New biology for new curricula

Observations from the 6th EMBO International Workshop on Science Education
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CONTENTS

Background

This document draws on and elaborates observations from a workshop organised by the European Molecular Biology Organization (EMBO), convening a broad cross-section of European professionals involved in biology education at secondary level (teachers and scientist-educators), curriculum design, and scientific research.[1] It addresses the representation of some key areas of modern molecular biology in curricula and teaching (systems biology, bioinformatics, molecular evolution and molecular medicine). It also attempts to tackle the question of the degree to which knowledge, understanding and skills should be taught in areas that are considered to be on the secondary education horizon, rather than occupying a central position.

Modern molecular life sciences

Medicine has fundamentally changed since the 1980s as a result of molecular techniques. Molecular biology and bioinformatics have remodelled many preconceptions that we had about the relatedness of species, and now place humans closest to chimpanzees (instead of gorillas), with a genome-wide difference of only 1.6%.[2,3] Systems biology is one of the fastest growing areas of science, as measured by the number of references to the term in the scientific literature.[4]

The scientific topics of the workshop are highly interrelated. The principle common to all is the combination of molecular biology, physical sciences and mathematics with classical biology to explain biological phenomena more comprehensively than is possible via any single biological discipline. This ultimately leads to applications beyond the reach of reductionist biology. One of the aims of modern biology is to produce a holistic understanding of biological systems via transdisciplinarity of approach.

Important considerations for secondary education

Ultimately, students will perform well in biology if they are simply interested in and enjoy the subject – regardless of the particular topic used to engage them. As the French pilot and writer Antoine de Saint-Exupery wrote *"If you want to build a ship, don't drum up people together to collect wood and don't assign them tasks and work, but rather teach them to long for the endless immensity of the sea."*

The learning of established knowledge must be complemented by the development of skills and the cultivation of curiosity, particularly for students who plan further study. Modern molecular biology provides many fascinating examples to use as "horizon-expanding" topics in school, together with or instead of older material.

The only way to ensure that all students – not merely those with particularly motivated teachers – have the chance of an insight into new and important fields is to include these areas in curricula and examinations. However, explicit inclusion simply perpetuates the problem of curricular overcrowding. Short curricula with broad categories are better suited to acquiring new areas and topics. Defining a free section of the curriculum drawing on recent advances is an additional complementary strategy.

A more general problem is that biology education in most schools has yet to make the transition from a mainly descriptive approach to the reality of contemporary research. For example, most schools in Europe teach evolution with reference only to similarity of anatomy, embryology and physiology. Talking about molecular evolution – the construction of probable evolutionary relationships by comparing protein and gene sequences between organisms – may sound like a revolutionary approach. However, as early as the 1960s a book on the subject had been published: "Evolving Genes and Proteins".[5] In 1977 Carl Woese and George E. Fox overturned our understanding of the relationship between prokaryotes and eukaryotes by comparing ribosomal RNA sequences between two branches of organisms hitherto considered bacteria.[6] The result was a new phylogeny relating Bacteria, Archaea (still prokaryotes, but much closer to eukaryotes), and Eukarya. More than 40 years after its beginnings, molecular evolution is only mentioned in a minority of secondary education curricula in Europe – despite the fact that it is a more scientific and robust way of investigating and demonstrating evolutionary relationships than comparing form or physiology.

Who needs to know what?

Systems biology is clearly a "horizon-expander" into an exciting new realm of biological understanding. At present it is highly theoretical and involves making complicated computer models, and because of that it might be considered beyond the scope of secondary education (that is not to say, however, that schools would not be able to teach it to some extent). Should, on the other hand, more established subjects such as bioinformatics, molecular evolution and molecular medicine be considered "extras" that only students wishing to study biology at university need to know about? One could even argue the converse, given that technological applications of relevance to many ordinary citizens' lives will increasingly – predominantly – come from new areas of the molecular life sciences.

If the general public is to assess the implications of these applications properly – or vote on their regulation – they need some understanding of the science behind them. The funding of basic research itself also needs to be justified via popular support. Knowledge of what genotyping and genetic analysis means will be key to effective genetic counselling and acquisition of informed consent from patients or research subjects. People will find it hard to make appropriate and informed decisions about their "genomics-based" health care without such knowledge. In this sense it is more a question of how deeply one goes, than whether the principles of bioinformatics, for example, are taught.

Where a more crucial differentiation between students should arguably be made is in the incorporation of complementary sciences and maths into biology education: For students wishing to study biology at university, ability in maths and the physical sciences has never been more important. This is because of the increasing transdisciplinarity of modern biology. In a complementary strategy, biological examples of phenomena can also be included in maths, chemistry and physics lessons.

To make contemporary biology and its techniques accessible to all students (whether they plan tertiary study or not), case-based exercises and examples of relevance to real life should be used. Starting with the applications of science, rather than theory and fact, also sidesteps the problem of theory and fact becoming outdated.

After leaving school, most people will never have another formal opportunity to learn about scientific advances of relevance to their lives. But teachers are not research biologists, and this fact influences the level to which they can communicate and educate with confidence on certain topics. At a certain point, the input of research scientists with communication skills is needed.

Representation of subjects in upper secondary curricula and teaching: status, suggestions and implications

- Systems biology appears not to be explicitly mentioned in any curriculum in Europe (22 countries surveyed).[a]
- The principles of bioinformatics are specifically mentioned in extremely few curricula in Europe.[b]
- Reference to molecular medicine approaches are mentioned in around 1 in 7 European curricula.[c]
- Molecular evolution appears to be represented in at most 30% of European curricula.[d] Large intra-national differences in representation are often seen in countries with regionally defined curricula (e.g. Germany).
- Molecular evolution, and especially molecular medicine, can easily be covered in teaching by reference to topics of general public relevance (e.g. animal models for human diseases).
- Bioinformatics may be considered an "extra" that is merely technically interesting. However, it can easily be introduced in conjunction with molecular medicine and molecular evolution, which rely strongly on it.
- A possible way to introduce new subjects in teaching is to reserve a portion of the upper secondary curriculum as dynamically changeable – e.g. incorporating suitably adapted current scientific literature. An education experiment at the Weizmann Institute, Israel, is assessing this approach.
- Inclusion of new material in the teaching plan does not have to decrease the time available to teach the older material. New material can often be used as the primer for covering older knowledge, hence saving time (e.g. the phenomenon of drug resistance in pathogens can be used to teach the principle of natural selection).
- Examinations define the material that teachers have to teach. If new skills or knowledge are to be taught, these have to be examinable – be that in a formal examination such as the IB, Abitur, A-level, or during continuous assessment.
- The need to examine students' ability in new areas leads to a need to include these areas in the curriculum and textbooks. A partial solution to ageing textbooks is to provide more information via the Internet, where it can quickly be updated.
- A new subject does not have to be included in the curriculum in order to be mentioned in class. Instead it can have a more intangible "horizon-expanding" effect. This, however, is entirely left to individual teachers.
- To be convincing to students, new subjects must be underpinned by thorough knowledge and confidence on the part of the teachers communicating them. Teachers also need to understand the whole of biology in an integrated way.
- Regular, formal in-service training for teachers is a prerequisite for all types of new knowledge or skills to be learnt by students, whether examined or not.

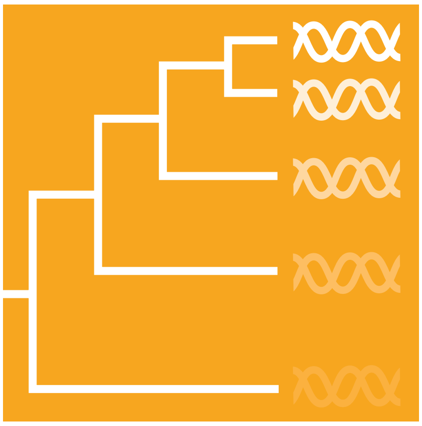
[a] Countries surveyed: Austria, Belgium Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Romania, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom (and Scotland)

[b] partially in Germany (some Länder), partially in the UK (some examination boards)

[c] Finland, partially in Germany (some Länder), Greece, partially in the UK (depending on specific A-level course)

[d] Finland, France, Belgium, partially in Germany (some Länder, or in optional courses), Slovenia, Sweden (in an optional course), UK (some examination boards), Scotland. Representation is often hard to judge: often, chemical theories of life, and the mere mutation of DNA or RNA bases are reported by educators as "molecular evolution".

Some ideas for introducing new concepts during teaching



Molecular evolution

The concept of a common ancestor (determined by comparing gene or genome sequences) is a scientifically more solid basis for presenting phylogeny evolution than the concepts of optimisation, or adaptation to new conditions. Model organisms used in biomedical research are a useful reference point in this respect: it is because of our shared molecular lineage that such animals can be used successfully (in very many cases) to model human diseases. "Experiments" for teachers in molecular evolution can be done with freely available bioinformatics tools and databases, as mentioned below. Molecular phylogeny can – superficially – be likened to the tracing of language origins by studying mutation of ancient word stems that gave rise to cognate words in today's European languages: e.g. "decem" (Latin = 10) shares a common ancestor with Old Saxon "tehan" and Old High German "zehan", which respectively give English "ten" and modern German "zehn". However, it is important to realise that the mechanisms of the evolution itself are different: linguistic evolution proceeds via the inheritance of acquired characteristics across generations (Lamarckian), but biological evolution happens by the selection of certain undirected mutations that prove advantageous (Darwinian).

Bioinformatics

Bioinformatics can be introduced with reference to genetic diseases and the screening of populations for "disease genes", or as the tool used by researchers in molecular evolution. Bioinformatics (in the sense of analysing entire genomes) recently allowed researchers to place chimpanzees (instead of gorillas) as our closest evolutionary relative.[2,3] Several countries in Europe now have national patient sequence databases, and that makes it possible to discuss interesting societal and ethical questions in the classroom. Using open databases and freely accessible services via the Internet (e.g. ENSEMBLE: *www.ensembl.org/* and BLAST: *www.ncbi.nlm.nih.gov/blast/*), simple sequence comparisons can be made, e.g. between haemoglobin sequences of horse, pig, cow, dog and human. The hypothesised evolutionary relationship can then be tested against known molecular phylogenies relating these species. A collection of bioinformatics experiments suitable for teachers can be downloaded at *www.embo.org/scisoc/tw03biocomputing.pdf*

Molecular medicine

From cancer to malaria, there is almost no disease that is not addressed by molecular biology. Molecular medicine is the realm of basic research, small companies and pharmaceutical giants. The leukaemia drug Gleevec® is a good example of its success. Gleevec® targets cancer cells specifically, and hence has much less severe side effects than traditional non-specific chemotherapy, which targets all rapidly dividing cells in the body. It is possible that 90 % of all drugs only work for 30 – 50 % of people:[7] that is a massive public healthcare problem worth discussing in school, and one that is addressed by molecular medicine's ability to produce more specific treatments. Gene therapy – a branch of molecular medicine that has demonstrated success in curing severe combined immunodeficiency (SCID)[8] – also raises interesting ethical questions, particularly with reference to prenatal diagnosis and possible germ line therapy.

Practical work in molecular biology

Simple practical exercises demonstrating important principles of current molecular biology in a manner suitable for schools certainly exist. However, in many cases consultation with scientists at a nearby university, or loan of equipment and provision of reagents, are necessary. Some experiments are only feasible if a teacher has a laboratory technician to help prepare. Bioinformatics can only be taught via practical experience, which involves working with computers on-line under the supervision of a teacher well versed in the use of the Internet, sequence analysis software and sequence databases.

Where are the good modern teaching materials?

Much good material is freely accessible on the Internet. The problems are finding it, and finding it in one's own language. English language resources (particularly from the USA) tend to dominate: a particularly good example is that of the Howard Hughes Medical Institute's BioInteractive website (www.hhmi.org/biointeractive/).

However, there are many excellent European resources also. EMBO's database of educational resources (www.embo.org/scisoc/teachers_db.php) contains a broad range of resources inside and outside Europe. The need for greater awareness, international exchange and translation of such materials is being addressed by the EU-funded project Volvox (www.eurovolvox.org). First resources are expected in 2008.

Films, short movies, 3D and 2D animations are much appreciated by teachers for their power in demonstrating biological principles or research techniques. Apart from those on the HHMI's BioInteractive website, many European examples exist, for example BioClips (www.bioclips.com), and "A stem cell story" (www.eurostemcell.org/Outreach/outreach_film.htm).

Teachers and immediacy

Curricula change and textbooks are revised, but they can never be truly up-to-date. Teachers are the living mediators of science, and many systematic problems in biology education can probably be overcome by increasing teachers' competence and confidence in new and emerging areas of the subject. Curricula and examinations should make it possible for teachers to creatively interpret basic concepts. By organising journal clubs teachers can come together (e.g. twice a year), present and discuss new areas of their subject and how to teach them. The addition of one or two appropriate scientists to this group would be invaluable. Journals such as Nature and Science can be scanned regularly for interesting material to mention during lessons.

An annual teacher training opportunity – in a different area of biology each year – is crucial. Many university staff members currently help teachers voluntarily and without recompense. However the demand far exceeds this generosity, and governments must fund larger scale, permanent interactions between tertiary and secondary educators. Curricula and textbooks cannot be prevented from becoming out of date, but teachers can.

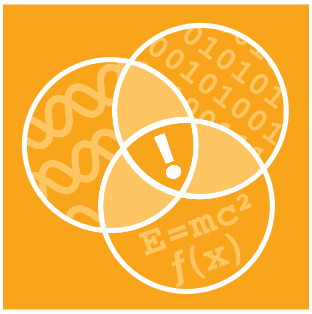
www.hhmi.org/biointeractive/

www.embo.org/scisoc/teachers_db.php

www.eurovolvox.org

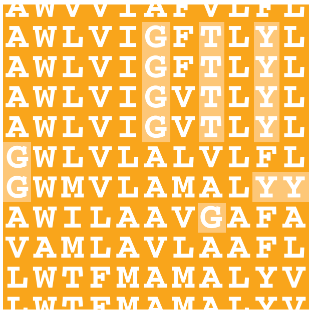
www.eurostemcell.org/Outreach/outreach_film.htm

DEFINITION OF TERMS



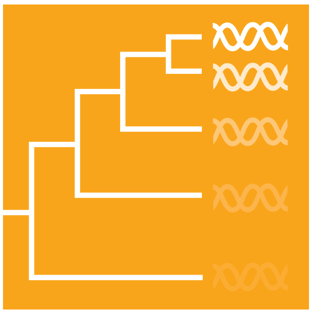
Systems biology

Is a discipline at the interface of biology, physics and computational sciences. It focuses on understanding and modelling a "system" as a whole, rather than merely exploring the characteristics of isolated parts of a cell or organism. The system can be anything from a metabolic pathway up to an ecosystem. The systems biologist aims to understand the physical and chemical mechanisms or "rules" that underlie the specific behaviour of the system under study: the interactions between components in the system, and the dynamic changes in concentration etc. The long-term goal is to apply these principles either to change the behaviour of an existing system, or to construct new systems with specific, desired characteristics (synthetic biology).



Bioinformatics

Combines mathematics, informatics, computer sciences, molecular biology and chemistry to solve biological problems usually on the molecular level. The identification of genes and their products (mainly proteins) in the genomes of organisms is one example of bioinformatics. It extends to predicting and discovering which proteins interact in a cell (proteomics) and the modelling of evolutionary relationships between organisms (molecular evolution). Bioinformatics can be considered a tool of modern biology.



Molecular evolution

Makes use of sequence analysis of similar proteins or genes between different organisms in order to reveal the probable evolutionary relationship between species. It uses the tools of bioinformatics to generate likely phylogenetic trees based on the sequence differences that arise in proteins and genes between species due to mutation over long periods of time. Certain proteins (e.g. haemoglobin and cytochrome C) are termed "molecular clocks" because they mutate at a fairly constant rate over time. More recently, whole genome sequences can be compared to define the evolutionary branching pattern between very closely related species.

Molecular medicine

Draws mainly on the fields of biochemistry, molecular biology and molecular genetics in order to establish the molecular mechanisms of disease. From malaria to cancer, it leads to developments such as molecular diagnostics and highly targeted treatments, therapies or cures (be they drugs, other biologically active molecules or genetic repair). In combination with bioinformatics, population genotyping and individual genotyping, it contributes to the development of personalised medicine: the right drug, in the right dosage, for the right person.

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AUTHOR

Andrew Moore
Programme Manager EMBO Science & Society

CONTACT

EMBO Science & Society Programme
scisoc@embo.org
www.embo.org/scisoc

PROOFREADING

Dean Madden
Les Grivell
Sandra Bendiscioli

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