Training biology's new romantics

The challenge of educating young biologists to keep up with the pace of modern molecular biology

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The biographies of great scientists such as Rosalind Franklin, Erwin Chargaff or Francis Crick enthral the reader with descriptions of exciting experiments and discoveries that laid the foundations of molecular biology. Books such as Horace Judson's *The Eighth Day of Creation* (Judson, 1996) or Robert Olby's *Hunter of Life's Secrets* (Olby, 2009) convey the unique mood of the 1940s to the 1960s in biological research. Even younger readers, born into a world shaped by molecular biology, will appreciate the excitement of those days and a field in its infancy. How small the world was: a handful of textbooks could cover the entire field; it was still possible to follow the scientific literature—submitted on paper through the post, by the way—and one needed to attend only one or two well-selected meetings, or exchange letters and phone calls with colleagues, in order to acquire the relevant knowledge.

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Moreover, because molecular biology was still a nascent research area, it was easy to know the most important people in person, which generated an open, friendly and enjoyably competitive atmosphere. In 1954, for example, George Gamow, James Watson and Leslie Orgel founded the RNA Tie Club to discuss how DNA translates into proteins. The club attracted eminent scientists who shared their ideas without fear of being scooped or copied—unthinkable in the competitive atmosphere of today. Back

then, just about anybody could understand the big picture and judge the broad significance of a discovery. In hindsight, this might have been the romantic period in biology.

Things have changed profoundly. Molecular biology has become one of the most important and largest research fields of the twenty-first century; it has a huge influence on other fields in biology, as well as on the economy and society. It has created new, multi-billion-dollar industries and has provided new means for understanding the development of human pathologies and for exploring the world around us. Yet this explosion of knowledge has come at a price: a biologist is no longer able to keep track of every important research area or discovery, except in narrowly defined fields. In the 1960s, biomedical research produced around 100,000 published articles per year; in 2010, it was almost 1 million (Fig 1). Today, one might need to read roughly 10 times more papers than 40 years ago, just to keep up with the literature.

Similarly, the repertoire of technologies and techniques that are now being used in research laboratories has grown enormously during the past two decades. The information in one of the most popular reference books for techniques in molecular biology has increased by fivefold in fewer than 20 years (Maniatis *et al*, 1982; Sambrook *et al*, 2001).

This exponential growth of knowledge presents a challenge for educators to cover the relevant experiments, discoveries and research areas. For example, less than 30 years ago, one textbook dedicated several pages to Seymour Benzer's classic experiments that led to the first fine-mapping of genes (Watson, 1976; Benzer,

1955). The newest edition of the same textbook covers the same results in just 15 lines (Watson *et al*, 2008). The reason for this compression is obvious: the amount of relevant knowledge grows exponentially, but a textbook inevitably has a limited number of pages. However, conveying an enormous amount of data in a limited space means that textbooks give up their ability to fascinate students by telling the stories of important discoveries—as does, for example, Stent and Calendar's *Molecular Genetics* (Stent & Calendar, 1978)—and instead present a more aesthetic, but condensed summary of facts.

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When I asked a German professor what a student with a degree in biochemistry should know, he responded: "This is a trivial question, he or she should master 'Stryer' or 'Lehninger'," referring to popular textbooks. Similarly, we might argue that a molecular biologist should know 'Alberts' or 'Lodish', and a geneticist 'Russell' or 'Snustad', but understanding these huge books is not a trivial undertaking. Moreover, even having read them and digested the vast amounts of information they contain, a student will still not have a comprehensive overview of the state-of-the-art of the discipline, whether it is biochemistry, molecular biology or genetics.

How many molecular biology students—and their teachers—are actually able to read and understand all articles in the *Journal of Molecular Biology*, which was established in the 1960s as a forum for molecular

biologists? How many students of genetics actually understand the methodology and the meaning of genome-wide association studies? To really appreciate and critically analyse the scientific literature requires knowledge of many topics that are beyond the scope of the main textbooks. This lack of a comprehensive picture of the whole of biology is reflected in recommendations about the training of biologists, such as the BIO2010 report by the US National Research Council about transforming the education of future undergraduate biologists (Committee on Undergraduate Biology Education, 2003), or the report by a committee of the Association of American Medical Colleges and the Howard Hughes Medical Institute on curricula for medical students (AAMC–HHMI Committee, 2009). These reports emphasize that “the ways in which most future biologists are educated are geared to the biology of the past, rather than to the biology of the present or future” (Committee on Undergraduate Biology Education, 2003), and that teaching of biologists should be as interdisciplinary as possible.

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However, there is a catch. If even individual disciplines are becoming increasingly impenetrable for scientists, owing to temporal and cognitive constraints, how can we expect that even the best students will be able to tackle and grasp additional, difficult subjects? There is a danger that university training will generate superficial dilettantes, rather than scientists with a broader knowledge and understanding of biology. The solution promoted thus far has been to direct students to narrow disciplines, producing specialists with a profound theoretical background, who are able to apply a particular set of techniques and methodologies that are specific to one field. A larger research project, in an interdisciplinary manner, then combines specialists from different fields with different methodologies to tackle the problem from several angles. This attitude is evident in many studies in high-profile journals, in which the list of the authors can be exceedingly long.

As the number of highly skilled specialists increases, scientists who are able to step back

Articles per year (thousands)

Fig 1 | Exponential growth of the number of articles published per year in PubMed (<http://www.ncbi.nlm.nih.gov/pubmed>).

and look at the larger picture of biology are gradually vanishing. Given the constraints of the current educational system, we cannot expect that a new generation of omniscient scholars will arise; even a genius will not be able to keep up with the pace of progress in the biological sciences. Are we therefore left with no choice but to produce *fachidioten*, specialists who will collectively gain new knowledge, but, individually, not be able to understand it in a broader context? Or can we re-structure curricula for biologists to enable them to cope with the challenges of modern biology?

The rapid advances in bioinformatics, systems biology and the various ‘omics’ fields increasingly require a strong background in mathematics or physics. This development is reminiscent of the birth of genetics and molecular biology, which was brought about by mathematicians and physicists including Robert Fisher, Sewall Wright, Max Delbrück and Francis Crick. For some time, intuition and common sense represented the basic tools for interpreting observations and experiments, but these are no longer adequate to explain and understand the complexity of biological systems, which requires sophisticated statistical and computational methods. Not surprisingly, genetics and cell and molecular biology have witnessed the arrival of another wave of talented mathematicians and physicists, who have become interested in biology only later in their careers.

The opposite path—moving from biology to mathematics—is not impossible, but it is certainly unlikely. The mathematicians contribute the quantitative and analytical skills that are needed for handling complex biological questions. Similarly, the nascent fields of systems and synthetic biology were largely inspired by mathematicians, physicists and engineers, who bring both their expertise and a new way of looking at and manipulating biological systems.

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Yet, the number of students in mathematics and physics is much lower than the number of aspiring biologists, so one cannot expect a flood of these individuals into biology. The only viable alternative for higher education to meet the increasing demand for these skills is to maintain a strong emphasis on chemistry and to increase substantially the teaching of mathematics and physics during the first years of biology undergraduate curricula. The goal is not to train every biologist to the point at which he or she is able to handle difficult mathematical problems, but to understand and appreciate the potential of mathematical analysis to address biological questions, and to communicate these

questions to professional mathematicians and physicists. In addition, more courses in mathematics and physics will provide students with the means to handle more complex biological problems and/or raise their interest in further exploring these areas. Even those specialized in classical biological fields would benefit, given the increasing demand for biologists of all flavours from evolutionary studies to synthetic biology.

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Finally, more training in mathematics and physics would have to take place at an early stage of the curriculum, when the mind is more flexible and able to absorb additional skills, which are more difficult to acquire later in life. The ambition of future biologists should not be to read and know every detail of 'Alberts' or 'Snustad'. Instead, we can go back to the original style of telling the story of a few relevant discoveries—even if they do not rely on advanced technology, such as Benzer's fine-mapping of a gene, or Erwin Chargaff's elegant experiment that showed the constant ratios of A:T and G:C in DNA—and try to communicate the basic principles of understanding how enzymes, cells, organisms or whole ecosystems work and evolve.

Analytical skills acquired at the early stages of undergraduate education, complemented by a general knowledge of the basic principles in biology and coupled

with more training in the basics of mathematics and physics, would improve the ability of students to deal with specialized problems later in their career without losing sight of the broader context. Such a move towards a less specialized education with a closer link to solving problems—rather than amassing knowledge—would be in the spirit of Wilhelm von Humboldt's ideal of higher education. Of course, there might be other and better means of restructuring biology curricula. In any case, it is prudent and important to start the discussion and exchange ideas among researchers and educators about how to prepare students for the demands of modern biological research. The romantic period of biology might have ended in the 1970s, but we should not give up on the romantic ideals of teaching and learning.

CONFLICT OF INTEREST

The author declares that he has no conflict of interest.

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