

Organizing Graduate Life Sciences Education around Nodes and Connections

Jon R. Lorsch^{1,*} and David G. Nichols^{1,2,*}

¹Department of Biophysics and Biophysical Chemistry

²Departments of Anesthesiology/Critical Care Medicine and Pediatrics

Johns Hopkins University School of Medicine, Baltimore, MD 21205, USA

*Correspondence: jlorsch@jhmi.edu (J.R.L.), dnichols@jhmi.edu (D.G.N.)

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Biomedical education is currently faced with a number of significant challenges, including the explosion of information and the need to train researchers who can work across traditional disciplinary boundaries. We propose a new integrated model for graduate education in the life sciences that addresses these issues.

Over the past 20 years, the rate of acquisition of biomedical knowledge has increased exponentially (Attwood et al., 2009). Although the increase in our knowledge of fundamental principles lags behind the rate at which total information accumulates, the amount of material that could be taught in advanced life sciences curricula today is much greater than it was 20 years ago.

Despite this information explosion, the way that we teach biological systems to graduate students has fundamentally changed little except perhaps for a few technological advances in the classroom, such as PowerPoint and eLectures. Although these advances enable us to present more information per unit of time, we can no longer teach even a fraction of what is known. Even if time permitted it, students could never absorb, process, or retain all of this information. Our current knowledge of living systems has outgrown the existing models for biomedical education at the postcollege level.

In addition, modern biomedical research increasingly requires interdisciplinary teams incorporating a variety of complementary tools to investigate problems (Connelly et al., 2009; Sharp et al., 2011). Innovations in undergraduate education are beginning to address the need for interdisciplinary learning and research (Alpern et al., 2009; Stryer et al., 2003), but graduate education appears to lag significantly behind.

We took an informal survey of top-ranked graduate programs in systems

biology and biochemistry, molecular, and cellular biology. In the past decade, some programs have embraced a more student-centered approach to education, giving students more choice in which courses to take. However, the traditional intellectual delineations that define their curricula have remained essentially constant.

Advanced education in the life sciences is generally organized along departmental boundaries (Figure 1, left). These silos are largely based on the scale at which the questions are asked in each field (i.e., the atomic scale up to that of whole organisms) and the methods used to answer them (e.g., X-ray crystallography or animal genetics). Typical curricula include biophysics, biochemistry, molecular biology, genetics, cell biology, and physiology, courses that likely derive from a time when each academic department had its own graduate program. Approximately 30 years ago, when the broader “umbrella” programs (including our own Biochemistry, Cellular and Molecular Biology program) became the predominant model for graduate training in the life sciences, these departmental course structures were used to build the new curricula for first-year students. Although this organization was politically and administratively simple, we believe that new educational models are required to overcome the challenges currently facing the life sciences: information overload, the need to train scientists whose research will transcend traditional departmental boundaries (Costello, 2009), and

the goal of translating basic science into medical and technological advances.

Bringing Method to the Mayhem

If the knowledge produced by each discipline, or silo (Figure 1), is separated from the underlying framework of methods that define it, we would be left with an armamentarium of techniques for studying biology at all levels, from the atomic to the organismal. A working knowledge of these methods would be a valuable foundation for students pursuing a research career. It would prime them to tackle fundamental biological questions with whatever methods are required, rather than limiting them to those techniques favored within their chosen subfields.

The primary goal of such a “Methods and Analysis” (“M&A”) course would be to give graduate students conceptual familiarity with key techniques and analytical tools, rather than to train them to actually perform the experimental methods. Instead, they would learn to conduct the techniques in later years at the bench, as the need arises. The course would: (1) specify the kinds of information each technique provides, (2) point out the strengths and weaknesses of each approach, and (3) focus on how to use, understand, and judge the quality of the final data produced by each method. By the end of the year, students would understand and use data created through a broad range of methods, such as protein crystallography, bioinformatic analyses, and yeast genetic screens. This practical

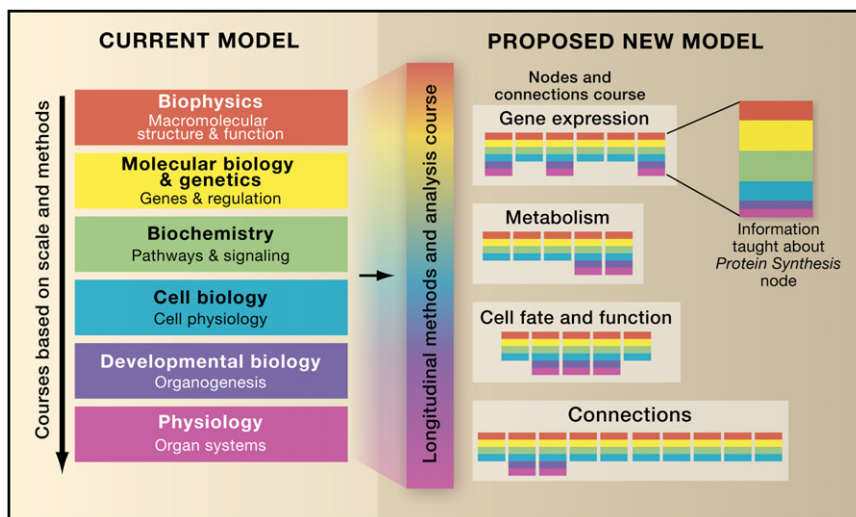


Figure 1. Modernizing the Graduate Curriculum

The current model of the first-year curriculum in a typical biomedical graduate program (left) separates fields into discrete units in both lecture and laboratory classes. In contrast, we propose a new model (right) in which key information is integrated across fields through a network of “nodes” and “connections,” similar to those networks described by systems biologists. The multicolored bars represent fundamental principles and essential facts about each key process integrated across scales, from the atomic level (red) up to the organismal level (violet).

knowledge would then translate into increased productivity in the laboratory; once a student embarks on a thesis project, he or she would already know how to manipulate protein structure files from the Protein Data Bank, compare aligned gene sequences, and select residues to target for a mutagenesis study. The student would also immediately grasp the goals and potential pitfalls of a collaborator’s yeast genetic screen.

Connecting the Dots in the Data Morass

In addition to a working understanding of biomedical methods, graduate students would also greatly benefit from learning the organizing principles that link key facts across the biological specialties. Fortunately, the mountain of information that we have accumulated through decades of research is not a morass of unrelated facts but instead self-assembles into a network of interconnected processes (i.e., nodes) that describes biological systems. We propose that the processes taking place in an organism can be broken into three broad categories—gene expression, metabolism, and cell fate and function—as well as the connections (i.e., communication pathways) among the nodes.

For example, protein synthesis is a node within gene expression. Our current understanding of protein synthesis is built from information obtained at all scales of investigation (Figure 1, right). Likewise, amino acid biosynthesis is a node in the metabolism category. These two nodes are connected to each other, as well as to the transcription node, by the general control nonrepressed 2 (GCN2) signaling pathway, which is also described by a body of information derived from each field.

In the current silos framework of advanced biomedical education (Figure 1, left), it is difficult for students to integrate information about a biological process at all scales because this information is scattered throughout the curriculum. For example, protein synthesis might be covered through an isolated lecture on ribosome structure and function, followed 2 months later by a lecture on protein secretion, followed a month later by a lecture on peptide hormone signaling.

We suggest that it makes more sense to teach the fundamental principles of each key node and connection using a framework in which knowledge is integrated across all scales. This “nodes and connections” (“N&C”) course would teach students about each key node from the

“bottom” (i.e., atomic and molecular scales) to the “top” (i.e., the cellular and whole animal scales) before moving on to the next node. The nodes would then be connected to the communication pathways among them using a similar integrated strategy.

We foresee significant advantages to teaching the life sciences with this model. First, biology is genuinely arranged as a set of interconnected processes—a fact recognized by the emerging field of systems biology (Kirschner, 2005). So teaching it this way would reflect the operation of living systems. It would also connect the atomic and molecular underpinnings of a system directly to the microscopic and macroscopic processes.

In addition, this arrangement would make it easier for educators to identify the fundamental principles and essential facts that students in a particular subdiscipline should know as a foundation for future learning and research. The acid test would be whether particular information is crucial for understanding the overall operation of the node or its connection to other nodes. For example, students do not need to know the names and putative functions of all 12 eukaryotic translation initiation factors to develop a working knowledge of the fundamental principles of protein synthesis. Instead, they need to know the central components and steps in the protein synthesis pathway that are common to all organisms and the key differences in the process between bacteria and eukaryotes (e.g., Shine-Dalgarno sequence in the mRNA versus the 5′-cap and poly[A] tail). The choice of nodes and connections included in the curriculum, as well as the range of information presented about each node or connection, would vary depending on the needs of the target students.

The third way that the N&C model would enhance biomedical education is by establishing a framework that students can use to organize the information that they acquire. We believe this framework would help them to retain more of what they learn and more easily expand their understanding of biological processes as new information is added throughout their careers.

Finally, organizing advanced life sciences education with the N&C framework would facilitate the formation of

interdisciplinary research collaborations. Teaching information across scales in this integrative fashion mirrors a recent proposal from Sharp et al. (2011) calling for a shift from field-specific research in the biomedical sciences to a “convergence” model in which investigators work together across disciplinary boundaries (Sharp et al., 2011). The N&C approach would facilitate the development of graduate programs focusing on multidisciplinary training, which are required for producing future generations of biomedical researchers (Connelly et al., 2009). Furthermore, it builds off current trends in undergraduate education toward more interdisciplinary teaching models (Stryer et al., 2003). Teaching a common framework for understanding and organizing information about biological systems would significantly enhance students’ abilities to communicate and work with researchers across different fields. The existence of a common framework would also speed the translation of scientific discoveries into medical and technological advances.

Diversity and Integration of Teaching Methods

We propose that the M&A and N&C courses would use a variety of synergistic educational methods to optimize learning and help students gain skills in formulating and answering critical questions. For example, each session of the M&A course would begin with a short lecture on the technique under study. A workshop would then follow in which students, individually or in teams, analyze data generated by this technique. The goal of this analysis would be to answer questions about a system that they are currently studying in the N&C course. Likewise, the N&C course would consist of a mixture of lectures, team-based exercises in which students design experiments to answer questions about the given system, and discussions of “great papers” in which small groups explore seminal works that informed our understanding of key aspects of each system. Each graduate program would specify a set of core nodes and connections that its students must study. However, the N&C course could also incorporate more student-centric learning by allowing students to choose additional modules to

study, depending on their interests. A capstone experience at the end of the first year would consist of teams of students with diverse backgrounds identifying important unanswered questions in the life sciences and developing multidisciplinary proposals for answering them.

Connecting the Clinic to Basic Science in Medical Education

For the same reasons outlined above, basic science education for medical students would significantly benefit from reorganization of its teaching model into an interconnected nodes (“systems biology”) approach. Understanding phenotypic variation among patients requires integrated knowledge of genomic, molecular, and environmental variation, reflecting the nodes and connections concept (Wiener et al., 2010). As scientists increasingly identify underlying molecular causes for macroscopic disease phenotypes, the N&C model will also create additional educational synergies. For example, it could improve medical students’ retention of basic science information by relating it directly to clinical information. This increased retention, in turn, would enhance the students’ abilities to diagnose and treat complex diseases when they become physicians. The integrative approach to learning about biological systems also dovetails with recent calls for competency-based, rather than course-constrained, premedical education (Alpern et al., 2009).

Above the Foundation: The Second Year and Beyond

Once foundational studies in the first-year M&A and N&C courses are completed, graduate students would begin their thesis research. At this stage, a graduate curriculum might include elective courses to expand students’ knowledge and skills in specific areas and to hone their abilities to identify important questions and design strategies to answer them. These courses could include traditional literature-based seminars and hands-on training in experimental techniques (e.g., mass spectrometry). They could also incorporate team-based projects that bring together groups of students from diverse backgrounds to brainstorm solutions to important scientific questions or unmet medical and technological needs

(Alberts and Fineberg, 2004; Humphrey et al., 2005).

Assessing Outcomes and Managing Change

One of our main goals in putting forward this framework is to catalyze new thinking about advanced life sciences education. However, no model, including those currently in use or the one that we propose here, should be deemed successful without solid evidence. As pointed out recently (Feldon et al., 2010), we currently have no standardized methods for assessing the efficacy of graduate biomedical education. We urgently need approaches for determining the value of graduate curricula, perhaps benchmarking them against the null hypothesis “students would do equally well with no course work at all outside of apprenticeship in the laboratory.”

There are many barriers to implementing our proposed changes, including a large commitment of faculty time and the necessary loss of some content that is currently taught. However, we feel that the potential benefits of our proposal outweigh these costs. The curriculum would better prepare students for the laboratory and would reduce the lag time for productive thesis research. In addition, the new teaching models required by this curriculum would catalyze collaborative, interdisciplinary research among both students and participating faculty, which we believe is a major benefit as support for field-specific science evaporates. Institutions, particularly medical schools, could further facilitate efforts for significant curricular change by explicitly recognizing them in both promotion and compensation considerations.

We fear that, unless scientists are willing to develop new models for advanced biomedical education and to rigorously test and compare these models, we will fail to adequately equip today’s students with the tools that are needed to push forward the boundaries of knowledge and to bring about the scientific and medical breakthroughs of the future.

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