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Genomics and biology education:
complex stuff and curricular overload

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Over the last four decades, researchers have made much progress in acquiring insight into the genetic background of cancer. Research has shifted from traditional (clinical) genetics research, typified by the hunt for genes that cause monogenic diseases, to multidisciplinary genomics research. Nowadays, it is realized that cancer is the result of a mismatch in complex cellular signalling networks involving large numbers of genes and proteins. To determine risks, prognosis and therapies for cancer patients, single biomarker tests have been replaced by characterization of tumours by several biomarkers (DNA, RNA, proteins). The first steps towards more individual diagnosis and treatment of cancer patients have also been taken, such as Herceptin and Glyvec (see for example Strausberg et al., 2004), based on molecular markers, e.g. using microarrays. In short, cancer researchers and physicians have moved from concentrating on the organ of the primary tumour to focusing on biomarkers that reflect the underlying cellular processes.

Another change in genomics research is the attention paid to the relationship between science and society. Since the announcement of James Watson that the Human Genome Project would devote a significant amount of its funding to the ELSI (Ethical, Legal and Social Implications) Research Program of the full human genome sequence, many research programmes and technological advances have been accompanied by studies of their potential ethical, legal and social impact (Kitcher, 2001).

But which of these trends in genomics should be included in new educational materials? Interviews with cancer genomics professionals (n = 6) suggest the following list of learning goals:

- Students should:
  1. Have a fundamental knowledge of genetics
  2. Be aware of future developments, such as the $1000 personal genome
  3. Comprehend the nature of science, including understanding:
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- The time span between laboratory and clinic
- Dealing with uncertainty in science (and society)
- Complexity and multifactoriality of diseases
- Risk assessment and perception.

Fundamental knowledge of genetics refers mainly to a basic conceptual understanding of DNA, RNA, the process of protein synthesis, i.e. transcription and translation, and the relationship of these cellular processes with phenomena at higher levels of biological organization. In addition, awareness of future societal implications and understanding the way science works are important learning goals for secondary students. Genomics studies the relationship between large networks of genes and/or gene products, and the behaviour of complex systems at higher levels of organization, e.g. metabolic pathways, cellular responses, development, etc. Genomics professionals regard it as important for future citizens and scientists to be aware of the complexity of these systems, including the notion that simple cause–effect relationships in disease development are the exception. This evidently has consequences for cancer risk prediction and the development of (individual) treatments.

The learning goals described by genomics professionals indicate that genomics education should prepare students for different communities of practice and different roles. Genomics education should empower students for individual decision-making in their personal lives and also for partaking in societal decision-making. Some students will be the scientists and doctors of tomorrow, so students should also be prepared for future professions in science or medicine.

Five genomics centres of excellence in the Netherlands have jointly developed a series of mobile DNA practicals that can be taken to secondary schools to give students a realistic impression of genomics research and the implications for society. These so-called DNA laboratories are offered free of charge to all Dutch upper secondary schools, and each laboratory focuses on a different field of genomics research. The DNA laboratory that focuses on cancer genomics is called ‘Tumour Talk’ (see also van Mil, 2007; and www.cancergenomics.nl – Societal Aspects). The practical takes two lessons and the teacher is expected to give an introductory and a concluding lesson, resulting in four lessons in total. Students learn how cancer can be diagnosed and how treatment may be tailored to the genetic make-up of a certain tumour (personalized medicine). The hands-on experiments of students consist of DNA isolation, copying DNA in a small portable PCR apparatus and running it on an agarose gel. Students then search for mutations in
three different genes and have to choose an adequate therapy. For example, a mutation in the HER2NEU gene means that administration of Herceptin is an adequate therapy. The intended learning outcomes of the various DNA laboratory topics include the ‘learning goals’ put forward by genomics experts, with particular focus on preparing students as future citizens, i.e. consumers of genomics information taking personal decisions and critical democratic citizens participating in societal decisions:

- Realistic views on science and technology
- Viewing knowledge as tentative
- Willingness to seek more information
- Critical reflection
- Gaining insight into their own and other people’s values
- Substantiation of their own position
- Preparation for any future decisions: opinion-forming competence.

Overall evaluation of the five DNA laboratories has revealed that they are successful in terms of reach and user satisfaction (Knippels et al., 2006). Teachers and students were enthusiastic and expressed a positive attitude towards genomics research. The success of the initiative is most obviously reflected in the number of schools that have visited the website and have ordered the DNA laboratory ‘Tumor Talk’. Since September 2005, ‘Tumor Talk’ has been fully booked and more than 17,000 students in 700 classes have been involved. However, the perceived learning outcomes were modest; students commented that they were able to grasp the how and why of genomics research, but seem to learn little about the functioning of and relationship between DNA, genes, proteins and phenomena at higher levels of organization. In addition, the initiative’s aim to encourage the formation of opinions about genomics research, as well as to stimulate the discussion of societal issues in the classroom, has not yet been achieved.

These findings were the reason for a revision of the DNA laboratories programme directed at enhancing students’ insight into the complexity of cellular interrelations, and at fostering each student’s competence to deal with genomics-related socio-scientific issues. An additional challenge is to embed the DNA laboratories in the existing biology curriculum, i.e. institutionalizing genomics education, without adding to the problem of curricular overload. For both challenges, the adoption of ‘systems thinking’ in upper secondary school biology education might be an important step towards a solution.
Systems thinking is linked with but not identical to systems biology. The latter focuses on the systematic study of complex and dynamic interactions in biological systems. Genomics contributes to this relatively new field of biology. In genomics, molecular technologies and bioinformatics are integrated to understand and predict complex cellular functions in relation to phenomena at higher levels of organization, e.g. concerning health and disease, agro-food and sustainability.

A survey of 22 countries indicated that systems biology is not explicitly mentioned in any science curricula in Europe (Moore, 2007); in addition, the principles of bioinformatics – an important discipline within genomics – are mentioned in very few. However, the exclusion of systems biology is not a unique oversight; the introduction of new scientific concepts and techniques into science education is hampered in general by the problem of curricular overload. Current European biology curricula cover many themes in a descriptive manner, each of which brings a large number of new concepts used at various levels of biological organization. In the Netherlands, for example, an average school textbook introduces no less than 577 new concepts related to cell biology alone, which illustrates that the curriculum is extremely heavy on factual content.

To investigate the extent of this information overload, the contents of two Dutch textbooks entitled ‘Biologie voor jou’ (‘Biology for you’) were analysed. These textbooks are used to teach pre-university biology by approximately 40% of biology teachers (Smits & Waas, 2000). The first chapter introduces biology as an empirical discipline and explains the structural organization of organisms in terms of organs, tissues and cells. In addition, the submicroscopic structure of plant and animal cells is elaborated in detail. Subsequent chapters focus on topics such as reproduction and development, genetics, DNA, homeostasis, behaviour and the immune system. As a focus for our analysis, the topic of cell biology was selected and all cell biological concepts – concepts connected to the theme of ‘the cell’ – were classified according to three main categories representing the molecular, cellular and organism levels (Verhoeff, 2003). Each new cell biology concept mentioned for the first time in the text or in the legends of figures was scored and checked for whether it was simply mentioned or whether it was also explained to the reader in terms of his or her prior knowledge.

Table 3 presents the results of this analysis. At the molecular level, the concepts presented in the textbooks covered topics including chemical compounds, chemical reactions – such as phosphorylation and polymerization – and molecular characteristics such as fat
solubility and oxidation. At the cellular level, the concepts ranged from substances – hormones and nutrients, for example – to processes such as diffusion or active transport, as well as cellular structures and their functions. At the organism level, the concepts related to bodily processes, structures – both organs and artificial replacements – and organism characteristics within the context of cell biology such as phenotypes, zygosity and trophism.

Professional biologists like biology teachers and genomics researchers often implicitly link certain concepts or phenomena to a specific level of organization and have acquired a coherent understanding of biological processes. Secondary students do not do this, i.e. many problems with acquiring a coherent understanding of cell biology can be typified as difficulties in interrelating different concepts at the cellular level, and interrelating concepts at the cellular and organism level (Verhoeff et al., 2008). To cope with these difficulties, a learning and teaching strategy that features the intentional use of systems thinking was developed (Verhoeff, 2003; Verhoeff et al., 2008). This means that systems thinking is considered not only as a tool for developing coherent biological knowledge, but also constitutes a desired learning outcome of the strategy. The main outcomes referring to systems thinking competence are outlined in Table 4.

Table 3. Introduction and use of biological concepts related to the topic of ‘cell biology’ in Dutch schoolbooks entitled ‘Biologie voor jou’, classified by level of biological organization

<table>
<thead>
<tr>
<th>Categories of cell biological concepts (n = 544)</th>
<th>Number of new concepts</th>
<th>Concepts coupled with explanation (%)</th>
<th>Concepts used after introduction and explanation (%)</th>
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<tbody>
<tr>
<td>Molecular level (e.g. compounds, chemical reactions, characteristics)</td>
<td>141</td>
<td>70</td>
<td>9</td>
</tr>
<tr>
<td>Cellular level (e.g. substances, processes, structures, functions, cell types)</td>
<td>357</td>
<td>77</td>
<td>19</td>
</tr>
<tr>
<td>Organism level (e.g. processes, structures, characteristics)</td>
<td>79</td>
<td>61</td>
<td>14</td>
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In contemporary research, systems biology refers to the integration of experimental and computational approaches to understand and predict complex cellular functions (Alberghina, 2007). One important characteristic of systems biology is that it is an iterative process of data-driven model building and model-driven data gathering. The fourth element of a systems thinking competence (Table 4) reflects this central role of the use of models. Although systems thinking gets little attention in secondary education, textbooks used in secondary education contain many two-dimensional and three-dimensional models that focus, for example, on different aspects of cells. The functionality of using models in science education has been widely acknowledged (see, for example, Gilbert, 1993; Coll & Taylor, 2005). In science education literature, an important distinction is made between idiosyncratic mental models and analogical scientifically accepted consensus models (Gilbert & Boulter, 2000) or symbolic models (Harrison & Treagust, 2000). In our study, students engaged in an active ‘model-based learning trajectory’ starting with their idiosyncratic mental models, via intermediate models, towards a systems theoretical target model (see Figure 3) (Verhoeff 2003; Verhoeff et al., 2008).

By going through the process of systems modelling, students were introduced to the scientific practice of developing and using models as tools for observation, exploration and the prediction of biological phenomena. In this way, a systems approach not only helped students to learn about biological systems at different levels of organization, but also fostered an understanding of the nature of science that is largely concerned with extending and refining systems models. Indeed, although educational or student models vary in many respects from scientific genomics models, we nevertheless see that

### Table 4. Four elements of a systems thinking competence to be acquired in biology education (Verhoeff et al., 2008)

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<tbody>
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<td>1.</td>
<td>Being able to distinguish between the various levels of biological organization, i.e. cell, organ and organism, and to match biological concepts with specific levels of biological organization.</td>
</tr>
<tr>
<td>2.</td>
<td>Being able to interrelate concepts at a specific level of organization (horizontal coherence).</td>
</tr>
<tr>
<td>3.</td>
<td>Being able to link biology concepts from different levels of organization (vertical coherence).</td>
</tr>
<tr>
<td>4.</td>
<td>Being able to think back and forward between abstract visualizations (models) to real biological phenomena.</td>
</tr>
</tbody>
</table>
an iterative process of modelling and testing is possible in education, and can prepare students for a strategy that they will later encounter in studies in which systems biology has a role.

The question of how systems thinking can diminish the curricular overload has not yet been completely answered. The answer is to be found in the attention that needs to be paid to coherence in students’ understanding of biological phenomena, starting at the concrete organism level. Phenomena like cancer or eating/digestion can act as a plot by which all details and characters of the story can be remembered. By building models of horizontal and vertical relationships related to a phenomenon, students construct a framework in which they can place new concepts (see, for example, a framework built by students around the phenomenon ‘cancer’ in Verhoeff et al., 2009). The use of such a framework as a so-called ‘advance organizer’ improves retention (Ausubel, 1968): it provides organizational cues and helps to connect the known to the unknown.

Systems thinking also means separating central concepts from peripheral ones, implying that fewer concepts need be learnt by heart because the framework indicates how and
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where information can be found. In genomics, for example, the gene is a central concept that will appear many times. As Knippels (2002) has shown, tuning the genetics vocabulary to the specific level of organization that students are dealing with at any given moment prevents confusion. Explicitly distinguishing levels of organization therefore helps to prevent the often-reported difficulties that students have with cytological concepts, chromosome structure and the homologous chromosome concept.

Systems thinking allows students to frame their knowledge in a matrix that includes a broad range of distinct organizational levels from the molecular up to and including the societal or population level. Inserting genomics in science curricula in this way might break what has been called the central dogma of biology – the primacy of DNA as the originator and primary ruler of cellular function – and help students to realize the influence of environmental stimuli on the proteins that turn on our genes, and therefore shape organisms’ ability to adapt and evolve. With this in mind, issues on the societal level concerning (public) health or sustainable use of resources can be discussed as well. Clearly, a gap exists between knowledge produced in academic research practices and the knowledge disseminated by our pre-university education system. In the light of this, a rethinking of the ‘essential’ biological concepts might actually reduce the cognitive load of the curriculum, which could then provide space for updating school curricula. However, the inclusion of genomics would also imply the introduction of another conceptual focus – one that gives credit to both the complexity of the topic and the societal implications of contemporary research practices. As we have argued, acquisition of a systems thinking competence should be a central focus for secondary biology education that helps students to acquire a coherent understanding of biological phenomena from the molecular level up to and including the societal level. In the Netherlands, the mobile DNA laboratories incorporate scientific practices of genomics in classroom practice and relate these to societal implications. Within the context of these educational laboratories, an educational research project has been started, funded by the Centre for Society and Genomics, that takes up the challenge of developing a model-based learning trajectory for genomics (www.society-genomics.nl). It explores how genomics experts use imagery to handle the dynamic nature of molecular processes and how this might inform ‘minds-on’ education accompanying the ‘hands-on’ DNA laboratories.
References


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