Teaching secondary biology

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Abstract The third edition of the ASE's *Teaching Secondary Biology* sets out a vision for teaching and learning biology. Learning biology is not *about* learning the contents of a textbook. It is about conceptual learning, learning what it means to do biology and learning what it means to be a biologist. Our hope is that *Teaching Secondary Biology* helps teachers of biology to achieve these aims. The author team with whom we worked kept in mind a secondary teacher confronted with the task of teaching a specific topic, for example photosynthesis or evolution, and the preparation they would need to undertake. This article provides an overview of the book, which has sister volumes in chemistry and physics, and discusses ways in which teaching biology has much in common with teaching the other sciences, but is distinctive too.

In the third edition of the ASE's *Teaching Secondary Biology* (Reiss and Winterbottom, 2021), our aim as the two editors has been to help biology to be taught so that secondary students develop their conceptual understanding of the subject, are interested and inspired by it, and learn to connect ideas from different areas of biology.

The author team with whom we worked kept in mind a secondary teacher confronted with the task of teaching a specific topic, for example photosynthesis or evolution, and the preparation they would need to undertake. Some teachers will approach this task with a deep understanding of the topic. However, we kept in mind that not all teachers of secondary biology have a degree in the subject and that, even if they do, very few degrees cover all of secondary school biology. Indeed, excellent subject understanding is itself not enough for a teacher. For this reason, the chapters focus on *how* each topic might be taught so as to help students learn and to be inspired.

The third edition differs substantially from the second edition, which was published back in 2011. In part this is because of changes to the way the topics are now treated in secondary school biology. In part it is because of innovations in practical work and digital technologies. In part it is because of changes in thinking about the biology curriculum – including thinking that derives from the 'Big Ideas of Science' movement (Harlen *et al.*, 2015).

Key concepts in biology

There are a number of key concepts in biology. Some are found in chemistry and physics too, such as the flow of energy and the circulation of materials. Many students find it difficult to understand that while both energy (the law of conservation of energy) and matter (the law of conservation of mass) are conserved, there is a fundamental asymmetry, in that energy continuously dissipates, whereas matter circulates; this is true whether we are thinking at the cellular or ecosystem scale.

Many key concepts are specific to biology, including:

- **Reproduction.** No individuals are immortal and so all organisms need to give rise to individuals in future generations.
- **Heredity.** In giving rise to the next generation, organisms may split into two (asexual reproduction) or produce specialised structures that enable either sexual or asexual reproduction.
- **Evolution.** Over the generations, organisms change. A key insight of Charles Darwin and some other biologists, notably his contemporary, Alfred Russel Wallace, was that natural selection is an inevitable consequence of: the overproduction of offspring; what we now call genetics; and the pressures exercised on organisms by the environment.
- **Homeostasis.** All organisms are able to regulate their internal environments to a very considerable degree – though this is more apparent in some (e.g. most mammals and birds) than in others.

Big ideas in biology

An influential pair of reports that link the big ideas of science to the science curriculum were produced by Wynne Harlen and colleagues (Harlen *et al.*, 2010, 2015). In the 2010 report, Harlen and her colleagues came up with ten big ideas of science, of which four were *of* biology:

- Organisms are organised on a cellular basis.
- Organisms require a supply of energy and materials, for which they are often dependent on, or in competition with, other organisms.

- Genetic information is passed down from one generation of organisms to another.
- The diversity of organisms, living and extinct, is the result of evolution.

Four of the big ideas were *about* science – which apply to biology and to the other sciences:

- Science assumes that for every effect there is one or more causes.
- Scientific explanations, theories and models are those that best fit the facts known at a particular time.
- The knowledge produced by science is used in some technologies to create products to serve human ends.
- Applications of science often have ethical, social, economic and political implications.

The big ideas in science movement started because of a wish to address what was perceived to be a fragmentation of students' learning experiences as a result of standard methods of summative assessment. Too often, it was felt, science is seen by students as requiring learning about a mass of information, with many students having little appreciation of *why* they are learning what they are – or of how different topics aggregate into significant big ideas.

The Harlen reports have had considerable impact in the UK and in a number of other countries. In England, Northern Ireland and Wales, it is hoped that work by the Royal Society of Biology, along with the equivalent professional organisations for chemistry and physics, will mean that the next version of the science National Curriculum is informed by them. For science teachers, one of the benefits of the Harlen reports is that they can facilitate departmental curriculum planning, helping to ensure that there is coherence in student experiences.

Doing biology

Scientists are always asking *why* things happen or *how* things happen. By asking questions like this, they may be able to come up with new theories to explain new findings, and then test those theories. Scientific ideas can never be said to be proven: every idea is potentially falsifiable if data eventually contradict it. But learning how to ask 'how' and 'why' is fundamental to educating new biologists. Such biologists may go on to an extraordinarily wide range of careers, many involving working with people (e.g. in the medical professions), some out-of-doors, and some in laboratories or other specialised sites such as zoos. Biologists are employed in an enormous number of different jobs and at every level, whether a student leaves school at the first opportunity or goes on to take a higher degree in the subject.

Practical biology

Biology is a practical subject, as much as any other science. It is therefore a matter of deep regret if students sometimes experience less practical work in biology than in other sciences, instead spending long periods of time making notes on things like the structure and function of organs or specialised cells.

At the same time, there are a number of distinctive characteristics about biology that mean that practical work in biology may differ from practical work in chemistry or physics. For a start, many organisms are sentient, that is, capable of experiencing pleasure and suffering (experiencing pain). This means that they cannot be used for certain experiments, whatever the educational benefits might be. Indeed, there is a need to be respectful to all living organisms, even if it seems certain that they are incapable of suffering.

Then there is the fact that organisms, even within a species or local population, are rarely identical. At school level, a chemistry or physics teacher does not have to worry about the possibility that different samples of copper sulfate or copper will have different properties: biology teachers cannot make comparable assumptions about their objects of study.

Related to this is the issue that it can be difficult in biology to control variables in a way that physical scientists would expect. Often, with care, this can be done, even when there are multiple variables, using appropriate data-collection design to remove any systematic bias. Even if it is difficult to control variables, their effect can also be accounted for in analysis through use of appropriate statistics. Nevertheless, biology does sometimes require more interpretation of data than in other sciences. Furthermore, there are times when biology can, with hindsight, be seen to have been more subjective. There is a long history of male, white biologists gathering data that 'showed' that women and people of other ethnicities were less intelligent than they (Gould, 1981). Much of this bias was probably unconscious – but bias it was.

Finally, although all the sciences can profitably be studied out of doors (Braund and Reiss, 2004), it is especially important that such study be undertaken in biology. Although much ecology can valuably be undertaken in the laboratory, the subject comes alive when studied out of doors, whether in school grounds or further afield. It is a matter of deep regret that fieldwork is increasingly threatened in school biology in the UK (Tilling, 2018).

Biological reasoning

Much of science is about reasoning – formulating hypotheses, making deductions, developing an argument and being able both to buttress it and to critique it. In biology, there is a particular need for students to develop the capacity to appreciate the importance of probability. Of course, probability plays an important role in other sciences (e.g. when a particular radioactive atom decays) but in biology probabilistic reasoning is important in many areas (in mutations, in independent assortment, in whether a predator catches a prey in a particular hunt, whether a tree is killed by lightning or not, whether succession takes one direction or another, and so on). One of the difficult things we want students to appreciate is when we can be pretty sure about what will happen next in biology and when there are a number of possibilities.

Biology is also somewhat distinctive (though it shares this feature with parts of earth sciences and cosmology) in the importance of historical reasoning. To get a good understanding of the history of life over the last three and a half thousand million years or so requires the ability to imagine and then to reason historically.

Biology in context

Some students love 'pure' biology but most are fascinated by biology in context. The student who may have little interest in the semi-permeability of membranes may become captivated by the realisation that the various problems that result from having cystic fibrosis can all be traced back to damage to certain proteins that carry ions across such membranes.

As a science, biology is fortunate in that so much of it can be taught in context. Perhaps two contexts stand out: health and the environment. There was a time when biology teaching about health for 11- to 16-year-olds consisted of little more than diatribes against cigarette smoking and the use of illicit drugs, along with a litany of things that could go wrong with various parts of the body (everything from vitamin deficiencies to cheerful lists of sexually transmitted infections). Now, there is far more of a link from molecular biology through cell biology to whole-organism biology, as in the cystic fibrosis example above.

Teaching about the environment has changed too over the years. No longer are contexts dominated by oil spills, the grubbing out of hedgerows, acid rain and the hole in the ozone layer. Nowadays, two anthropogenic instances of environmental damage stand out: climate change (including global warming, more extreme weather events, ocean acidification and rising sea levels) and the ever-accelerating loss of biodiversity.

Ethics in biology

Every science needs to take account of ethical implications (Jones, McKim and Reiss, 2010) but no science more so than biology. Indeed, almost every biology topic seems to throw up ethical issues. Should we change the genes of individuals to prevent genetic diseases, as is becoming increasingly possible? Is it right to exterminate certain species – for example the *Anopheles* mosquitoes that transmit malaria? At what stage during development does an embryo become a person or does this happen at fertilisation? How much money should we spend conserving a species so that it does not go extinct? Should badgers be culled to prevent the spread of bovine tuberculosis? And so on.

Too often, biology courses simply raise such ethical questions. While this is useful, it can overwhelm students. To help them move forward, they may benefit from being taught one or more ethical frameworks applicable at school level.

Learning biology

When learning biology, students should not only learn biological concepts, but also get a good understanding of how biology is undertaken. By designing teaching and learning approaches that enable students to learn and to experience 'doing' biology, biology teachers should be able to give students the chance to develop the feeling that biology 'is for me' and is also of broader value to society. This means that teaching and learning requires individuals to think.

Constructing understanding

Building learning by requiring students to think ideas into existence is in accord with constructivist ideas about learning. The theory of social constructivism says that such building of ideas happens better in social interaction with others, such as a teacher or a student's peers. Such interaction scaffolds students' developing understanding. The way in which learning activities are designed by a teacher enables such scaffolding to take place. Hence, teachers have to consider a learner's starting point, and how best to enable (or scaffold) them to build up ideas.

Thinking together through a rich diet of talk is essential for developing successful learners, and building biological reasoning skills. When educational dialogue works well, students listen to each other, they share their ideas, they justify their ideas, and engage with each other's views. The teacher's role in this is important, and includes inviting students to build on each other's ideas ('*Do you agree?*', '*Can you add something?*'), challenging ideas ('*Are you sure?*'), inviting reasoning ('*Why?*', '*How?*'), coordinating ideas ('*So we all think that* …'), connecting ('*Last lesson* …), inviting reflection ('*What have you learned?*'), guiding the dialogue or activity ('*Have you thought about?*'), and inviting original ideas ('*What do you think about?*').

Conceptual change

Some of students' prior ideas can be very different to scientifically accepted knowledge. These ideas can be labelled misconceptions or, perhaps better, alternative conceptions, as many such ideas are simply students' attempts to make sense of their world using 'common sense' rather than scientific logic. It is difficult for students to give up their alternative conceptions, so lessons and learning activities need careful design. Teachers need to know the alternative conceptions their students hold, and students need opportunities to make their ideas explicit, to encounter alternative ideas, and to assimilate such ideas into their thinking.

Making students realise that their ideas may be mistaken, by generating conflict in their minds between their own ideas and evidence, is one approach to changing their ideas. For example, a teacher may ask students to make a prediction before a piece of practical work. Their prediction is based on their prior ideas, and makes those ideas explicit to the teacher, but also to the students themselves, because the data they collect may conflict with those ideas. A teacher can do the same with simulations: ask students to make predictions, run the simulation, and generate that kind of conflict in their minds. Concept cartoons can help achieve the same aims, but through dialogue. A concept cartoon provides a picture of a scientific phenomenon, with different people giving alternative explanations of that phenomenon. Inviting students to say what they think or to decide how much they agree with the alternative explanations, and then justify their position to each other, creates dialogue that can help students to unpick their current understanding.

However, such cognitive conflict is not the only way to think about conceptual change. An 'evolutionary change' model views conceptual change as being a more gradual and ongoing process, where students' prior conceptions are used as resources for learning, regardless of whether these prior conceptions are scientifically accurate or misconceptions. Whichever model a teacher exploits (and many would adopt both, depending on the circumstances), the teacher has to structure ideas in sequence, ensuring good progression, with ideas building on each other over time, and making connections to other curriculum areas, within biology, to other sciences, and to other subjects.

Practical work and inquiry

Engaging with practical work (including fieldwork) gives students a sense of what it means to be a biologist. It may help students to develop:

- essential practical skills training;
- their observation abilities;
- problem-solving skills;
- classification skills;
- conceptual ideas.

Practical work may also be used by a teacher as a demonstration to support an explanation or simply to illustrate a phenomenon.

In biology, good practical inquiry is sometimes hard to fit into a single or double lesson, and so teachers often default to more illustrative practical tasks. Biological inquiry may involve extended project work, data collection over time, and inferences from observation, rather than only from experimentation. Inquiry typically features some (occasionally all) of the following components:

- a question to investigate;
- collection of evidence;
- analysis of data;
- explaining the evidence;
- connecting their explanation to existing scientific knowledge;
- communicating and justifying their explanation;
- reflecting upon and evaluating their inquiry.

There can be value in teachers providing a mixture of inquiry types over the years of secondary education so that students experience open, closed and guided inquiry work.

Learning in context

Biology teachers are fortunate. Biology students often feel a connection to biology because they themselves are living things, situated in their own habitat and ecosystem. Because of this, when students learn about biology through contexts, they are often more motivated, and their interest in biology lessons is maintained. Contexts also help students perceive relations between science and everyday life, enhancing the relevance of biology lessons. Contexts can be introduced through use of media, including newspapers, magazines, television and the internet.

Final thoughts

In the third edition of the ASE's *Teaching Secondary Biology*, our aim as the two editors has been to help biology to be taught so that secondary students get an excellent understanding of the subject, are interested and inspired by it, and learn to connect ideas from different areas of biology. In today's world, biology is central to so many of the problems that humanity faces: anthropogenic climate change, loss of biodiversity, the risks from pandemics and antibiotic resistance, and so on. We need school leavers, whether they continue with biology or not, not only to have an understanding of these issues but to appreciate their importance and urgency. Our hope is that this book helps secondary biology teachers to meet this need.

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