation and other forms of enquiry are either ignored or shoe-horned into the fair testing model.

The arrival of the new specifications from 2006 offers a much broader interpretation of the scientific method and an opportunity to examine the way particular scientific discoveries were made and acknowledge this dimension in our teaching.

**Task 2: The place of practical and investigative work in your lessons**

Use resource 2.1 to list investigative and practical activities you have done with pupils in the last fortnight. For each one identify what your intended outcomes were for pupils and categorise these as either knowledge or skills based. For each activity complete the remaining columns as appropriate.

**Reflection**

- How much investigative/practical work have you done in the last fortnight? What percentage of lessons included this dimension?
- Is there any pattern in your use of investigative/practical work?
- Are your intended outcomes mostly skills based, knowledge based, or a mixture of both?
- Have pupils experienced a range of different types of enquiry or are fair tests dominant?
More than one way to teach science: towards a common vocabulary for discussion

Much of the previous section focused on ‘what’ pupils need to learn rather than ‘how’ they might learn it. The rest of this guide addresses the more complex question of how to best approach the teaching and learning of key aspects of science.

We all know that there is more than one way to teach a given aspect of science. This section explores different approaches to the same lesson and introduces the idea of ‘teaching models’ as a way of categorising and describing them.

**Task 3: Many hows for a given what**

Ideally you should work with a colleague for this activity. Each of you should look at one of two lesson plans ([resource 3.1](#) or [3.2](#)). Spend a few minutes looking at the structure and sequence of the activities in your version of the lesson. Now work with a colleague and compare your lesson with theirs.

- What are the similarities?
- What are the main differences?
- Have either of you taught this aspect of science recently? If so, what approach did you use and how successful was it?

The lessons you have looked at cover the same aspect of science (types of radiation) and have similar learning outcomes for pupils. However, they apply different approaches or ‘teaching models’: one uses **deductive enquiry**, the other uses **inductive enquiry**.

In this case the difference between the two teaching models is quite subtle. For example, both lessons use almost identical resources. There are two important messages to be drawn from this.

- Adopting a teaching model dimension to lesson planning does not require you to start from scratch with your schemes of work. Much of the planning and many of the resources already exist.
- The subtle nature of the difference in approach means that the decision to adopt one model or another may currently not be a conscious one. The aim of this unit is to make that decision a conscious dimension of your lesson planning. It can promote a dialogue between your colleagues and yourself about which model might be most effective with a particular group of pupils in a given context.
Before …

Well, Newtonian gravitation with set 6 was a total disaster. I couldn't get them down off the ceiling for 30 seconds!

I told you it was too hard! I just gave mine a text book and got them to copy out some notes and even then one of them ate his pencil by mistake.

After …

My deductive approach to Newtonian gravitation didn't achieve the learning outcomes I had planned for set 6.

That's interesting. Last week I used an inductive approach and it seemed to work well.

Now watch a science subject leader, a science teacher and an LA science consultant talking about the challenge of the teaching models vocabulary.
Task 4: What ‘teaching models’ are commonly used in science teaching and what do they look like in practice?

- Look at resource 4.1 which illustrates the episodes in lessons using five teaching models commonly used in science.
- Can you link the pattern of activity from the lessons you have just looked at to the relevant teaching model?
- Thinking back to the starter task in the introduction, which teaching models did your science teacher use to teach you?
- Which models do you think work best for your own learning?
- Which models do you use in your lessons?

A note on ‘using models’ and ‘modelling’ in science teaching

There is the potential for confusion between the use and meaning of the terms ‘using models’ and ‘modelling’.

Modelling is a teaching technique where the teacher shows the pupils what he or she wants them to do or what the end product of their endeavours should look like. In science a teacher might model what a good conclusion should look like, perhaps by examining a range of different conclusions and helping pupils to highlight the key features of a good one. Science teachers commonly model how they would like pupils to carry out an experiment or do a task using a set of the apparatus before sending pupils off to do the activity by themselves.

In the context of this resource ‘using models’ refers to one of five teaching models:

- Direct interactive
- Enquiry/inductive
- Enquiry/deductive
- Using models
- Constructing meaning (constructivist)

When teachers adopt ‘using models’ from the above list, models are used to develop pupils’ understanding of science. Typically in Key Stage 3 and 4 these models take the form of simple physical representations of more complex phenomena or systems. Examples include the plastic cup and sweet model of energy transfer in an electric circuit or a group of boiling tubes containing hot water to represent a cluster of huddling penguins.

In using models the approach is characterised by the explicit teaching of the model including the exploration of the relationship between the model and the thing/system it represents. This should include questioning along the lines of ‘what in real life is represented by this in the model?’
What do you want to do next?

You now have a choice about what you would like to do next. Use this page to navigate your way around the resources.

Click on the box you have chosen to move to that activity. Once you have finished an activity, click on the link provided to return you to these choices.

You should aim to have explored each option before moving on to the next section.

- Look at another pair of lessons exemplifying two different teaching models for the same context: **task 5**

- Think about applying the models to the way you teach some common lessons: **task 6**

- Explore which models are commonly used as part of the scheme of work in your school: **task 7**

- Explore the background to the four dimensions of a teacher’s professional knowledge

- Explore the characteristics of five teaching models commonly used in science

- Watch video footage of two of the teaching models in action

- See a teacher talking about the impact the teaching models dimension has had on her teaching.

- See a science subject leader talk about how he has used a project on teaching models to develop teaching and learning in his department
**Task 5: Comparing two teaching models**

Ideally you should work with a colleague for this activity. Each of you should look at one of the two lesson plans (*resource 5.1 or 5.2*). Spend a few minutes looking at the structure and sequence of the activities in your version of the lesson. Match the episodes in the lessons to the strip cartoons showing the common teaching models in resource 4.1. Now work with a colleague and compare your lesson with theirs.

- What are the similarities?
- What are the main differences?
- Have either of you taught this aspect of science recently? If so, what approach did you use and how successful was it?
- Have you used either of these teaching models in your lessons recently?

**See these lessons in action**

Watch two teachers discussing the enquiry/inductive lesson

Watch two teachers discussing the using models lesson

See what pupils thought about the two lessons

Return to the options
Teaching models in action

Click on each step in turn to see the lessons in action

**Enquiry Inductive lesson**

Pupils are shown images of different products from crude oil and develop ideas about what these products are and where they come from.

Each group of pupils is given two sets of data cards, representing a fraction from the distillation of crude oil. One set shows the name and boiling point, on the other set the name and chain length. Pupils explore possible relationships between the two sets of cards encourage and are encouraged to make a hypothesis linking the two variables.

The teacher demonstrates the distillation of crude oil.

Pupils are given a diagram of a fractional distillation column and discuss the temperatures at the top and the bottom. Pupils place their cards where they think they should be on the column. Pupils are given data cards for two more fractions and asked to fit these into the pattern. Pupils could be asked to guess the chain lengths first and then add them to their diagrams.

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enquiry/Inductive:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pupils gather information</td>
<td>Pupils classify and sort</td>
<td>Based on our information we think …</td>
<td>Pupils re-sort information to test hypothesis</td>
</tr>
</tbody>
</table>

Based on our information we think …

Pupils make hypothesis
Using Models lesson

Pupils are taught a model for carbon chains in hydrocarbons using popper beads to represent the atoms in the chain

Pupils use the popper bead models to investigate viscosity

Pupils do a practical to compare the viscosity of two oils

Pupils use the model to suggest explanations for their observations about the relationship between chain length and viscosity

Pupils explore whether their model can explain other properties of hydrocarbons and hence explore the limitations of their model.

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Using models</strong></td>
<td><strong>Model or idea is taught</strong></td>
<td><strong>We can explain this phenomenon using this model ...</strong></td>
<td><strong>We can change the model to make it better or generate our own models and analogies</strong></td>
</tr>
<tr>
<td><strong>Model or analogy</strong></td>
<td><strong>Pupils visualise abstract ideas</strong></td>
<td></td>
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</tbody>
</table>

With thanks to Cumbria LA science team and the Gloucester LA Pedagogy group.
Task 6: We do this already

This task works well in a department meeting where several pairs can choose different lessons and share their ideas together at the end of the task.

In pairs, choose one of the common lessons from the list below or agree a lesson with your colleague.

- Take turns to describe how you typically deliver this lesson.
- Use the teaching models Resources 4.1 and 4.2 to identify which teaching model(s) you use.
- Did everyone use the same teaching model(s)?
- Is there another teaching model that would work equally well or is perhaps better for some pupils?

See below for some common science lessons

Common science lessons

- Fermentation of yeast
- Magnetic field patterns
- Rate of reaction of marble chips with acid
- Current and voltage associated with a resistor
- Falling parachutes
- Electrolysis of copper sulphate solution
- Osmosis of potato in sugar solution.

Return to the options
Task 7: What teaching models are in common use in our department?

This task works well in a department meeting or INSET day when a larger sample of schemes of work can be covered. Work with a colleague as a pair.

- Look at a lesson plan from one of your schemes of work.
- Use the teaching models resource 4.1 to identify which teaching models are used. Does the scheme of work favour one model?
- Are there occasions where a different model might be equally appropriate or perhaps more successful for some pupils?
- If time allows, review several schemes of work – perhaps an example from each key stage. Is there a difference in the most frequently used models in different key stages?

Note that it is quite likely that any given lesson will use more than one teaching model. This is good practice as the choice of teaching model should be appropriate for the intended learning outcomes for that episode of the lesson.

Return to the options
Which teaching model is best?

Before we can begin to answer this question, we have to ask what we mean by ‘best’. For any situation the most appropriate model will depend on:

1. the nature of the scientific context
2. the strengths of the pupils
3. the strengths of the teacher

There is no best model overall. The best teaching model in a given situation is the one that is most successful in delivering the intended learning outcomes for the pupils. Successful teaching will make use of a range of different models and may well employ more than one model in any given lesson. For example, in a GCSE applied science microscopy unit the lesson sequence might be as follows.

Move from directly teaching how to use a graticule with a microscope and giving learners the opportunity to practise this skill (direct interactive) to

Exploring students’ misconceptions about the size of cells and organelles by eliciting what the learners already know about cell structure and life processes and linking this to their observations under the microscope (constructing meaning) to

Using this skill and previous knowledge to investigate and identify yeast cells in bread culture (enquiry/deductive)
## Exploring the strengths of different teaching models

The success of a given teaching model in a given situation depends to a large extent on the teacher and the pupils having the skills needed to teach and learn in the way proposed by the model. Many less successful lessons result from a skills gap on the part of either teacher the pupils, or both, rather than the unsuitability of the teaching model to the context of the learning. The following table gives an idea of the pupils’ skills needed for each model and the areas of learning for which the model is particularly suited.

<table>
<thead>
<tr>
<th>Description of model</th>
<th>Teacher skills</th>
<th>Types of questions</th>
<th>Good for …</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Enquiry/inductive:</strong> a structured sequence of teacher-directed steps</td>
<td>Questioning, card sorts, categorising, rule building</td>
<td>Can you see any pattern? Can you group these into …? Is there a rule?</td>
<td>Developing or exploring a concept</td>
</tr>
<tr>
<td>Identify an area of study (a context containing the concept to be explored)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Pupils collect and sift information then classify the data</td>
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<tr>
<td>They construct categories for the information</td>
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<tr>
<td>They generate and test hypotheses about their categories, reclassifying if necessary, and so consolidate their understanding</td>
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</tbody>
</table>

<p>| <strong>Enquiry/deductive:</strong> a method of problem solving by generating and testing hypotheses using deductive reasoning | Questioning, experimentation, practical work, research and modelling each stage, reasoning scaffolding, card sorts | What might affect …? What possible reasons might there be for …? What might this be the result of? If this is so, what might we expect to happen and when? How could you find out? Which of the hypotheses is right and which not? Why? | Developing investigative skills Developing an understanding of causal relationships |
| A problem is posed | | | |
| Hypotheses are generated and the data to be gathered to test them is considered and predictions made | | | |
| Data is collected directly or from secondary sources and then presented in such a way that it confirms or refutes the hypotheses | | | |
| Conclusions are drawn | | | |</p>
<table>
<thead>
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<th>Teacher skills</th>
<th>Types of questions</th>
<th>Good for ...</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Constructing meaning:</strong> this method recognises that pupils already hold ideas about the world. It seeks to help them reformulate and refine their understanding through metacognitive processes</td>
<td>Questioning, structured group discussion, concept mapping, use of concept cartoons, experimentation</td>
<td>What do you know/understand about ...? Have a think about this ... But what about this? So do we need to rethink in the light of ...? How might we explain this now?</td>
<td>Concept development</td>
</tr>
<tr>
<td>Pupils' ideas and understanding are made explicit so that the range of potential views can be explored</td>
<td></td>
<td></td>
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<tr>
<td>Pupils engage in restructuring ideas through cognitive conflict and clarification and evaluation</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>The newly agreed views are then applied to new situations to test understanding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finally, pupils review their understanding through discussion</td>
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<tr>
<td>This model builds and reconstructs prior knowledge/understanding through cognitive conflict</td>
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<tr>
<td>There is a strong emphasis on exploration through talk</td>
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</tr>
<tr>
<td><strong>Using models:</strong> this method uses model and analogy to help pupils visualise ideas; it also helps them to think creatively</td>
<td>Questioning, card sorts, demonstration, physical construction, thinking analogously</td>
<td>What does your picture represent? What else is this like? Which part represents which? What does it look like to you? How good is the model/analogy? What can't it explain? What is it like? How is it like ...? What do you think it feels like to be a ...?</td>
<td>Concept development</td>
</tr>
<tr>
<td>Pupils are first exposed to models or analogies to explain a particular idea</td>
<td></td>
<td>Explanation of abstract ideas</td>
<td></td>
</tr>
<tr>
<td>They are asked to consider the strengths and limitations of the model</td>
<td></td>
<td>Developing creativity</td>
<td></td>
</tr>
<tr>
<td>They generate their own models and test them out in explanations</td>
<td></td>
<td>Explain processes</td>
<td></td>
</tr>
<tr>
<td>In some subjects the use of direct analogy and personal analogy can be used to aid creative thought</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description of model</td>
<td>Teacher skills</td>
<td>Types of questions</td>
<td>Good for …</td>
</tr>
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</tbody>
</table>
| **Direct interactive:** a structured sequence that guides the development of new knowledge and skills | Questioning, feedback, modelling, guiding, demonstrating, defining conventions, composing together, scaffolding first attempts, reviewing new learning, mnemonics | Watch what I am doing  
What am I doing here?  
How did I do this?  
How could you do this …? | Knowledge acquisition  
Acquiring new skills such as practical procedures |
| The sequence often begins with whole-class exploration of features of the skill or knowledge to be acquired, with modelling, demonstration or illustration |                                                                                |                                                        |                                |
| Individuals or pairs help to either remember new knowledge and fit into existing ideas or apply and practise the new skill, perhaps with some additional guidance |                                                                                |                                                        |                                |
| The learning ends with a whole-class review, attempting to move pupils from dependence to independence |                                                                                |                                                        |                                |
Developing your own practice: identifying teaching models in action

The chances are that once you have begun to discuss the features of different teaching models you will begin to recognise them in your own lessons and in those delivered by colleagues.

Task 8a: Looking for teaching models in action

You need to pair up with a colleague for this activity. You should arrange to observe each other teaching a lesson, preferably on different topics. The lessons need to be fairly close together so you can remember both of them clearly when you come to discuss them.

On the first run through the lessons do not need to have been planned with teaching models particularly in mind – choose groups you are comfortable with and lessons with which you are familiar (one which you have taught before).

Observe a lesson and keep a record of what you see, using column one only, on form [resource 8.1].

If you have the facilities available you may wish to video key parts of the lessons.

Task 8b: Discussing what you observed

You will need at least an hour of uninterrupted time for this task. In discussion with your colleague, identify the teacher’s and pupils’ action that corresponds to the different stages in the teaching model(s) in use. Use the rest of resource 8.1 to support the process.

Here are some things to consider.

- Use resource 4.1 and 4.2 to help pick out which models were in use and when.
- There will be more than one teaching model in use in each lesson.
- Take care to agree what type of activities the teacher and the pupils were engaged in during each part of the lesson.
- Remember to stay focused on identifying teaching models. Do not stray off into other aspects such as classroom management.
- At the end of the session broaden the discussion to include considering what alternative teaching models might have been used for different episodes in the lesson.
- Keep your agreed lesson observation forms. Along with those completed by colleagues they will build into a useful resource of exemplar material for teaching models in your department.

If time permits you might plan an alternative approach to an episode in one of the lessons (or to a similar episode in a different lesson) using a different model. Arrange to teach it with your colleague observing.
Ready for more?

As a department you could use the approaches in task 8 with pairs of colleagues across the department.

You might want to focus on lessons in one year or on the lessons which develop a specific idea across Years 7 to 11.

From the post-lesson discussions draw out the examples of different teaching models and the teacher and pupil actions associated with these.

Use these materials to build up a pedagogy portfolio for your department. This will be useful to audit the range of teaching models in common use and help you target future INSET. It will be useful for new members of staff who you want to bring up to speed with approaches to teaching and learning in your department.
The scientific method and teaching models

How often do you refer to the way scientists made their original discoveries in your teaching?

The nature of original scientific discovery, often seen as the history of science, does not play a major role in much science teaching. More often than not pupils are given a systemised presentation of the end point (or more usually the established wisdom at a point in the late nineteenth century) which makes no reference to the long and often tortuous journeys taken by science to reach this point.

Occasionally, reference is made to scientists and their discoveries. Usually this takes the form of an anecdote, often amusing, which at best provides a human dimension to science (‘Look children, Isaac Newton was a real person . . .’).

In the context of the new programmes of study much has been said about the need to expose pupils to more of the stories behind scientific discoveries. It is seen as a way of helping them to understand how science works (or perhaps more accurately ‘how science worked’ given the historical contexts).

What if there was a more compelling reason for engaging with the way scientific discoveries were made? What if the way the scientists went about making these discoveries had a direct bearing on the ‘best’ way for pupils to learn about the science itself?

The last section of this guide explores the hypothesis:

‘Teaching that models how science originally made a discovery is more likely to be successful than that which ignores this dimension.’

For example, when teaching pupils about Darwin and the theory of evolution, an inductive approach where pupils examine data about variation in species and suggest patterns may be more successful than, say, a direct interactive approach. The inductive model promises pupils not only an understanding of the science but also an understanding of how science arrived at that particular view. In other words, it helps pupils ‘make sense’ of the science rather than just taking it on trust.
Task 9: Looking at the work of some famous scientists

Look at the mini-biographies in resource 9.2. Compare the way the scientist worked with the characteristics of the five common teaching models. (resources 4.1 and 4.2)

Which teaching model most closely represents the way each scientist worked?

If we are going to include reference to the way scientific discoveries were made in our lesson planning it presupposes that we too, as science teachers, know something about the way these discoveries were made.

Let’s see what two teachers think about the idea of linking the way scientists worked to the teaching model we use in our lessons.

Task 10: How much do you know about how familiar scientific discoveries were made?

How much do you know about how key scientific breakthroughs were made?

This is a dimension which has not had a lot of emphasis in the past and is one which can benefit greatly from the pooling of knowledge.

Work with a colleague or collectively as a department and pool what you know about the scientific discoveries in resource 10.1.

Agree a common view on how a discovery was made. Compare the process with the characteristics of the five common teaching models (resources 4.1 and 4.2). Which teaching model is closest to the way that science made this discovery?

Discuss the way each of these aspects is taught in your department at the moment. Which teaching model do you currently use?

Ready for more?

Pick one of the areas identified in the previous task where the use of a teaching model which reflects the way the science was done originally may help pupils get to grips with the ideas.

Redesign the lessons in your scheme(s) of work using the new teaching model(s). Try these lessons with pupils and arrange to feedback to colleagues about the changes you made and the impact they had in the classroom.
Further reading

*Pedagogy and Practice: teaching and learning in secondary schools unit 1: structuring learning* DfES (0424-2004G)

*Pedagogy and Practice: teaching and learning in secondary schools unit 2: teaching models* DfES (0425-2004G)

Triple science support programme [www.triplescience.org.uk](http://www.triplescience.org.uk)

- Teaching triple science GCSE physics
- Teaching triple science GCSE chemistry
- Teaching triple science GCSE biology


Activity P1

From scientific enquiry to How science works

Outcomes

- Increased awareness of the 'How science works' aspect of the new Programme of study (PoS) for GCSE science.
- Increased understanding of the progression between scientific enquiry in Key Stage 3 and 'How science works' at GCSE.
- Increased understanding of progression within 'How science works' at GCSE.
- Improved planning for teaching scientific enquiry and 'How science works'.

Activity guidance

10–15 minutes including discussion.

Cut up page 4 of this handout into cards. These are the 'How science works' statements from the Key Stage 4 PoS.

Enlarge pages 2 and 3 of this handout to A3 size. This sheet contains the scientific enquiry statements from the Key Stage 3 PoS.

Introduce the task by saying that this activity explores the progression between scientific enquiry in Key Stage 3 and the How science works aspects of the new PoS for GCSE science.

Group colleagues into pairs or threes and ask them to place the 'How science works' statements onto the A3 sheet to show progression from Key Stage 3 to 4, as well as identifying aspects that are new at Key Stage 4.

Related tasks

Some colleagues may wish to organise their Key Stage 4 cards into a progression through the two years of the GCSE course and then reflect on the extent to which this progression is actually reflected in the department’s current scheme of work (SoW) for Key Stage 4.

Ask colleagues to think about where the Key Stage 3 scientific enquiry skills are currently taught and how the existing Key Stage 3 SoW could be adjusted to better prepare pupils for Key Stage 4.
From scientific enquiry to *'How science works'*

<table>
<thead>
<tr>
<th>Key Stage 3: scientific enquiry</th>
<th>Key Stage 4: <em>How science works</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Teaching should ensure that <strong>scientific enquiry</strong> is taught through contexts taken from the sections on <strong>life processes and living things, materials and their properties</strong> and <strong>physical processes</strong>.</td>
<td>Teachers should ensure that the <strong>Knowledge, skills and understanding</strong> of <em>'how science works'</em> are integrated into the teaching of the <strong>Breadth of study</strong>.</td>
</tr>
</tbody>
</table>

**Ideas and evidence in science.** *Pupils should be taught:*

| a. | about the interplay between empirical questions, evidence and scientific explanations using historical and contemporary examples (for example, Lavoisier’s work on burning, the possible causes of global warming) |
| b. | that it is important to test explanations by using them to make predictions and by seeing if evidence matches the predictions |
| c. | about the ways in which scientists work today and how they worked in the past, including the roles of experimentation, evidence and creative thought in the development of scientific ideas. |

**Investigative skills.** *Pupils should be taught to:*

**Planning**

<p>| a. | use scientific knowledge and understanding to turn ideas into a form that can be investigated, and to decide on an appropriate approach |
| b. | decide whether to use evidence from first-hand experience or secondary sources |
| c. | carry out preliminary work and to make predictions, where appropriate |
| d. | consider key factors that need to be taken into account when collecting evidence, and how evidence may be collected in contexts (for example, fieldwork and surveys) in which the variables cannot readily be controlled |
| e. | decide the extent and range of data to be collected and the techniques, equipment and materials to use (for example, appropriate sample size for biological work) |</p>
<table>
<thead>
<tr>
<th>Key Stage 3: scientific enquiry</th>
<th>Key Stage 4: How science works</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Obtaining and presenting evidence</strong></td>
<td></td>
</tr>
<tr>
<td>a. use a range of equipment and materials appropriately and take action to control risks to themselves and to others</td>
<td></td>
</tr>
<tr>
<td>b. make observations and measurements, including the use of ICT for datalogging [for example, variables changing over time] to an appropriate degree of precision</td>
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</tr>
<tr>
<td>c. make sufficient relevant observations and measurements to reduce error and obtain reliable evidence</td>
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<tr>
<td>d. use a wide range of methods, including diagrams, tables, charts, graphs and ICT to represent and communicate qualitative and quantitative data</td>
<td></td>
</tr>
<tr>
<td><strong>Considering evidence</strong></td>
<td></td>
</tr>
<tr>
<td>a. use diagrams, tables, charts and graphs, including lines of best fit, to identify and describe patterns or relationships in data</td>
<td></td>
</tr>
<tr>
<td>b. use observations, measurements and other data to draw conclusions</td>
<td></td>
</tr>
<tr>
<td>c. decide to what extent these conclusions support a prediction or enable further predictions to be made</td>
<td></td>
</tr>
<tr>
<td>d. use their scientific knowledge and understanding to explain and interpret observations, measurements or other data, and conclusions</td>
<td></td>
</tr>
<tr>
<td><strong>Evaluating</strong></td>
<td></td>
</tr>
<tr>
<td>a. consider anomalies in observations or measurements and try to explain them</td>
<td></td>
</tr>
<tr>
<td>b. consider whether the evidence is sufficient to support any conclusions or interpretations made</td>
<td></td>
</tr>
<tr>
<td>c. suggest improvements to the methods used, where appropriate.</td>
<td></td>
</tr>
</tbody>
</table>
### How science works (cut up into cards)

#### Data, evidence, theories and explanations

- **Pupils should be taught:**
  - 1a. how scientific data can be collected and analysed
- **Pupils should be taught:**
  - 1c. how explanations of many phenomena can be developed using scientific theories, models and ideas
- **Pupils should be taught:**
  - 1b. how interpretation of data and using creative thought provide evidence to test ideas and develop theories
- **Pupils should be taught:**
  - 1d. that there are some questions that science cannot currently answer, and some that science cannot address

#### Practical and enquiry skills

- **Pupils should be taught to:**
  - 2a. plan to test a scientific idea, answer a scientific question, or solve a scientific problem
- **Pupils should be taught to:**
  - 2c. work accurately and safely, individually and with others, when collecting first-hand data
- **Pupils should be taught to:**
  - 2b. collect data from primary or secondary sources, including using ICT sources and tools
- **Pupils should be taught to:**
  - 2d. evaluate methods of collection of data and consider their validity and reliability as evidence

#### Communication skills

- **Pupils should be taught to:**
  - 3a. recall, analyse, interpret, apply and question scientific information or ideas
- **Pupils should be taught to:**
  - 3c. present information, develop an argument and draw a conclusion, using scientific, technical and mathematical language, conventions and symbols, and ICT tools
<table>
<thead>
<tr>
<th>Pupils should be taught:</th>
<th>Applications and implications of science</th>
</tr>
</thead>
</table>
| 3b. use both qualitative and quantitative approaches | **Pupils should be taught:**
|                          | 4a. about the use of contemporary scientific and technological developments and their benefits, drawbacks and risks |
| **Pupils should be taught:** | 4c. how uncertainties in scientific knowledge and scientific ideas change over time and about the role of the scientific community in validating these changes |
| 4b. to consider how and why decisions about science and technology are made, including those that raise ethical issues, and about the social, economic and environmental effects of such decisions | **Pupils should be taught:** |
Activity P2

Highlighting the 'How science works' aspects in the new GCSE grade criteria

Outcomes

- Increased awareness of the 'How science works' aspect of the new programme of study (PoS) for GCSE science.
- Increased understanding of expectations for pupils’ success in the new GCSEs.
- Appreciation of the importance of teaching 'How Science Works' for pupils' success at GCSE.

Activity guidance

10–15 minutes including discussion.

Resources needed – three different colours of highlighter pen.

Introduce the task by saying that this activity explores the requirements for success at different grades in the new GCSE courses. All GCSE science specifications share these grade criteria which are used by the Qualifications and Curriculum Authority (QCA) as part of a process to ensure comparability between specifications.

Group colleagues into pairs or threes. Give each pair/three a copy of pages 2–5 of this handout. Allocate each pair one of grades A, C or F. Ask them to highlight on the grade criteria any sentences or part sentences that relate to the PoS for 'How Science Works' from the new GCSE. It is easier if you give each grade group a different highlighter colour.

After five minutes ask all the F groups to hold up their sheets so people can see the extent of the shading. Repeat with C and A grades.

A significant part of each criterion should be shaded in with the proportion increasing as you go from F to A grades.

Related tasks

Do the same activity for the grade criteria from the ‘relic’ specifications – compare new with old. This should show much less emphasis on 'How science works' outcomes in the older specifications. Link this to the need to change teaching and learning in Key Stage 4 in response to the changes to the specifications.
Grade A
Candidates demonstrate a detailed knowledge and understanding of science content and *how science works*, encompassing the principal concepts, techniques and facts across all areas of the specification. They use technical vocabulary and techniques with fluency, clearly demonstrating communication and numerical skills appropriate to a range of situations.

They demonstrate a good understanding of the relationships between data, evidence, and scientific explanations and theories. They are aware of areas of uncertainty in scientific knowledge and explain how scientific theories can be changed by new evidence.

Candidates use and apply their knowledge and understanding in a range of tasks and situations. They use this knowledge, together with information from other sources, effectively in planning a scientific task such as a practical procedure, testing an idea, answering a question, or solving a problem.

Candidates describe how, and why, decisions about uses of science are made in contexts familiar to them, and apply this knowledge to unfamiliar situations. They demonstrate good understanding of the benefits and risks of scientific advances, and identify the related ethical issues.

They choose appropriate methods for collecting first-hand and secondary data, interpret and question data skilfully, and evaluate the methods they use. They carry out a range of practical tasks safely and skilfully, selecting and using equipment appropriately to make relevant and precise observations.

Candidates select a method of presenting data appropriate to the task. They draw and justify conclusions consistent with the evidence they have collected and suggest improvements to the methods used that would enable them to collect more valid and reliable evidence.

Grade C
Candidates demonstrate a good overall knowledge and understanding of science content and *how science works*, and of the concepts, techniques and facts across most of the specification. They demonstrate knowledge of technical vocabulary and techniques, and use these appropriately. They demonstrate communication and numerical skills appropriate to most situations.

They demonstrate an awareness of how scientific evidence is collected and are aware that scientific knowledge and theories can be changed by new evidence.

Candidates use and apply scientific knowledge and understanding in some general situations. They use this knowledge, together with information from other sources, to help plan a scientific task such as a practical procedure, testing an idea, answering a question, or solving a problem.

They describe how, and why, decisions about uses of science are made in some familiar contexts. They demonstrate good understanding of the benefits and risks of scientific advances, and identify related ethical issues.
They carry out practical tasks safely and competently, using equipment appropriately and making relevant observations appropriate to the task. They use appropriate methods for collecting first-hand and secondary data, interpret the data appropriately, and undertake some evaluation of their methods.

Candidates present data in ways appropriate to the context. They draw conclusions consistent with the evidence they have collected and evaluate how strongly their evidence supports these conclusions.

**Grade F**

Candidates demonstrate a limited knowledge and understanding of science content and how science works. They use a limited range of the concepts, techniques and facts from the specification, and demonstrate basic communication and numerical skills, with some limited use of technical terms and techniques.

They show some awareness of how scientific information is collected and that science can explain many phenomena.

They use and apply their knowledge and understanding of simple principles and concepts in some specific contexts. With help they plan a scientific task, such as a practical procedure, testing an idea, answering a question, or solving a problem using a limited range of information in an uncritical manner. They are aware that decisions have to be made about uses of science and technology and, in simple situations familiar to them, identify some of those responsible for the decisions. They describe some benefits and drawbacks of scientific developments with which they are familiar and related issues.

They follow simple instructions for carrying out a practical task and work safely as they do so.

Candidates identify simple patterns in data they gather from first-hand and secondary sources. They present evidence as simple tables, charts and graphs, and draw simple conclusions consistent with the evidence they have collected.

© Qualifications and Curriculum Authority.
Programme of study: Key Stage 4 science: Knowledge, skills and understanding

Teachers should ensure that the Knowledge, skills and understanding of 'How science' works are integrated into the teaching of the Breadth of study.

'How science works'

Data, evidence, theories and explanations

1. Pupils should be taught:
   a. how scientific data can be collected and analysed
   b. how interpretation of data, using creative thought, provides evidence to test ideas and develop theories
   c. how explanations of many phenomena can be developed using scientific theories, models and ideas
   d. that there are some questions that science cannot currently answer, and some that science cannot address.

Practical and enquiry skills

2. Pupils should be taught to:
   a. plan to test a scientific idea, answer a scientific question, or solve a scientific problem
   b. collect data from primary or secondary sources, including using ICT sources and tools
   c. work accurately and safely, individually and with others, when collecting first-hand data
   d. evaluate methods of collection of data and consider their validity and reliability as evidence.

Communication skills

3. Pupils should be taught to:
   a. recall, analyse, interpret, apply and question scientific information or ideas
   b. use both qualitative and quantitative approaches
   c. present information, develop an argument and draw a conclusion, using scientific, technical and mathematical language, conventions and symbols and ICT tools.
Applications and implications of science

4. Pupils should be taught:
   a. about the use of contemporary scientific and technological developments and their benefits, drawbacks and risks
   b. to consider how and why decisions about science and technology are made, including those that raise ethical issues, and about the social, economic and environmental effects of such decisions
   c. how uncertainties in scientific knowledge and scientific ideas change over time and about the role of the scientific community in validating these changes.

During Key Stage 4 pupils learn about the way science and scientists work within society. They consider the relationships between data, evidence, theories and explanations, and develop their practical, problem-solving and enquiry skills, working individually and in groups. They evaluate enquiry methods and conclusions both qualitatively and quantitatively, and communicate their ideas with clarity and precision. All pupils develop their ability to relate their understanding of science to their own and others’ decisions about lifestyles, and to scientific and technological developments in society. Most pupils also develop their understanding and skills in ways that provide the basis for further studies in science and related areas.

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Activity P3

Return

Developing a shared understanding by matching terminology and definitions from GCSE How Science Works

Outcomes

- A shared understanding and greater confidence on the part of teachers about the meaning and use of key pieces of terminology associated with 'How science works'.
- Explicit teaching of terminology gives pupils increased ability to discuss key aspects of 'How science works', such as reliability and accuracy.

Activity guidance

10–15 minutes including discussion.

Cut up pages 2–5 of this handout into separate cards – enough sets for colleagues to work in pairs on the task.

Introduce the task by saying that this activity explores the terminology used in 'How science' works with a view to developing a shared understanding of key terms.

Group colleagues into pairs or threes. Give each pair/three a set of cards each and ask them to link the terms to the definitions. Go through the terms to check that there is agreement amongst colleagues about the meaning of each.

Alternatively if you have a large department you could run the activity as a loop card game by producing terminology cards with the definition which is immediately below the correct one in the next column on the back.

Allocate each pair two or three terms and ask them to write a pupil-friendly explanation of the meaning of each one – including a sentence showing the correct use of the term. Use page 6 of this handout to help.

Related tasks

Decide as a team whereabouts in the scheme of work it is best to teach pupils each piece of terminology.

Do the same matching activity with pupils using all or some of the cards.

Ask pupils to produce definitions of the terms.
**Key terminology associated with 'How science works' (cut up into individual cards)**

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>accuracy</td>
<td>How close a measurement of something is to its true value.</td>
</tr>
<tr>
<td>argument</td>
<td>Statements offered in support of your conclusion or opinion.</td>
</tr>
<tr>
<td>benefits and costs</td>
<td>When you do anything, it may make some things better. These are the benefits. But it may also make some things worse. These are the costs.</td>
</tr>
<tr>
<td>best estimate</td>
<td>When you measure something, you cannot be sure you have found its true value. There is always some uncertainty in measurements. All you can do is say what you think the true value is most likely to be.</td>
</tr>
<tr>
<td>correlation</td>
<td>A pattern in the data about two things that suggests they are linked; for example when ice cream sales rise, the level of hay fever also increases.</td>
</tr>
<tr>
<td>cause</td>
<td>When two things are correlated and there is a reason to explain how one leads to the other (a mechanism).</td>
</tr>
<tr>
<td>conclusion</td>
<td>The answer you can give to a question – based on data (or evidence) and argument.</td>
</tr>
<tr>
<td>control</td>
<td>A sample that has not been given the treatment you are testing, or has not been exposed to the factor you are investigating. You can use this for comparison.</td>
</tr>
<tr>
<td>data</td>
<td>Pieces of information about a process or object. Good data are both valid and reliable.</td>
</tr>
<tr>
<td>ethics</td>
<td>Rules about how to behave, based on what is right and what is wrong.</td>
</tr>
<tr>
<td>evidence</td>
<td>Data used to support an argument, conclusion, or explanation.</td>
</tr>
<tr>
<td>experiment</td>
<td>A practical procedure, carried out to collect data to test a hypothesis.</td>
</tr>
<tr>
<td>explanation</td>
<td>A series of linked statements, or story, that accounts for something happening. It can only be called 'scientific' if it is accepted by a group of other scientists.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>factor</td>
<td>Anything that can affect something else.</td>
</tr>
<tr>
<td>hypothesis</td>
<td>A suggested explanation for how something happens. A hypothesis is usually based on observations.</td>
</tr>
<tr>
<td>mean</td>
<td>An average from a set of data. (Worked out by adding up a set of measurements, then dividing by the number of measurements.)</td>
</tr>
<tr>
<td>mechanism</td>
<td>A description of how a factor causes an outcome (a cause leads to an effect).</td>
</tr>
<tr>
<td>observation</td>
<td>Something you can say about the world, based on information from your senses.</td>
</tr>
<tr>
<td>outcome</td>
<td>Something that happens because of other things happening. A change in one of these other things (factors) can lead to a change in what happens.</td>
</tr>
<tr>
<td>outlier</td>
<td>A measurement that does not fit the pattern of other data collected.</td>
</tr>
<tr>
<td>peer review</td>
<td>Scientists publish their data and explanations as articles in journals. Before they are published, other scientists read the articles. They evaluate the way the scientist has done their work, the quality of their data and how good their explanation is.</td>
</tr>
<tr>
<td>prediction</td>
<td>What you think will happen in a particular situation. Based on current explanations for how something works, e.g. if the mass on the spring is doubled, the extension of the spring will double.</td>
</tr>
<tr>
<td>range</td>
<td>The lowest to the highest of a set of measurements, e.g. in 24 hours the range of John’s heart rate was 50–125 beats per minute.</td>
</tr>
<tr>
<td>real difference</td>
<td>Too big to be put down to chance. You can be fairly sure that the difference between two mean values is real if their ranges do not overlap.</td>
</tr>
<tr>
<td>regulations</td>
<td>Rules that are made by an authority, such as the government, e.g. all motor vehicles over three years old must have an MOT test.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>---------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>reliability</td>
<td>When repeated measurements of the same thing are close to each other, the data is reliable. You can have more confidence in conclusions and explanations if they are based on reliable data.</td>
</tr>
<tr>
<td>replication</td>
<td>Repeating something, e.g. taking two or three measurements of the same value in an experiment.</td>
</tr>
<tr>
<td>risk</td>
<td>The chance of something happening, and the consequences if it does. Can be classified as perceived, actual, precautionary.</td>
</tr>
<tr>
<td>sample</td>
<td>A group taken from a population.</td>
</tr>
<tr>
<td>sample size</td>
<td>How many there are in a sample.</td>
</tr>
<tr>
<td>scientific community</td>
<td>A group of scientists who work in the same field. They may share ideas, and discuss each other’s work.</td>
</tr>
<tr>
<td>technical feasibility</td>
<td>Something that it is possible to do. This does not mean it should be done.</td>
</tr>
<tr>
<td>validity</td>
<td>A measurement is valid if it measures the thing it is supposed to be measuring.</td>
</tr>
<tr>
<td>variable</td>
<td>A quantity that may change, e.g. the temperature of the air.</td>
</tr>
</tbody>
</table>

With thanks to Jennifer Burden, Co Director, Twenty-First Century science project, University of York.
### What does it mean?

<table>
<thead>
<tr>
<th>Term</th>
<th>Pupil-friendly definition</th>
<th>Sentence using the term correctly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>How certain you can be about your conclusion.</td>
<td>We need to take some more repeat readings to increase the reliability of our conclusion.</td>
</tr>
</tbody>
</table>
### The place of practical and investigative work in your lessons

<table>
<thead>
<tr>
<th>Investigative/practical activity</th>
<th>Intended learning outcomes</th>
<th>Skills (S) Knowledge (K)</th>
<th>Type of enquiry Fair test (FT) Other (O)</th>
<th>Who generated the title/focus of the activity? Pupil (P) Teacher (T)</th>
<th>How and what did pupils record?</th>
<th>What decisions did pupils make during the activity?</th>
</tr>
</thead>
<tbody>
<tr>
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</table>
## Resource 3.1

### Enquiry/inductive teaching model: lesson plan

| ‘How science works’ focus | 1b Interpretation of data provides evidence to test ideas and develop theories  
| 4 Applications of science in police work |
|---|---|
| Breadth of study context | 7c Radiations, including ionising radiations, can transfer energy |
| Lesson objectives | - Be able to identify and describe the properties of each type of radiation  
- Describe the possible hazards associated with different types of nuclear radiation  
- Be able to identify the form of radiation that killed Alexander Litvinenko |
| Outcomes |  |
| Teaching model focus | Enquiry/inductive Radiation types (alpha, beta, gamma) |
| Planned sequence of activities, including starter and plenary. | Starter  
Find out what they already know about Litvinenko. Set the scene without giving too much information now. |
| Describe for each activity its purpose in the teaching sequence. | Main  
Students will take on the role of police officers trying to identify the type of radiation that killed Litvinenko.  
Will be provided with information from BBC news websites along with a set of questions. Use information to answer questions and also create a fact-file on each of the types of radiation.  
May be appropriate to demonstrate the three types of radiation and their penetrating abilities. |
| | Plenary  
Which type of radiation have they decided killed Litvinenko? Find out their thought processes behind how they came to this decision. Did they discard any evidence that might support their hypothesis?  
Extension: pupils can gather further evidence to test their hypothesis from [http://news.bbc.co.uk](http://news.bbc.co.uk). |
| Significant or uncommon resources | See attached materials  
Use of radioactive source – appropriate precautions will need to be taken. |
| Any particular advice or instructions for the teacher | Try to avoid telling students too much. It is their job to find out! Best not to let them search the Internet for information themselves, as they will be able to find out it was alpha radiation. |
| Other notes | Information and ‘alpha, beta, gamma’ image taken from [http://news.bbc.co.uk](http://news.bbc.co.uk). |

With thanks to Gloucester LA pedagogy group.
What killed Alexander Litvinenko?

1. What was the radioactive substance that was believed to have poisoned Alexander Litvinenko?

2. How could this have been administered to Litvinenko?

3. Have any other members of the public been affected? Is there a general risk to the public?

4. Compile a fact file on each of the three forms of radiation – alpha, beta and gamma.

5. From what you know of the three forms of radiation, which form do you think was emitted by the radioactive material?

‘No radiation risk’ public told

Experts investigating the death of Russian ex-spy Alexander Litvinenko say there is no radiation risk to those who had contact with him. The radioactive substance responsible, polonium-210, is naturally found at very low traces in some foods. It is poisonous only at higher doses when eaten or inhaled. Health Protection Agency experts stressed that polonium-210 cannot pass through the skin so should not be caught by direct physical contact. Professor Roger Cox of the HPA said: ‘Having contact with Mr Litvinenko physically does not pose any risk.’

Time line: former Russian spy case

1 November: Mr Litvinenko meets two Russian men at a London hotel – one a former KGB officer. He also meets academic Mario Scaramella at a sushi bar where he is said to have received documents about a journalist’s death. Several hours after his meetings, Mr Litvinenko complains of feeling sick and spends the night vomiting.

25 November: Tests are to be performed on people who may have come into contact with Mr Litvinenko, including those who were at the Itsu sushi bar in London. Police were searching the sushi bar and a bedroom at the Millennium Hotel.

27 November: Police confirm traces of radioactive polonium-210 have been discovered at two more central London addresses: Grosvenor Street, Mayfair, and Down Street in west London. Three people linked to the central London venues Mr Litvinenko visited on 1 November are referred to a clinic for radiological tests, after reporting possible radiation symptoms.
**Sophistication behind spy’s poisoning**

The poisoning of the former Russian spy Alexander Litvinenko would have required considerable scientific know-how, according to experts. Mr Litvinenko’s death on 23 November was linked to a ‘major dose’ of radioactive polonium-210 found in his body. Polonium-210 occurs naturally in the environment and in people at low concentrations. But acquiring enough of it to kill would require individuals with expertise and connections. Experts estimate that less than a microgram (one millionth of a gram) of the radioactive substance could have been responsible for Mr Litvinenko’s death. ‘If you had had it in a glass or tin vessel, you wouldn’t be able to detect it outside. Which makes it rather ideal as a poison,’ said Dr Frank Barnaby, a nuclear consultant to the Oxford Research Group. ‘But once that container is open, polonium-210 particles have a tendency to creep out and contaminate the surrounding environment.’

**What is the risk to other people from the dose Mr Litvinenko received?**

It cannot pass through the skin, and must be ingested or inhaled into the body to cause damage. And because the radiation has a very short range, it only harms nearby tissue. However, there is a theoretical risk that anyone who came into contact with the urine, faeces and possibly even sweat of Mr Litvinenko could ingest a small amount of the polonium.

**Exposure threat**

Contact with carrier’s sweat or urine could lead to exposure. Polonium-210 must be ingested to cause damage. Radiation has very short range and cannot pass through skin. Washing eliminates traces.
<table>
<thead>
<tr>
<th>Type of radiation</th>
<th>Description:</th>
<th>Mass:</th>
<th>Charge:</th>
<th>Penetrating effect:</th>
<th>Ionising effect:</th>
</tr>
</thead>
<tbody>
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</table>
## Resource 3.2

### Enquiry/deductive teaching model: lesson plan

| ‘How science works’ focus | 1b Interpretation of data provides evidence to test ideas and develop theories  
4 Applications of science in police work |
<table>
<thead>
<tr>
<th></th>
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<tbody>
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<td><strong>Breadth of study context</strong></td>
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</table>
| **Lesson objectives** | Be able to identify and describe the properties of each type of radiation  
Describe the possible hazards associated with different types of nuclear radiation  
Be able to identify the form of radiation that killed Alexander Litvinenko |
| **Outcomes** | Enquiry/deductive  Radiation types (alpha, beta, gamma) |
| **Teaching model focus:** | |
| **Planned sequence of activities, including starter and plenary.** | **Starter**  
Find out what they already know about Litvinenko and radiation. Set the scene.  
**Main**  
Go through presentation on the three types of radiation and demonstrate the three types and their penetrating abilities.  
Students will take on the role of police officers trying to identify the type of radiation that killed Litvinenko. Detective Inspector Rutherford has heard that gamma radiation is very dangerous and believes this is what killed Litvinenko. Students test Rutherford’s hypothesis.  
Students will be provided with information from BBC news websites along with a set of questions. Use information from the presentation, demonstration and news articles to answer questions and compile a fact file on each type of radiation. Draw a conclusion based on what they have found out.  
**Plenary**  
Was Detective Inspector Rutherford’s hypothesis correct? Why? Students must justify their answer.  
Students need to re-evaluate the hypothesis. What alternative hypotheses could they suggest and what evidence is there to support this?  
For example, it was alpha radiation because … |
Significant or uncommon resources | See attached materials. Use of radioactive source – appropriate precautions will need to be taken.

Any particular advice or instructions for the teacher | Litvinenko was killed by alpha radiation. Potential extension to review more up-to-date evidence at http://news.bbc.co.uk.

Other notes | Information and ‘alpha, beta, gamma’ image taken from http://news.bbc.co.uk.

With thanks to Gloucester LA pedagogy group.
What killed Alexander Litvinenko?

1. What was the radioactive substance that was believed to have poisoned Alexander Litvinenko?

2. How could this have been administered to Litvinenko?

3. Have any other members of the public been affected? Is there a general risk to the public?

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5. From what you know of the three forms of radiation, which form do you think was emitted by the radioactive material?
Radiation

The three types

What is radiation?

• There are three main types: alpha, beta and gamma
• All three types of radiation have different properties
• Radiation can damage cells and high doses can kill cells
• Radiation can be detected by photographic film or a Geiger-Muller tube
How can radiation be used?

• Radiation has many practical uses
• Radiation is used:
  – in smoke detectors
  – to sterilise equipment
  – to date rocks
  – to measure the thickness of materials
  – to treat cancer
  – as tracers in the body to detect chemicals

Alpha radiation

• Consists of alpha particles which are identical to the nucleus of a helium atom
• Each particle is made up of 2 protons and 2 neutrons
• Only travels a few centimetres in air
• Is the least penetrating type and can be stopped by a sheet of paper
Beta radiation

- Consists of high energy electrons
- Can travel 10cm in air
- Can penetrate air and paper
- Can be stopped by a thin sheet of aluminium

Gamma radiation

- Is part of the electromagnetic spectrum
- Has a short wavelength and a high frequency
- Travels many metres in air
- Is the most penetrating type of radiation
- Low levels can penetrate air, paper and thin metal
- High levels can only be stopped by many centimetres of lead or a few metres of concrete
The three types of radiation

\[ a = \text{alpha} \]
\[ b = \text{beta} \]
\[ y = \text{gamma} \]

Penetration power of radiation

Images Scientific Instruments Inc. Used with kind permission.
‘No radiation risk’ public told

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It is poisonous only at higher doses when eaten or inhaled.

Health Protection Agency experts stressed that polonium-210 cannot pass through the skin so should not be caught by direct physical contact.

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‘But once that container is open, polonium-210 particles have a tendency to creep out and contaminate the surrounding environment.’

What is the risk to other people from the dose Mr Litvinenko received?

It cannot pass through the skin, and must be ingested or inhaled into the body to cause damage.

And because the radiation has a very short range, it only harms nearby tissue.

However, there is a theoretical risk that anyone who came into contact with the urine, faeces, and possibly even sweat, of Mr Litvinenko could ingest a small amount of the polonium.

Exposure Threat

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Washing eliminates traces.
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</table>
Common teaching models

**Enquiry/Inductive:**
- Pupils gather information
- Pupils classify and sort
- Pupils make hypothesis
- Pupils re-sort information to test hypothesis

**Enquiry/Deductive:**
- Students set out to test hypothesis
- Pupils identify what data needs to be collected
- Pupils draw conclusions from data collected
- Pupils evaluate new evidence against hypothesis

**Constructing meaning:**
- Teacher explores range of pupil views
- Pupils undertake activities that provide cognitive conflict
- Pupils apply restructured ideas to reinforce learning

**Hypothesis**
- What data do we need to test this hypothesis?
- Our conclusion is...
- Does the new evidence fit our hypothesis?

**Elicit pupil ideas**
- I’m just a facilitator

---

*Resource 4.1*
Constructing meaning

Teacher explores range of pupil views

Pupils undertake activities that provide cognitive conflict

Pupils apply restructured ideas to reinforce learning

I’m just a facilitator

Using models

Model or idea is taught

Pupils visualise abstract ideas

We can explain this phenomenon using this model …

We can change the model to make it better or generate our own models and analogies

Direct interactive teaching

Pupils undertake a pre-planned sequence of activities

Pupils answer questions individually or in small groups

What have we found out?

With thanks to Cumbria LA science team and the Gloucester LA Pedagogy group.
## Resource 5.1

### Enquiry/inductive teaching model: lesson plan

| ‘How science works’ focus | 1b How interpretation of data, using creative thought, provides evidence to test ideas and develop theories.  
1e How explanations of many phenomena can be developed using scientific theories, models and ideas. |
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<thead>
<tr>
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<tbody>
<tr>
<td>Breadth of study context</td>
<td>6d The properties of a material determines its use.</td>
</tr>
<tr>
<td>Lesson objectives</td>
<td></td>
</tr>
</tbody>
</table>
Outcome(s)  
- To describe how oil can be separated using fractional distillation.  
- To explain how the properties of each fraction relates to its chain length.  
- Students should be able to generate a hypothesis and then test it using further given data. |
| Teaching model focus      | Enquiry/inductive Fractional distillation of crude oil |
| Planned sequence of activities, including starter and plenary. | Lesson 1 Starter demonstration  
Show images of different products from crude oil and elicit ideas about what these products are and where they come from.  
Main  
Give each group of students two sets of four data cards, each card representing a fraction from the distillation of crude oil (petroleum gases, diesel oil, petrol and kerosene). On one set there should be the name and boiling point, on the other set the name and chain length (this could be just simple pictures of the molecules).  
Students have to look to see if there is a relationship between the two variables.  
Once the relationship has been established, encourage students to make a hypothesis linking the two variables. It does not matter if their reasons are not the ‘correct’ ones, as long as some reasons are offered. Spend some time getting feedback from each group on the wording of their hypothesis.  
Give out an A4 sheet with a fractional distillation column and discuss the temperatures at the top and the bottom. Get students to place their cards where they think they should be on the column. Ask them to come up with ideas on how distillation works.  
Demonstrate the distillation of crude oil and go through the stages, etc.  
Look at the some of the actual products of the distillation of oil and ask the students to think about how viscous (‘runny’) they are. See if they can come up with a hypothesis about viscosity. Could extend this to testing the fuels for how easy they are to ignite to incorporate the flammability of the fractions. |

### Return

### Enquiry/inductive teaching model: lesson plan

| 'How science works' focus | 1b How interpretation of data, using creative thought, provides evidence to test ideas and develop theories.  
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Look at the some of the actual products of the distillation of oil and ask the students to think about how viscous (‘runny’) they are. See if they can come up with a hypothesis about viscosity. Could extend this to testing the fuels for how easy they are to ignite to incorporate the flammability of the fractions. |
Give the students data cards for two more fractions and ask them to see if they fit the pattern. You could ask them to guess at the chain lengths first and then add them to their diagrams.

**Plenary**

Present further ‘fractions’, on similar cards, which do not actually belong to this group, e.g. ethanol, water. Encourage students to group these cards with the others. This will cause some cognitive conflict. Should the hypothesis be changed or is this an exception, limitation or qualification?

<table>
<thead>
<tr>
<th>Significant or uncommon resources</th>
<th>Ampoules of fractions from distillation of oils. <a href="http://www.bpes.com">www.bpes.com</a> provide a good teacher’s resource pack. Data cards as described.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any particular advice or instructions for the teacher</td>
<td>Take care with distillation of crude oil demonstration, see CLEAPSS advice on how to prepare a mock crude oil for this experiment.</td>
</tr>
<tr>
<td>Fraction name</td>
<td>Length of carbon chain (an example of a molecule)</td>
</tr>
<tr>
<td>------------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>Petroleum gases</td>
<td>$C_1$ to $C_4$</td>
</tr>
<tr>
<td></td>
<td><img src="image1" alt="Diagram of Butane" /></td>
</tr>
<tr>
<td>Petrol</td>
<td>$C_4$ to $C_{12}$</td>
</tr>
<tr>
<td></td>
<td><img src="image2" alt="Diagram of Isoheptane" /></td>
</tr>
<tr>
<td>Kerosene</td>
<td>$C_{11}$ to $C_{15}$</td>
</tr>
<tr>
<td></td>
<td><img src="image3" alt="Diagram of Isoundecane" /></td>
</tr>
<tr>
<td>Diesel oils</td>
<td>$C_{15}$ to $C_{19}$</td>
</tr>
<tr>
<td></td>
<td><img src="image4" alt="Diagram of Octodecane" /></td>
</tr>
<tr>
<td>Lubricating oils and waxes</td>
<td>$C_{20}$ to $C_{50}$</td>
</tr>
<tr>
<td></td>
<td><img src="image5" alt="Diagram of Sealane" /></td>
</tr>
<tr>
<td>Mystery molecule 1</td>
<td>Mystery molecule 1</td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>C₂H₅OH</td>
<td>~78°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mystery molecule 2</th>
<th>Mystery molecule 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>~100°C</td>
</tr>
</tbody>
</table>

With thanks to Gloucester LA Pedagogy group.
## Resource 5.2

### Using models teaching model: lesson plan

| ‘How science works’ focus | 1b How interpretation of data, using creative thought, provides evidence to test ideas and develop theories.  
1c How explanations of many phenomena can be developed using scientific theories, models and ideas. |
<table>
<thead>
<tr>
<th></th>
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<td>Breadth of study context</td>
<td>6d The properties of a material determine its use.</td>
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<td>To describe how oil can be separated using fractional distillation.</td>
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<td>To explain how the properties of each fraction relate to its chain length.</td>
</tr>
<tr>
<td></td>
<td>Students should be able to generate a hypothesis and then test it using further given data.</td>
</tr>
<tr>
<td>Teaching model focus</td>
<td>Using models  Fractional distillation of crude oil</td>
</tr>
<tr>
<td>Planned sequence of</td>
<td>Lesson 1 Starter demonstration</td>
</tr>
<tr>
<td>activities, including</td>
<td>Show images of different products from crude oil and elicit ideas about what these products are and where they come from.</td>
</tr>
<tr>
<td>starter and plenary.</td>
<td>Main</td>
</tr>
<tr>
<td>Describe for each activity its purpose in the teaching sequence.</td>
<td>Using a fractional distillation diagram describe the process and explain that the properties of fractions are different because they have different chain lengths. This is the model students will be working with and needs to be established explicitly at the start of the lesson.</td>
</tr>
<tr>
<td></td>
<td>Explain that the chain lengths can indicate particular properties about the fractions including the boiling point, viscosity, flammability and volatility. Keywords and definitions will need to be looked at to make sure the terms are clear in students’ minds.</td>
</tr>
<tr>
<td></td>
<td>In groups of three or four, give the students either popper-style beads or beads and string and ask them to put together beakers with four different fractions in them. Ask them to show and explain each of the properties using their own models (a writing frame may be helpful for lower ability).</td>
</tr>
<tr>
<td></td>
<td>Give out an A4 sheet with a diagram of a fractional distillation column and discuss the temperatures at the top and the bottom. Get students to add the fractions onto the diagram using their model to help them. Ask them to come up with ideas on how it works.</td>
</tr>
</tbody>
</table>
Practical: viscosity of fractions. Get students to perform an experiment to test their model using real fractions. (Time how long it takes for oils to run through funnels.)

How good is this model? Ask students to consider what the limitations of their bead model were. Are there any properties that this model does not explain well? Can they think of any ways to refine this model so it provides a better way of thinking about fractions?

**Plenary**

The key task in this episode is for students to describe the relationships between chain lengths and the key properties outlined earlier. This could be approached in a variety of ways depending on the abilities and learning styles in the class.

For example:

- ‘Show me’ boards could be used to express opinions on whether one fraction has a higher or lower boiling point than the previous one (*play your cards right* style).
- Cloze exercises with key words to place.
- Thumbs up/down for questions that can be answered by yes/no/not sure.
- Students write their own description comparing properties of two fractions.

### Significant or uncommon resources

Ampoules of fractions from distillation of oils: [www.bpes.com](http://www.bpes.com) produce these and a teachers’ resource pack.

### Any particular advice or instructions for the teacher

Take care with distillation of crude oil demonstration: see CLEAPSS advice on how to prepare a mock crude oil for this experiment.
Teaching models: the fourth dimension to a teacher’s professional knowledge

The following section presents views on teaching and learning which will help you think about, plan and discuss science lessons that enable pupils to learn effectively about ‘How science works’.

What follows is drawn from theorised views of pedagogy. It is not the only way to consider teaching and learning but it provides a useful framework for the context in which science teachers are working.

Teaching is complex and teachers need to draw on a wide range of knowledge and understanding to design for effective learning. This range of professional knowledge can be characterised as having four overlapping dimensions.

Click on the diagram below to explore each dimension in turn. Return to choices.

Teachers’ professional knowledge

Return
Subject knowledge

This is about knowing your subject well. It is about understanding:

- the key concepts or big ideas in the subject;
- the common misconceptions that pupils have at different ages;
- progression within the subject;
- how to use assessment effectively;
- contemporary applications of the subject in everyday life and the world of work;
- technical expertise related to the subject;
- new subject knowledge as it becomes available, and understanding its implications for teaching and learning;
- the most effective teaching models.

Skills and techniques

These are activities that demand the active engagement of pupils and promote thinking. The key techniques promoted by the Secondary National Strategy are:

- directed activities related to text;
- relational diagrams and cognitive maps;
- analogy;
- argumentation;
- classification;
- odd one out;
- mysteries.

What is often not realised is that many of these techniques are subsets of teaching models that have been developed from theories about learning. For example, classifying is a subset of the inductive teaching model. These techniques are set out in the Teaching and learning in secondary school materials (DfES 0423-2004G), in the units ‘Active engagement techniques’, ‘Leading and learning’ and throughout a range of other units.
Conditions for learning

When supporting effective learning, teachers need to draw on their understanding of learners and their characteristics: how pupils learn and how they differ in their response to approaches at different ages and from subject to subject. For different groups of pupils, they need to understand how to:

- manage a class, a group, and an individual, and establish routines;
- interact effectively with learners to include them;
- use language to build mutual respect;
- vary approaches to ensure that pupils learn in a variety of ways;
- ensure that learning builds on prior attainment;
- use the environment as a tool for learning;
- organise learning spaces, including practical areas and equipment to meet different needs;
- make the best use of e-learning.

These ideas are developed in units 18, 19 and 20 of the *Teaching and learning in secondary school materials* (DfES 0423-2004-G)

Return to diagram
Teaching and learning models

These have been developed as a direct consequence of theories about learning. Those promoted by the Secondary National Strategy are:

- direct interactive;
- enquiry/inductive;
- enquiry/deductive;
- using metaphor;
- concept attainment;
- using models;
- constructing meaning (constructivist);
- group problem solving;
- exploratory.

Those highlighted in bold are commonly used in science teaching.

Researchers argue that introducing pupils to these methodologies and helping them to recognise how they can help to solve problems or process information will provide pupils with their own tools for learning.

Different models will suit different objectives, subjects and ages of pupils. However, by the end of age 16 pupils should have met them all and should recognise how they can be used to help think, learn and present themselves to others.

The successful use of a given model is intrinsically linked to the other dimensions. Different models place different demands on a teachers’ repertoire and each requires particular ‘conditions for learning’ to be present.
## Exploring five teaching models commonly used in science teaching

### Characteristics of teaching models commonly used in science

<table>
<thead>
<tr>
<th>Teaching model</th>
<th>Characteristics</th>
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| Direct interactive   | Whole-class introduction which often explores some feature of the skill or knowledge to be learned. May include modelling, demonstration or illustration. Individual or small-group work to learn and remember new knowledge or skill. Whole-class plenary to review and to move pupils from dependence to independence.  
Example: Teaching pupils about the heart using models, diagrams, a practical activity to measure or hear rates under different circumstances, with a whole-class annotation of a diagram to capture what was learned. |
| Enquiry/inductive    | Students gather, sort and classify information, suggest and then test hypotheses to identify relationships within the information and between it and other information.  
Example: Learning about the reactions of alkali metals by undertaking practical activities and sorting and classifying the outcomes.  
(Darwin used inductive thinking to arrive at his theory of evolution.)                                                                                   |
| Enquiry/deductive    | Often starts with a hypothesis about an event. Requires pupils to identify what data needs to be gathered to test it, how to gather it and then to draw conclusions, including whether or not more information is needed.  
Example: Looking at how temperature or concentration of reactants might affect a chemical reaction, or what colour of light enables a cress seedling to grow fastest. |
| Using models         | Teachers demonstrate the model, making sure that pupils can picture it. Pupils test the model by using it to explain phenomena. Teachers provide phenomena that challenge the model to identify its limitations. Pupils restructure or change the model to one that is more sophisticated. They apply this to phenomena and possibly explore its limitations.  
Example: Modelling atomic structure and applying it to chemical bonding.                                                                                  |
| Constructing meaning| Teacher sets the scene (orientation) and elicits pupils’ prior ideas. Pupils undertake activities to restructure those ideas using situations that provide cognitive conflict. Pupils apply the restructured ideas to reinforce them. The class then reviews the learning to reflect on the extent to which their ideas have changed.  
Example: Applying the particle model of an atom to learning about atomic structure and perhaps atomic radiation.                                              |
<table>
<thead>
<tr>
<th>Date</th>
<th>Teacher</th>
<th>Group</th>
<th>Learning Objectives</th>
<th>Learning outcomes</th>
<th>Teaching model</th>
<th>What the teacher was doing</th>
<th>What the pupils were doing</th>
<th>Lesson commentary</th>
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### Scientific discoveries

<table>
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<th>How was the science done?</th>
<th>Which teaching model might be most appropriate?</th>
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<td>Discovery of DNA</td>
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<td>The rock cycle</td>
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<td>Plate tectonics</td>
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<td>Helio-centred solar system</td>
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<td>The big bang theory</td>
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<td>Wave theory of light</td>
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<td>Theory of combustion</td>
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<td>Periodic table of elements</td>
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<tr>
<td>Kinetic theory of matter</td>
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A brief history of the scientific method

Introduction

Science has developed many models and approaches to studying the natural world. Each of these has been referred to at various times as ‘the scientific method’. Whether or not there is just one method and whether this reflects ‘How science works’ is a matter of debate. It is useful to consider briefly how science has developed over the past 2000 years and how this may inform our approach to the process of science and science teaching today.

Three periods may be considered as defining in the history of science: the ancient Greek philosophers and their attempts to explain science from a naturalistic standpoint; the Baconian revolution in science and the development of inductive reasoning; and the major developments of the twentieth century with the work of Thomas Kuhn, Karl Popper and Paul Feyerabend.

The Greek naturalistic movement: Thales and Aristotle

The Greek philosopher Thales of Miletus (circa 624 BCE – 546 BCE) is often credited as an originator of ‘the scientific method’ and a founder of the school of natural philosophy. Rather than rely on a supernatural explanation of observed phenomena, i.e. the causal explanation for everything being ‘the Gods’, Thales and the Greek natural philosophers searched for naturalistic explanations. For Thales, there must have been a primary substance or primary principle from which all things originate. His conclusion was that this primary principle was water. His problem was explaining how everything originated from water and how, eventually, everything returns to water.

His answer was that the Earth, as either a disc or cylinder, ‘floated’ on a universal sea of water. To explain how the Earth floats on this cosmic ocean, he thought that it had properties similar to that of wood. Miletus, a Mediterranean coastal town, would have had a harbour and, most likely, wooden ships sailing in and out all the time. It is possible that seeing how ‘heavier than water’ wooden ships could float on the sea prompted Thales’ ideas that the Earth, to which he gave properties similar to wood, could then float on a cosmic ocean. The region is also well known for its volcanic activity and the observation of lighter than water rocks (such as pumice stone common in Mediterranean areas) may also have prompted Thales’ notion of a lighter than water Earth.

Some 200 years after Thales, Aristotle (384 BCE – 322 BCE) – one of history’s most prolific natural philosophers – made countless observations of nature, especially the habits and attributes of plants and animals, and focused on categorising things. He also made many observations on the large-scale workings of the universe, which led to the development of a comprehensive theory of physics. His method of working included the implementation of questions and answers in order to arrive at ‘truths’ or axioms. He applied this logical method at deriving ‘truths’ to his many observations and
developed ‘laws of reasoning’ to arrive at conclusions about the nature of his observations and, more importantly, explanations for those observations.

The aim of Aristotle’s written works was to develop this universal method of reasoning so that it would be possible to learn everything there is to know about reality. Aristotle produced descriptions of things in terms of their properties, states and activities. This is a form of deductive reasoning.

Deductive reasoning starts with known facts or ‘premises’. These, by necessity, lead to conclusions that must be correct. For example:

- an eagle is a bird;
- all birds have wings;
- therefore an eagle has wings.

In this case the ‘known fact’ is that an eagle is a bird (the major premise). That all birds have wings is also a ‘known fact’ (the minor premise) and leads us to the conclusion that eagles have wings. This is an example of valid deductive reasoning. It does not follow that deductive reasoning will always give a valid conclusion. Take the following example:

- a bird has wings;
- a bat has wings;
- therefore a bat is a bird.

This is an example of invalid deductive reasoning. The major premise is true, as is the minor premise, but the conclusion does not have to be true and in this case it is not. What is happening here is that we are using what we know to be true as a substitute for the logic of the statement. We need to be sure that we do not make linked assertions that seem reasonable but in fact are logically incorrect.

Some people make such assertions deliberately, using logic that seems valid to persuade others of their case.

**The scientific revolution**

Sir Francis Bacon (1561–1626) is one of the prime figures of the so-called ‘scientific revolution’. Although Bacon gave science a way of working, he was not primarily an experimental scientist. Bacon promoted the study of science from a position of gathering data and then, by inference or inductive reasoning, to come to conclusions.

With inductive reasoning the initial premises may support the conclusion but do not ensure that the conclusion is correct. We can ‘infer’ from the premises that something is correct. For example, take a traveller making many observations of sheep on farms in the Welsh countryside. All the observed sheep are white, therefore the traveller may infer that all sheep are white. The more observed white sheep the traveller records the stronger the inference and the conclusion he or she makes. The conclusion, however, is not taken to be true. The conclusion can be tested by making more observations. If, on another journey, the traveller observes a black sheep then the conclusion would be shown to be false and a new idea for sheep colour would be needed.

The more observations (premises) that you base your conclusion on the stronger your inductive reasoning.
The above example is an example of strong induction. There are also weak inductive arguments, often made from weak premises. For example, it could be reported that many Antisocial Behaviour Orders (ASBOs) are given to teenagers. Would it be correct to assume therefore that all teenagers will get an ASBO? This is an example of weak induction. Not every teenager will have an ASBO and we must examine where the evidence comes from. If we are looking at the reporting of ASBOs in newspapers then there may be a bias in reporting ASBOs on teenagers. If the evidence covers all ASBOs given nationally we may find that the proportion given to teenagers is the same as that given to people in their twenties or thirties. It may turn out to be true that many more are given to teenagers, but the conclusion that all teenagers will at some time receive an ASBO is still incorrect.

**Popper, Kuhn and the nature of science**

Bacon’s inductive method was prevalent for over 300 years, but its application in certain areas was seen as limited by Sir Karl Popper (1902 –1994). Popper believed in a creative force in scientific thinking and that everyone, including experimental and theoretical scientists, would have a bias. He stated that science advances by ‘deductive falsification’ through a process of ‘conjectures and refutations’ (the title of his 1963 book). He asserted that if a theory can be shown to be falsifiable then it is scientific, if it cannot then it is pseudoscience. He went on to claim that experiments and observations test theories, they do not necessarily produce them.

In contrast, Thomas Kuhn (1922–1996) put forward a view of how science proceeds or operates through ‘revolutions’. He stated that competing scientific workers initially generate a number of theoretical standpoints or frameworks, which are in direct competition. Over time, one of these becomes the dominant framework, i.e. the one that explains the largest number of phenomena observed. Kuhn called this a durable ‘paradigm’. Once this paradigm is accepted and used, during a period that Kuhn calls ‘normal science’, contradictory observations and accounts test it – undermining its dominant position. New frameworks are then developed to account for the anomalous observations and eventually a new ‘paradigm’ is adopted. This is what Kuhn called ‘scientific revolution’. What is important is that the new model or paradigm does not always completely replace the old paradigm and the two may co-exist, for example, Newtonian physics and Einsteinian physics.

**Feyerabend’s anarchistic theory of science**

Paul Feyerabend (1924–1994) argued against the notion of any scientific method. Feyerabend later conceded that he had merely introduced another rigid concept, perhaps even another form of scientific method. Science for Feyerabend is an anarchistic enterprise, his idea being that theoretical anarchism is more humanitarian and more likely to encourage progress than any ‘law-and-order’ alternative. This, he believed, was shown both by an examination of historical episodes and by an abstract analysis of the relation between ideas and actions. The only principle that did not inhibit progress for Feyerabend was ‘anything goes’.
The scientific method and school science

Neither Bacon, Popper, Kuhn nor Feyerabend provides us with an uncontroversial picture of what science is or, indeed, how it works. By reading their views on science we can gain a much deeper understanding.

Scientists are not all Baconian observers; they may indeed ‘become Baconian’ when they describe their observations in their published work. Scientists are rigorous in how they present and finally publish their work. Data are the currency of science and they are always treated with great regard and respect. Should data have been found to have been improperly generated or reported it rightly shocks the community and brings harsh penalties on those who perpetrate scientific fraud.

Scientists do not have to falsify their own theories; there are many others who will oblige and attempt to falsify a rival’s theory. Although Kuhn’s notion of scientific revolutions may suggest wholesale step changes in how we view the workings of the world around us, scientific progress is perhaps more incremental than revolutionary. The science of the twentieth century has undoubtedly provided more explanation and more detailed understanding of natural phenomena than the explanations for those same phenomena put forward in the seventeenth and eighteenth century. It is almost a foregone conclusion that as the twenty-first century progresses so too will our knowledge and understanding progress. The move from Newtonian physics to Einsteinian physics was a revolution, but science and the physics textbooks have not thrown out all of Newton’s ‘laws’ and neither should they.

The fundamental question of whether or not there is one agreed ‘scientific method’ and that this is indeed ‘How science works’ appears to have no simple answer. Alan Chalmers, in his book What is this Thing Called Science? (1990), says that, ‘… the reconstructions of philosophers bear little resemblance to what actually goes on in science’, his reaction to this being that we should, ‘give up altogether the idea that science is a rational activity operating according to some special method or methods.’

Conclusion

‘How science works’ does, to some extent, depend on the science that you are looking at. The theoretical physicist will work differently from the chemist who in turn will differ in their working from a biologist or geologist. There are commonalities that we can derive from the way that scientists work, for example, observation; critical and creative thinking; deductive and inductive reasoning. The ‘scientific methods’ described here will necessarily have some overlap and the processes will be of use in different circumstances. The important thing about school science is that ‘How science works’ is much wider than the experimental method, i.e. just doing experiments and investigations. It is a way of approaching science that allows individuals to look at evidence, assess the conclusions presented and apply logical thinking skills to distinguish valid from invalid conclusions. It also allows those studying science to gain an understanding of the limitations of science in being able to answer questions.
Further Reading


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The work of famous scientists

1: Marie Curie

Marie Curie is one of the most famous scientists ever. She won two Nobel prizes – one for chemistry and one for physics.

Curie worked on a new area of science – radioactivity. She studied minerals that were radioactive because they were compounds of radioactive elements (uranium and thorium). However, she found that the minerals were more radioactive than they should have been given their chemical make-up and the activity of the radio-isotopes they contained.

Curie had the idea that the minerals contained small amounts of impurities that were highly radioactive. To test this idea she had to use careful chemical techniques to separate out the impurities. Curie’s results suggested that the minerals contained very small amounts of unknown elements that were very strongly radioactive – she had to process tonnes of minerals to extract tiny quantities of the new substances.

Curie isolated substances that are now known as polonium (after Curie’s homeland) and radium. Radium was so radioactive that its compounds glowed in the dark.

Curie’s work involved long hours working ‘at the bench’ with large quantities of radioactive materials – materials now known to be very dangerous. Marie Curie’s work involved the difficult task of isolating radioactive elements that were present in very low concentration in minerals such as pitchblende.

2: Albert Einstein

Einstein is one of the most famous scientists ever. Most people would recognise his iconic image and one of his formulas: \( E=mc^2 \).

A lot of people also know that the work that made Einstein’s reputation was not completed in a laboratory but while he was working as an office clerk (checking patent applications). This was possible because Einstein was a theoretical physicist: using pencil and paper to work out his ideas. Einstein’s most important apparatus of course, was his brain, and he carried out ‘thought experiments’.

When he tried to imagine what it would be like to move alongside a beam of light, he decided that it was not possible to travel at the speed of light. Before Einstein’s work, most scientists believed in a simple principle of relativity that had been discussed by Galileo – that relative speeds can be worked out by simple arithmetic.

For example, if two beams of light pass each other in opposite directions, each travelling at \( 3.0 \times 10^8 \) ms\(^{-1} \), then the speed of one beam, relative to the other should be \( 3.0 \times 10^8 \) ms\(^{-1} + 3.0 \times 10^8 \) ms\(^{-1} = 6.0 \times 10^8 \) ms\(^{-1} \).
However, Einstein decided to build up a new model by starting with the assumption that the speed of light (in empty space) is invariant – always measured to be $3.0 \times 10^8$ ms\(^{-1}\) relative to any observer no matter how fast they were moving.

Einstein developed a range of models, mostly using mathematics, to work out the consequences of his ideas. He developed a mathematical model that fitted data about what happens when light is shone on different metal surfaces; and another about the effects of the random movement of molecules. He is most famous, though, for his theories of relativity.

Einstein’s theories fitted with some recognised problems in science. For example, a well-known idea suggested that light needed a medium to travel (called the ether, or æther) but experiments had been unable to detect it. Einstein’s ideas fitted the experimental data, and we now say that light can travel through a vacuum.

Another known problem was that the observed orbit of the planet Mercury did not quite fit the prediction of astronomers who used the well-established theories of Newton. Astronomers had known for many years that calculations based on Newton’s theories led to predictions that were close but not as accurate as they would have expected. Newton’s ideas were used as they were the best available – but Einstein’s theories of gravity were found to be a better fit with the observations.

Einstein’s ideas were also used to make new predictions. These included predictions about the path of light being deflected by mass (‘gravitational lensing’, later tested by observing solar eclipses) and about the passage of time being different for observers at different speeds (later tested by flying clocks into space). These predictions were considered as the basis for crucial tests of the theory.

### 3: William Harvey

William Harvey was a physician working long before modern medical techniques such as X-rays and microscopes were available. In 1635 he carried out an autopsy on a man who was believed to be 152 years and nine months. Harvey described the state of the man’s internal organs and suggested that he might have lived even longer if he had not changed his lifestyle in his old age. (He had gone from being an agricultural labourer to a celebrity living in the polluted city, eating too much fatty food and not taking enough exercise – some medical advice has not changed much over the years!)

Harvey is famous for arguing for the theory of the circulation of blood. According to Harvey the heart pumped blood to and from the lungs and all around the rest of the body:

‘The pulsation of the left ventricle of the heart forces the blood out of it and propels it through the arteries into all parts of the body’s system … further, that the blood flows back again through the veins and the vena cava and right up to the right auricle …’

This was a brave claim. There was a long accepted view that the blood only moved from the heart to the organs, not back again. Indeed, centuries of anatomical investigations had not suggested any means by which blood could circulate, as there did not appear to be any way that veins and arteries were connected. (Capillaries are too small to be seen without magnification and microscopes had yet to be invented.)
Harvey based his view on a wide range of observations and experiments. They were carried out on people and a range of other animals, ‘through ever wider and more meticulous inquiry, involving frequent examinations of the insides of many different living animals and the collation of many observations’.

For over a thousand years medical ideas and investigations had been based on the work of Galen. Harvey begins his arguments by listing problems with Galen’s ideas: where they did not seem logical or where they did not fit his anatomical observations.

Harvey argued strongly for his theory of blood circulation, for example, by suggesting calculations that showed that the amount of blood pumped by the heart in half an hour was more than the total amount of blood in the body. This did not prove he was right but showed that the blood must be constantly produced by the body at a very high rate if it was not being recycled – something that seemed ridiculous.

Harvey suggested experiments that would support his theory. When cut, the arteries ‘spout relatively freely and abundantly a rushing torrent of blood’. Readers were instructed to ‘put the matter to the test in a sheep or a dog’ by cutting the neck artery.

One ‘special experiment’ Harvey recommended to his readers concerned opening up a snake. This involved squeezing off the blood vessels either side of the heart between finger and thumb, and then watching to see how the heart either swells and turns purple (if blood is prevented from leaving) or turns pale and stops beating (if the blood is prevented from reaching it from the veins).

4: Robert Millikan

Millikan was an American (US) physicist who was best known for his ‘oil drop’ experiment. At the time when Millikan did his experiments, around 1910, it was not known if electrical charge could take any value (‘continuous’) or whether it only existed in discrete quanta (‘packets’).

Millikan’s experiment was quite complicated but the principle was simple. A small drop of oil would fall under gravity, but if the oil drop was electrically charged the weight of the drop could be countered by an electrical force attracting the drop upwards. In practice his apparatus required observing tiny oil drops as they slowly fell through electrical fields and making careful measurement. He also had to use X-rays to charge his drops and his calculations had to allow for other forces that might have an effect (air resistance when the drop was moving, and the upthrust due to its buoyancy).

Because each of the measurements was subject to experimental error (the limit on how precisely one can measure something) Millikan had to average results from many runs to get a reliable result. However, because the apparatus was difficult to operate, the experiments sometimes had to be abandoned before any results were obtained. Millikan worked on refining his apparatus and collecting data for several years.

Millikan eventually reported that his results showed that electrical charge is quantised, although the basic unit of charge was very small \( e \approx -0.000\ 000\ 000\ 000\ 000\ 000\ 000\ 2\ \text{Coulombs} \).
Other scientists working at the time were doing experiments that they thought suggested that the electrical charge could take any value. The different scientists disputed each other’s conclusions (and sometimes suggested that the other’s results could fit their findings). We now accept Millikan’s work gave a reliable answer and that the electronic charge = 1.6 × 10⁻¹⁹ C.

When Millikan’s laboratory notebooks were examined many years later it was found that he had run his experiment about 140 times. However, he had rejected about 80 of these experiments and excluded them in drawing his conclusions – because he believed he could tell which results were reliable and which derived from times when something must have gone wrong with his apparatus.

One re-examination of Millikan’s notebooks suggested that, had he not excluded so many results, his best value for the electronic charge would be approximately e/3. Scientists now believe that subatomic particles called quarks may carry charge of value e/3 and so the charge on an electron is not the smallest possible charge. However, according to accepted scientific theories, quarks are always joined into groups and single quarks are only found in extreme conditions (such as powerful particle accelerators). So Millikan’s oil drops could not have had charges of e/3 … or could they?

5: Barbara McClintock

Barbara McClintock studied cells and the genetics of plants – in particular maize (sweet corn). Her work as a young researcher won a lot of respect and she was recognised as a capable biologist.

However, over time McClintock’s research led to ideas that other scientists found unconvincing. In particular, McClintock interpreted the results of her experiments to suggest that genes were not always fixed to a single location but could sometimes move along the chromosome, or even to a new chromosome (transposition). The notion of ‘jumping genes’ (transposons) seemed an odd and unlikely finding to other scientists who were studying genes. Most geneticists believed that genes are arranged in fixed places on chromosomes. It did not seem possible that they could move about (except during sexual reproduction when some ‘shuffling’ occurred).

For many years McClintock was seen as something of an eccentric. Perhaps it did not help that McClintock seemed to focus on individual plants in great detail rather than using statistical approaches to average out individual differences:

‘The important thing is to develop the capacity to see one kernel that is different, and make that understandable’.

Worse, perhaps, McClintock admitted to relying on what might be called ‘insight’, or even ‘intuition’, to carry out her science. She saw her brain as being like the ‘black box’ processor in a computer. She did her experiments, made observations and drew conclusions (she ‘understood’ the plant) without understanding how her brain was ‘integrating’ the information.

As other scientists carried on their studies into genetics over many years, they discovered that the way genes work was more complicated than they had first expected. Some genes control other genes, effectively turning them on or off. It is not always possible to assign a single, simple role to a particular gene without considering
what else is going on in the organism, or in the cell, at that time. It is as if there are several layers to the way genetics works and it is not possible to understand what is going on by only paying attention to one layer of the system at a time.

It is now realised that McClintock’s approach, even if she did not always fully understand how it worked herself, provided insights into the complexity of genetics that other scientists only recognised many years later. McClintock is now recognised as an important pioneer in genetics.

6: Crick, Franklin, Wilkins and Watson

Although some scientific discoveries are largely the work of one scientist, modern science is usually a collaborative process with groups of researchers working together.

One of the most important discoveries of the twentieth century was the basic structure of DNA: the so-called ‘double helix’. It was not realised quite how important this ‘problem’ was until it was solved. Crick and Watson published a paper proposing a structure and pointed out that it suggested a way that genetic material was copied in cell division and reproduction.

Crick and Watson ‘discovered’ the likely structure by building a molecular model rather than doing any experiments on DNA. Watson worked on the model, like a jigsaw puzzle, until he found a way to get the pieces to fit. Watson did not actually know very much chemistry as he was a biologist with a particular interest in ornithology. However, he was able to bring together a range of different ideas and information in order to build the model. This was soon accepted as being substantially the ‘correct’ structure.

It was not possible to build the model until a great deal of data was collated and understood. Crick and Watson’s first attempt to build a model was a failure, as colleagues from another laboratory soon pointed out how it did not fit the experimental data available. Wilkins and Franklin from King’s College, London travelled up to Cambridge to see the model but Rosalind Franklin told them the model did not match her experimental results. Franklin, who was much more familiar with the latest experimental data, could immediately see that the model could never fit the available evidence.

Wilkins, and particularly Franklin, were working on a difficult experimental technique called X-ray diffraction that can give some information about structures of substances that can be crystallised. Franklin worked long hours on careful experiments and then had laborious calculations (without machines to help in those days) to undertake before she could estimate some of the dimensions of the DNA structure. Because Franklin’s colleague Wilkins was a friend of Crick, information about Franklin’s research reached Crick and Watson. Their work depended on information from other scientists as well.

The physicist Schrödinger had written a book that alerted Crick and Watson to the area of research. Various chemists had undertaken experiments showing what the chemical components of DNA were and how much of each of the different components were present. The idea of building a model had been copied from Linus Pauling who had used a similar approach to explore protein structures. Finally, Crick himself made a major contribution when he worked out the mathematical theory that predicted the X-ray diffraction pattern produced by crystals of helical molecules.
7: Galileo Galilei

Galileo is most famous for his argument with the Catholic Church about whether the Earth moved around the Sun. At the time most people believed that the Earth was still at the centre of the world (i.e. the Universe) and that the Sun and stars moved in circles around the Earth – although some of the stars ‘wandered’ a bit (i.e. the planets). The Church believed that this was the meaning of some of the passages in the Bible.

Galileo had evidence from his scientific investigations to suggest that the Earth moved round the Sun and he opposed the Church view. Eventually he was arrested by the inquisition (the religious authorities) and made to ‘confess’ that he was mistaken. He is supposed to have confessed but then mumbled ‘under his breath’ that he actually knew the Earth did move through space.

Galileo was a clever scientist who undertook many important studies at a time when laboratory apparatus was rather primitive. For example, he used his pulse to time things.

It was not surprising that people thought the Earth was stationary. It does not feel or look like it is moving at very high speeds, even though we now think it is. The orthodox view was that everything in the heavens moved in circles (if sometimes circles within circles) around the Earth. Galileo used the newly-invented telescope to see ‘heavenly bodies’ in much more detail than earlier observers. He discovered four moons that moved around Jupiter rather than the Earth.

It seems strange now that many people refused to believe Galileo, even though he tried to show them what he could see through his telescope. Some looked, but did not see the moons, and others refused to look. The first telescopes were crude with imperfect lenses and where some saw a new star, others saw smudges or other artefacts of the apparatus. Some of those who refused to look were not being obstinate – not understanding the theory of how a telescope works, they did not know how they were meant to interpret the patterns they might see through it.

Galileo was brave to hold to his views against strong opposition, but he was also a political operator. He tried to get powerful people on his side (dedicating the new moons to an important prince) and attempted to take advantage of his long-standing friendship with the Pope. However, he also annoyed many people by being arrogant and argumentative.

Galileo eventually agreed to confess his ‘mistake’ after being shown the inquisition’s instruments of torture. Most prisoners would agree to cooperate with the authorities when taken on a tour of the torture chamber. Galileo was not as ‘brave’ as Bruno, a scientist with similar ideas, who ‘decided’ to be burnt at the stake for his heresy rather than admit to being wrong.

Another famous story about Galileo is that he dropped a cannon ball and a musket ball from the leaning tower of Pisa as an experiment to prove that they would fall at the same rate. This was not really an experiment, as he already knew what would happen from many earlier tests in his laboratory, but he used this as a dramatic way to demonstrate his findings.
8: Lise Meitner

Austrian scientist Lise Meitner was so keen to study physics that she managed to persuade the university teachers to let her attend their classes even though she was female. She attained her doctorate in 1906.

Despite being an exceptional student, Meitner was only able to find work as a research scientist by working for many years without any pay. She was not allowed to work in proper laboratories where the paid male scientists worked and had to set up her workbench in a disused workshop. However, over time, Meitner was recognised as a brilliant scientist and eventually she was even paid for her work.

Meitner explored radioactivity with Otto Hahn and Fritz Strassman, in Berlin, and her research group undertook experiments that led to important discoveries in the new science. They did this by developing ideas and techniques that derived from the work of the Curies and others. These theories showed that radioactivity involved the atomic nucleus ejecting small particles, leading to new elements being discovered. Because the rules by which radioactive changes occurred had been established, careful experimental work could identify which elements were present before and after radioactive changes.

Meitner fled Germany when the Nazis started persecuting scientists and others who were Jewish (or considered to be Jewish under Nazi laws). She continued to communicate with Hahn and Strassman about the experimental work.

Hahn and Strassman’s experiments started producing very strange results. These did not fit with the known mechanisms of radioactive decay (known as α-decay and β-decay) which led to elements changing into others that were very close in the periodic table (so an element with atomic number 92 could change into one with atomic number 93 or 90). Hahn and Strassman found their experiments were producing elements that were much lighter than the uranium they started from. Other scientists had previously obtained the same results but dismissed them as impossible and due to impurities. Hahn and Strassman found that no matter how careful they were in preparing pure samples, they still found that uranium (atomic number 92) seemed to be changing into barium (atomic number 56).

Lise Meitner discussed the strange results with her nephew (another scientist) Otto Robert Frisch. She came up with the idea that a totally new mechanism caused the result. Meitner and Frisch proposed that some large nuclei can sometimes split into parts. This became known as nuclear fission and Meitner’s idea was soon found to be useful in physics (and is now well accepted).

The importance of nuclear fission was recognised in 1944 when a Nobel Prize was awarded to Otto Hahn. For many years, Meitner’s workbench was displayed in a German museum labelled as belonging to Otto Hahn (it has since been reassigned to include Meitner and Strassman).
9: Jane Goodall

Goodall is a **primatologist** (a **naturalist** who studies primates – monkeys and apes). She has spent many years closely studying the behaviour of chimpanzees in Africa. Goodall studied the animals in their **natural habitat** and observed how they behaved in their ‘natural groups’. This involved spending long periods watching the animals, getting to recognise individuals, learning about their relationships and developing an appreciation for their social groupings.

Because Goodall was interested in how these animals behave in their usual environment, she based her work on **observations** rather than on **experiments** (interventions, trying to **control the ‘variables’**). To understand the way chimps organise socially she had to watch the animals for many years to see how different chimps took on and lost roles in chimp ‘society’.

As she did not use an experimental approach, Goodall had to build her models on the observation data that became available over time and accept that her findings may have to be reviewed in the light of further evidence.

Goodall found examples of chimps using tools (something previously thought to be characteristic only of humans). In her early reports of chimp society Goodall described how chimp ‘communities’ were **largely peaceful and mostly vegetarian**. However, she later found evidence of chimps hunting other animals for meat and examples of chimps killing other chimps for food. She also observed a ‘war’ break out in one of the groups she observed. The group split into two and over time all the animals in one of the new groups were killed by members of the other group.

Goodall has had to change some of her ideas about what is typical in chimpanzee society as new evidence has become available. However, over time, she has been able to build a well-supported account of the structure of chimp groups and the changing roles animals take in the group as they mature and grow old.

10: Johann Kepler

Johann (or Johannes) Kepler (or Keppler, Khepler, Kheppler, Keplerus) was not very consistent in giving his name. However, he reported that he had been born on 27 December 1571, **at 2.30 in the afternoon**, having been conceived on the previous 16 May, **at 4.37 in the morning**. Kepler was careful in recording numbers precisely. His life’s work concerned producing an accurate model of the solar system using mathematics.

Kepler believed the general principle of the **heliocentric** (Sun-centred) model of Copernicus, which had the Earth and the other known planets travelling around the Sun. At that time most people believed the Sun moved around the Earth (the **geocentric** model). But neither Copernicus, nor astronomers supporting the geocentric view, were able to present a **simple model** of the paths of the heavenly bodies that **matched observations**. Most of the models involved assuming complicated patterns of planets moving in circles that themselves move around other circles.
Kepler believed that the planets could be organised into a simple geometric arrangement and made it his life’s work to study this. As producing mathematical models of ‘the world’ did not pay well in those days, he and his family made great sacrifices for his calling. Kepler moved from his native Germany when he managed to get himself a position working for the metal-nosed Danish astronomer Tycho Brahe at his island observatory. This was where the most accurate observations of the night sky were being made.

Brahe had developed his own model of the solar system and only allowed each of his assistants access to the data they needed for the job assigned to them. Kepler was given the job of making sense of the Mars data. Later, when Brahe died (after a short illness apparently initiated by drinking too much wine at a banquet where it would have been considered rude to leave the room to empty the bladder), he left all his observations to Kepler believing that Kepler was the person most likely to be able to interpret them.

Kepler’s first assumption was that planets moved in perfect circles. He could not fit the data to such a model, no matter how eccentric (off-centre) he assumed the Sun. He had to reject his preferred idea. He thought about various possibilities, including the ellipse, but decided instead to calculate what an oval (egg-shaped) orbit would be like (on the basis that the planet was likely to follow a different shape path when nearer the sun than when further away). However, he could not produce an oval orbit that fitted the data either and rejected this idea.

Eventually he tried the ellipse (even though it seemed too symmetrical), and found that it could fit with the data if he assumed that the planet moved around the ellipse faster when nearer the Sun. (Newton’s gravitational theories later explained this.) Kepler found that he could get ellipses to fit observations for all the planets.

Kepler’s other great project was to try to find a pattern in the distances that the different planets were from the Sun. He developed a complicated model based on the series of regular solids (tetrahedron, octahedron, etc. – solids where all the faces are identical) acting like a set of Russian dolls. However, he could not find any way to get the observations to fit his model. Kepler wrote up his work in detail, explaining how he constructed his model and showing why it did not fit the available evidence.

Acknowledgements

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