What should be in the biology curriculum?

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ABSTRACT The ever-increasing amount of biological knowledge has resulted in compression of topics in the curriculum to a précis of current understanding. This gives the impression that biology is about a list of things we know. This misconception is extremely damaging, contributing to the idea that science is an impersonal process that generates facts, thus reducing pupil engagement. The curriculum should instead focus on big concepts, tracing their origin and evolution, illustrating how evidence accumulates to support hypotheses. Understanding how current biological understanding was generated provides a solid foundation for students to assess critically and assimilate the plethora of easily available information.

I am a biologist, or, more specifically, a geneticist. I have been active in research and undergraduate teaching in biology for the best part of 20 years. Over that time, biology has been expanding rapidly. Every year there are new discoveries, new technologies and new ways of thinking about the subject. This is not just tinkering around the edges adding detail, but major new discoveries and new concepts of fundamental importance to the discipline.

In genetics, there used to be Mendel and the principles of heredity. These could be linked through to Watson and Crick, and the basic structure and function of DNA. The core idea was encapsulated in the central dogma: DNA makes RNA, makes protein. The general idea was that Mendel's 'hereditary factors' could be defined cleanly in terms of stretches of DNA (genes) that were transcribed into messenger RNA and translated into specific proteins. The direction of travel intellectually was from a concept defined by organismal-level phenomena to a precise and detailed mechanistic understanding, defined at the level of molecular biology and biochemistry. Reductionism would reveal all.

Now, there is whole-genome sequencing, epigenetics, diverse roles for small RNAs in gene regulation, and growing awareness of the dynamic nature of genomes and their role in directing the development and function of an organism, sensitive to the world around it. With this has come the realisation that, while reductionism can define the parts of a system, a full understanding requires an integrative synthesis. The most useful and powerful concepts, such as the gene, will never be accurately defined as a precise physical entity and indeed their very utility is in encapsulating an idea about how things work, rather than labelling a physically distinct part. Of course, we have invented names for parts that help us to describe biological systems, and they are useful. But biology is not about learning the names of parts, it is about understanding how they work, and understanding is all about concepts and ideas. The terminology we have developed to describe biological systems is useful, but it is not biology. Even the detailed descriptions of what these parts do give the wrong impression. In my experience, most of the students arriving at university think that biology is about learning 'facts'. They find these to be very interesting facts and they understand that they are useful for medicine, agriculture and ecosystem management; but they think of biology for the most part as a set of cold, hard, immutable facts plus some bits which we don't know about yet, but soon they too will be conquered and lined up in the row of existing cold, hard, immutable facts.

For many years, the first assignment I gave my first-year tutorial group was to write an essay entitled 'Discuss the evidence that DNA is the genetic material'. Rabbit-in-headlights eyes looked back at me. '*What do you mean "evidence"?*'

I was asked, '*It is the genetic material.*' '*Yes, but how do we know it is the genetic material?*' Frequently, what resulted was a pile of essays explaining how DNA makes RNA, makes protein, which QED makes DNA the genetic material. Of course, some students coped well with this challenge, but it really shouldn't be a challenge.

In the desperate quest to cram the ever-increasing amount of biology into an ever-more-cramped curriculum, the teaching of biology now almost always cuts to the chase. Students are presented with a summary of current understanding, as though it were 'fact'. This is not the fault of the teachers, it is the fault of a curriculum and an assessment system that do not include sufficient coverage of how our current understanding was derived. There is coverage of 'How science works', but this is a separate part of the curriculum and, in my experience, students struggle to integrate it with their knowledge of biological systems.

This is the crux of the issue. The term 'fact' can reasonably be used to describe the reproducible results of an experiment. Scientific data are factual but often it is interpretation, hypothesis or theory that are described as 'scientific facts'.

This is dangerously wrong and in fundamental contradiction to the way science works. At best, we have hypotheses that have such excellent explanatory and predictive power that they are firmly embedded in the way we think about things, but even these could be found wanting in the future. When our current understanding of how a biological system works is misleadingly presented as a fait accompli, it creates serious problems both for those who want to pursue careers in science and for those who will not study it beyond GCSE.

These problems are twofold. First, the impression is given that science can deliver some kind of absolute truth, that our descriptions and understanding of biological systems can in some way completely encapsulate reality. Life is not like that. We have looked very hard at living systems and have identified patterns and processes to which we give labels and attribute function. We have formulated hypotheses about how these systems work and tested them experimentally. This is very exciting and very significant and provides those models of the world, mentioned above, that have impressive explanatory and predictive power. However, it would be a mistake to imagine that the classification system that we have developed for the parts of life is the only one that is possible, or even the only one that is useful, or that it is capable of capturing all the properties of living systems.

The second major problem is that biology presented as a catalogue of current knowledge depersonalises it, making it seem cold, hard and immutable. This reinforces the stereotype of science as the province of boffins. Boffins are both superhuman in their brainy quest for Ultimate Truth and subhuman in their robotic pursuit of cold, hard, immutable facts. This is not what science is about at all. It is a human activity driven by curiosity and carried forward by creative inspiration. Boffin science alienates many students, including some of the brightest and most imaginative students who would make exceptional scientists, because it underplays the creativity of science. Furthermore, it leads to an image of science as an activity separate from normal human endeavours, requiring peculiar boffin-like characteristics, an idea resonant of C. P. Snow's concept of two separate cultures. This produces barriers that prevent people from engaging with science, disempowering them from making decisions about their lives that require such engagement.

So what should be done? What should be in the curriculum that will provide simultaneously the background needed by students who want to go on to study biology, the inspiration for a greater number of students to have such ambitions and the confidence for all students to engage with science as an integral part of their lives? My solution would involve three main elements.

First and foremost, the curriculum should be built around the big concepts in biology, such as evolution, cellularity, heredity, photosynthesis, respiration, homeostasis and ecosystem stability, and, crucially, the focus should be on how our current understanding of these concepts has evolved to reach its current state. Unless students are exposed to examples of progress in science, how ideas are developed and tested, how evidence accumulates and how new technologies transform understanding, they will emerge with a profoundly mistaken idea of what science is, and what it can and can't tell you.

Through this approach, students will gain knowledge of core concepts in biology but, much more importantly, they will also gain skills in how to assess evidence critically, how information from different sources can be synthesised, and how to design experiments to test a hypothesis or how to distinguish between two alternative hypotheses. This will empower them to engage more fully with science. These days it is extremely easy to find information, but much less easy to filter and assess its relevance and importance. A historical approach to the evolution of scientific ideas will equip students with the skills they need to make the most of the wealth of science they will encounter, whether by choice or necessity.

Secondly, the curriculum must include practical work that is truly investigative. Practical work is important because biology is an experimental subject and because, for many students, it provides a more effective way to learn than oral or written presentation of material. At present, matching the fait accompli focus of the curriculum, too much practical work is aimed at demonstrating or illustrating a 'fact' by following a prescribed list of instructions. This is amply illustrated by the queue of students at the end of a practical session wanting to know whether or not their results are correct. Practical classes should provide students with the opportunity to design their own experiments around a theme. For example, students could generate hypotheses about bacterial diversity from different sources and design an experiment to test them (subject to health and safety risk assessment). A complementary approach is to provide students with the results of a series of experiments (real or imagined) and ask them to interpret them, formulate a hypothesis to explain them, and then suggest experiments to test their hypothesis. Both these activities work well in groups, reflecting how most biological research is now carried out.

Thirdly, all of the above must include quantitative data whenever possible and students need the mathematical skills to analyse and interpret these data. How do you know whether the difference observed between two samples is just random variation? How can you predict quantitatively what result you would expect if your hypothesis is correct? These skills are important to allow people to make crucial decisions, for example whether or not to have their children vaccinated when the safety of a vaccine has been called into question. They are also essential for those who want to pursue biology as a career. Progress in biology is increasingly dependent on mathematical modelling of biological systems and this can be amply illustrated with both historical and contemporary examples, such as what is predicted to happen to agricultural productivity under climate change, or what the effect will be of a drug targeting a homeostatic process in the body.

Students need to know what the big ideas are in biology, where they came from, and where they might be going. It is somewhat more difficult to design assessments to support this type of curriculum that are still fair, reliable and easy to administer in comparison with assessment for a curriculum focused on information that students have; however, it is certainly not impossible. There are plenty of problem-solving question types that can be used, in addition to recall-based questions that address the evidence supporting an idea or concept.

There are good examples of virtually all the things mentioned above in the current and nascent future curricula. It is not that concepts and evidence do not feature at all, or that there are no opportunities to trace the history of important ideas, or that all practical classes are entirely formulaic. However, according to my own anecdotal evidence, the balance is currently far from where it should be. Students come to university expecting to learn some more 'facts'. They ask for lists of what they need to know for the exam. They have learned about how science is done, and how to conduct a fair test for a hypothesis, but this aspect of the curriculum appears to be entirely divorced in their minds from the biological knowledge it has produced. Meanwhile, the wider community is mistrustful of science, at least in part because it is not the infallible oracle which they had gained the impression it should be.

We are living at a time when many of the world's most pressing problems, such as food security, disease and environmental degradation, can be tackled using biological understanding. To address these urgent problems we need imaginative, creative scientists and a societal culture capable of evaluating and, where appropriate, embracing the solutions they provide. The school science curriculum has a central role to play in delivering these imperatives. It needs to be less about what and more about how.

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