What Skills Should Students of Undergraduate Biochemistry and Molecular Biology Programs Have Upon Graduation?

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Abstract

Biochemistry and molecular biology (BMB) students should demonstrate proficiency in the foundational concepts of the discipline and possess the skills needed to practice as professionals. To ascertain the skills that should be required, groups of BMB educators met in several focused workshops to discuss the expectations with the ultimate goal of clearly articulating the skills required. The results of these discussions highlight the critical importance of experimental, mathematical, and interpersonal skills including collaboration, teamwork, safety, and ethics. The groups also found experimental design, data interpretation and analysiand the ability to communicate findings to diverse audience to be essential skills. To aid in the development of appropriate assessments these skills are grouped into three categories, 1) Process of Science, 2) Communication and Comprehension of Science, and 3) Community of Practice Aspects of Science. Finally, the groups worked to align these competencies with the best practices in both teaching and in skills assessment. 41(5):297–301, 2013

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Introduction

All biochemistry and molecular biology (BMB) students should acquire a sound understanding of their discipline's foundational concepts as well as fundamental BMB facts and theory. In addition to these expected student outcomes, program goals often contain language about "what-students-can-do" relating to the skill sets of students. One set of skills can be directly correlated to the "hands-on" training in techniques and tools. However, the knowledge expectations for a successful career in BMB fields extend beyond technical abilities. These additional expectations relate to broader skills including communication, problem-solving, and social interaction that are important for success in science. However, in the effort to cover content, these skills frequently are ignored, avoided, or assumed to be the responsibility of others to be fulfilled through institutional general education requirements. Both are necessary as Stephen Brookfield declared, *If college teachers define themselves only as content or skill experts within some narrowly restricted domain, they effectively cut themselves off from broader identity as change agents in helping students shape the world they inhabit* [1].

This dichotomy between content and process means that students can have a strong understanding of textbook knowledge but have little practical experience in communicating their knowledge or functioning in a laboratory environment. Certain things students must learn by doing and

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TABLE I *Skills recommended by ASBMB as part of the undergraduate curriculum*

- Understanding of the fundamentals of chemistry and biology and the key principles of biochemistry and molecular biology.
- Awareness of the major issues at the forefront of the discipline.
- Ability to assess primary papers critically.
- Good "quantitative" skills such as the ability to accurately and reproducibly prepare reagents for experiments.
- Ability to dissect a problem into its key features.
- Ability to design experiments and understand the limitations of the experimental approach.
- Ability to interpret experimental data and identify consistent and inconsistent components.
- Ability to design follow-up experiments.
- Ability to work safely and effectively in a laboratory.
- Awareness of the available resources and how to use them.
- Ability to use computers as information and research tools.
- Ability to collaborate with other researchers
- Ability to use oral, written and visual presentations to present their work to both a science literate and a science non-literate audience.
- Ability to think in an integrated manner and look at problems from different perspectives.
- Awareness of the ethical issues in the molecular life sciences.

with practice. This "tacit knowledge" [2] is what one knows, but cannot describe effectively in words. For example, one can describe how to purify an enzyme conceptually and procedurally, yet that information would be insufficient for a student who was not familiar with making buffers, using a centrifuge or spectrophotometer, assaying an enzyme, and a multitude of other skills that biochemists learn through observation, hands-on experience, and practice. Processing and communication are required skills in order for students to design, carry out, analyze, and interpret experiments. Yet even students with extensive laboratory experience often are restricted by an inability to communicate their knowledge or experiences. Communicating the problem and the results to diverse audiences is an ability that, like other skills, must be learned and practiced.

A focus on skills in addition to more traditional content area was suggested some years ago [3] and was formally incorporated into the American Society for Biochemistry and Molecular Biology (ASBMB) recommended curriculum for BMB majors in 2003 [4] and are summarized in Table I. The vision and change final report [5], which focused on biology education, released in 2010, formally grouped skills into six conceptual areas outlined in Table II. These also align with more generic lists of skills [6, 7] associated with a liberal arts education. While numerous papers have been written about BMB concepts and skills (e.g., refs. 8, 9] and references therein), no broad survey of faculty had been undertaken to determine what faculty consider critical in undergraduate education of BMB majors. The ASBMB has undertaken this task.

Aligning with the *Vision and Change* document [5], the ASBMB with funding from the NSF's Research Coordination Network (RCN) program is in the process of producing a central resource of core concepts and assessment tools for BMB educators. In the first phase of the project, the society conducted a series of small regional meetings attended by faculty who teach BMB at universities and liberal arts colleges [10]. Meetings have been held in various US locations collectively representing a spectrum of biochemistry, biology, molecular biology, or combined BMB programs from a spectrum of institutions types. The two objectives of this ongoing process are 1) to create a network of faculty involved in undergraduate BMB education and to learn from these practitioners what knowledge and skills they feel are important for their graduates, and 2) to bring together people skilled in assessment and these discipline related faculty to help create focused assessment tools that can be used to enhance student centered education.

Participating groups of faculty and scientists have identified essential concepts and skills during the first two years of this project. As we move into the next phase of the overall project, ASBMB is organizing meetings around assessment issues and will collect and disseminate ways to assess students' knowledge and skills. This article is one in a series designed to communicate the outcomes and consensus statements from the meetings in the past two years and

TABLE II *Vision and change focus on "Skills"*

- Ability to apply the process of science:
- Ability to use quantitative reasoning :
- Ability to use modeling and simulation:
- Ability to tap into the interdisciplinary nature of science:
- Ability to communicate and collaborate with other disciplines :
- Ability to understand the relationship between science and society:

specifically addresses the expected bachelor's level BMB skills discussed during these meetings. Other articles in the series will discuss foundational concepts of the molecular life sciences and underlying concepts of chemistry, physics, mathematics [11, 12].

Faculty at one of our meetings drafted the following consensus statement:

Students will develop the ability to design controlled experiments that test specific hypotheses, find relevant data in electronic repositories, and assess the quality of both. Further, they will be able to quantitatively model and interpret data, form conclusions and new hypotheses, and clearly communicate their findings to diverse audiences.

This consensus statement of what students should "know" and "be able to do" was transformed by faculty, into explicit lists such as the one below.

Students should demonstrate ability to:

- Access and assess appropriate scientific literature.
- Develop hypotheses and propose appropriate experiments to test them.
- Use data bases and bioinformatics tools.
- Design and conduct experiments and to record/archive the data appropriately.
- Use appropriate data analysis and interpret the results of experiments.
- Present the overall goals and detailed results of experiments in a variety of formats to a variety of audiences.
- Work safely, both alone and in an effective team.
- Summarize and convey information orally, visually, and in writing.
- Recognize and understand the ethical issues involved in both the conduct of research and in the dimensions of research.

While this is not necessarily an exhaustive list, it is representative of many essential skills in which students need to become proficient. A number of the statements can be categorized as data analysis and communication related skills, while other statements are directed at scientific behaviors or research tools for working with data or information. Not surprisingly, the skills noted overlap with other foundational concepts in BMB, biology, and chemistry as well as those in cognate fields such as physics and mathematics [11, 12]. Although there is significant overlap between the various lists of skills discussed here each contains an area not clearly common to the other lists. The various regional meetings held in the last 24 months did not explicitly identify "Awareness of the major issues at the forefront of the discipline" from the ASBMB recommended curriculum but did emphasize "teamwork" as opposed to collaboration, almost certainly as a result of industry input at several of the meetings. Although the Vision and Change list is more succinct, its clear emphasis on "modeling and simulation" as a skill is important to note since it does not appear on the other skill lists.

When faculty were asked about the essential laboratory skills students need to learn, they generally responded with myriad lists of techniques and methods typically taught to undergraduates (i.e., pipetting, preparation of solutions, chromatographic methods, spectrophotometry, protein assays, electrophoresis, etc…). The challenge is in trying to align laboratory related skills with desired outcomes and abilities. The groups collaborated to distill the skills requirements into a list defining the expertise required to carry out meaningful project development and analysis. A student might, for example, exhibit proficiency of these demonstrable skills:

- Given raw sequence data, be able to use electronic databases to identify biological molecules.
- Given an experimental data set, be able to use appropriate quantitative models to assess error and glean biological meaning.
- Given current knowledge (or data), create a testable hypothesis and design and execute an appropriately controlled experiment.
- Given a hypothesis, be able to evaluate the strengths and limitations of various experimental approaches.
- Given a body of experimental data, be able to communicate the results in visual, written, and verbal formats.
- Given a body of experimental data, be able to find relevant information from prior scholarship.

These statements allow the skills to be assessed if the appropriate tools and rubrics are developed. Evidence of these abilities is consistent with the most advanced levels of Bloom's learning objectives [13].

As the community moves towards developing assessment tools it should be pointed out that with some of these areas, simple to use, reliable tools already exist, such as the "Experimental Design Ability Test," which has been validated and uses a simple scoring rubric [14]. Such tools can serve as a valuable model on which to base the development of future tools.

Table III represents an attempt to organize the various skills discussed into three broad general categories, which can be used as a basis for development of appropriate assessment tools that focus on the essential concepts encompassed by these three areas rather than more "content" dependent skills. The three areas are 1) Process of Science, 2) Communication and Comprehension of Science, and 3) Community of Practice Aspects of Science, each with distinctly different types of skills that could form the basis of appropriate assessment tools that do not depend upon specific disciplinary knowledge.

Methods used in biochemistry are considered foundational technical skills associated with laboratory instruction in the context of program development and assessment have been detailed previously [15]. These skills are also

TABLE III *A consensus list of skills to guide assessment*

Overall conceptual area	*Necessary abilities*	*Potential learning objective areas*
Process of Science		
	Can develop a hypothesis, design and conduct appropriate Experiments	When presented with an experimental observation can develop a testable and falsifiable hypothesis. Given a hypothesis can identify the appropriate experimental observations and controlable variables. Can accurately make up and use appropriate volumes of reagents and perform the required experiments.
	Is able to analyze and interprete data using appropriate quantitative modeling and simulation tools	Can use averages and standard deviations to relate the significance of experimentally obtained data. Can use appropriate equations to analyze experimental data and obtain parameters. Can use equations and models to predict outcomes of experiments.
Communication and Comprehension of Science		
	Can Access, Assess and Use Available Information	Can find and use the primary literature. Can use data bases and bioinformatic tools. Given appropriate background and information can identify consistencies and inconsistences.
	Is able to present scientific data in an appropriate context and in a variety of ways at different levels	Understands the big picture aspects of current challenges in the molecular life sciences. Can use visual and verbal tools to explain concepts and data. Can translate science into everyday examples
Community of Practice Aspects of Science		
	Appreciates the opportunities for interdisciplinary collaboration and the ethical dimensions of science	Understands the importance of, and keeps an accurate laboratory notebook. Given a case study can identify both scientific and societal ethical aspects. Can understand cross-disciplinary concepts such as modularity, energy etc.
	Can work safely alone and in an effective team	Knows how to access and interprete safety information. Is able to give and take directions to be an effective team member.

considered critical for undergraduates to learn and practice, although there is some variety in how these skills are taught and utilized. A number of published reports exist that describe approaches to teaching specific BMB laboratory skills. The traditional approach in which students are required to follow a defined procedure to generate a known outcome is often used. On the basis of studies demonstrating that the skills listed above are not effectively developed through the traditional "cookbook" teaching methods [16, 17], many BMB faculty have now begun imparting these skills through independent research experiences [18, 19], investigative laboratory exercises [12, 20], and exploratory learning communities often spanning several disciplines [21–24]. While not every technique can be mastered, providing opportunities to utilize these skills will eventually foster long-term acquisition of the so-called demonstrable skills.

Assessment of student learning is one of the goals of the RCN project, and the framework of skills outlined here provides an organization for both currently available assessment tools and the future development of assessment tools targeted to the three organizing principles outlined in Table III. Working with faculty we hope to collect best practices for both teaching and assessing student understanding and performance to disseminate to our collective community of BMB faculty. We also need to take note of the input of industry where significant population of students will ultimately become employed. Many faculty have not worked directly in industrial environments, and input from industry professionals is essential in understanding the key features of basic research and communication skills that are necessary, in addition to a sound understanding of biological and chemical principles for bachelor's level scientists entering the workforce or going on to graduate school. Reaching a national consensus on the desired student outcomes is challenging, but will provide firm directives for program development, teaching, and learning methods and styles, and assessing student learning and abilities.

Finally, we would like to thank the many people who have attended the various RCN-UBE workshops sponsored by this grant over the past several years and have contributed to the discussion. We would invite all interested faculty to give us feedback on our attempt to synthesize this information into this "white paper" and to send ASBMB appropriate assessment tools that they have used and are willing to share with the community.

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