Special Section: Foundational Concepts and Assessment Tools for Biochemistry and Molecular Biology Educators, Part 1: Essential Concepts and Skills

Essential Concepts and Underlying Theories from Physics, Chemistry, and Mathematics for "Biochemistry and Molecular Biology" Majors

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Abstract

Over the past two years, through an NSF RCN UBE grant, the ASBMB has held regional workshops for faculty members from around the country. The workshops have focused on developing lists of Core Principles or Foundational Concepts in Biochemistry and Molecular Biology, a list of foundational skills, and foundational concepts from Physics, Chemistry, and Mathematics that all Biochemistry or Molecular Biology majors must understand to complete their major coursework. The allied fields working group created a survey to validate foundational concepts from Physics, Chemistry, and Mathematics identified from participant feedback at various workshops. One-hundred twenty participants responded to the survey and 68% of the respondents answered yes to the question: "We have identified the following as the core concepts and underlying theories from Physics, Chemistry, and Mathematics that Biochemistry majors or Molecular Biology majors need to understand after they complete their major courses: 1) mechanical concepts from Physics, 2) energy and thermodynamic concepts from Physics, 3) critical concepts of structure from chemistry, 4) critical concepts of reactions from Chemistry, and 5) essential Mathematics. In your opinion, is the above list complete?" Respondents also delineated subcategories they felt should be included in these broad categories. From the results of the survey and this analysis the allied fields working group constructed a consensus list of allied fields concepts, which will help inform Biochemistry and Molecular Biology educators when considering the ASBMB recommended curriculum for Biochemistry or Molecular Biology majors and in the development of appropriate assessment tools to gauge student understanding of how these concepts relate to biochemistry and molecular biology.

Keywords: *assessment and the design of probes for student understanding and learning; assessment of educational activities; curriculum assessment*

Introduction

Biochemistry and Molecular Biology, as a unified discipline as recognized by the American Society for Biochemistry and Molecular Biology, has existed for some time rather than as two separate and distinct disciplines or subdisciplines−Biochemistry, centered in Chemistry, and Molecular Biology, centered in Biology. THE AMERICAN SOCIETY FOR BIOCHEMISTRY AND MOLECULAR BIOLOGY (ASBMB) developed a suggested curriculum focusing on foundational concepts and skills, which was published in 2002 [1]. In the decade since then, a number of reports, most recently the Vision and Change Report [2] and PCAST Report [3], have suggested that education in the life sciences should be focused on broad conceptual understanding of the "Big Ideas" of the discipline rather than detailed knowledge of discipline specific content, and on how these broad concepts relate to other disciplines, such as Chemistry and

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Physics, and on the necessary skills needed to pursue a career in science. The major rationale for this is that modern molecular life science is increasingly interdisciplinary, both from the conceptual perspective and from the experimental perspective, and that the advances of the future will increasingly be made at the interface between the disciplines [4]. Students, therefore, need to understand both foundational disciplinary concepts and how they relate to broader interdisciplinary concepts as well as broad themes from the allied field disciplines of Chemistry, Physics, Mathematics, and Computer Science. This places an increased emphasis on presenting the essential concepts and themes from the allied fields in the context of the molecular life sciences, either in traditional Biochemistry and Molecular Biology courses or in the currently emerging "blended" courses [5–7] that bring together the foundations of Chemistry, Physics, and Mathematics/Computer Science.

To move education of our students from the more traditional content based education to this new vision of education requires broad agreement on what the disciplinary foundational concepts are and on how to assess conceptual understanding rather than the more traditional specific fact based knowledge. To address these challenges ASBMB applied for, and was awarded, a grant from the National Science Foundation (The Undergraduate Biology Education track in the Research Coordination Network program (RCN-UBE) Award number 0957205 "RCN-UBE: Promoting Concept Driven Teaching Strategies in Biochemistry and Molecular Biology through Concept Assessments," Ellis Bell PI).

Members of the American Society for Biochemistry and Molecular Biology (ASBMB) are seeking to define the "core principles" or foundational concepts of Biochemistry and Molecular Biology. These foundational concepts are not only discipline specific, but also include skills specific to the discipline and foundational concepts in other disciplines. The foundational concepts in other disciplines are necessary to both increase the depth of conceptual understanding in the field of Biochemistry and Molecular Biology (BMB) and foster interdisciplinary thinking. The foundational concepts from Physics, Chemistry, and Mathematics are similar to what is considered as crosscutting concepts. The crosscutting concepts and their corresponding differences in relation to the nature of science (i.e., patterns and cause-and-effect), sizes and mathematical relationships (i.e., scale, proportion, and quantity), and concepts that unify all areas of science (i.e., systems and system models, energy and matter, structure and function, and stability and change) are detailed by Duschl [8], and are also considered in the new framework for K-12 Science Education, titled, "Practices, Crosscutting Concepts, and Core Ideas [9]." Finally, the American Association for the Advancement of Science [10] states: "Some important themes pervade science, mathematics, and technology and appear over and over again, whether we are looking at an ancient civilization, the human body, or a comet. They are ideas that transcend disciplinary boundaries and prove fruitful in explanation, in theory, in observation, and in design."

To ascertain the core principles and skills that are necessary to become experts, groups of BMB educators met in several focused workshops to discuss the expectations with the ultimate goal of clearly articulating the Core Concepts in Biochemistry and Molecular Biology, the necessary skills, and the required Foundational Concepts in allied fields. The results of these discussions highlight the critical importance of experimental and mathematical skills.

As part of this project, the Project Steering group assembled an initial consensus list of foundational concepts of the allied fields in Chemistry, Physics and Mathematics. This list was developed through a series of regional workshop meetings involving several hundred educators from a wide variety of institutions including major research universities, liberal arts colleges, and minority serving institutions, and well attended sessions at both the Annual Experimental Biology National Meeting and the ASBMB sponsored small education meeting, held in Richmond in 2011. The essential concepts from chemistry, mathematics, and physics were grouped into five general concept areas that emerged from the discussion. These were:

- Foundational mechanical concepts from physics.
- Foundational energy and thermodynamic concepts from physics *and chemistry*
- Foundational concepts of structure from chemistry.
- Foundational concepts of reactions from chemistry.
- Essential mathematics.

(Note: "and chemistry" was added after the survey as a result of suggestions made in response to the survey).

Table I is the Allied Field group's unpacking of the foundational concepts of the allied fields that can be used to organize appropriate related learning objectives for courses within a biochemistry and molecular biology major. Once the foundational concepts have been identified, the goal is to align curriculum-instruction-assessment in courses so biochemistry and molecular biology education can be coordinated around "making student thinking visible." Biochemistry and Molecular Biology (BMB) students should have a conceptual understanding of foundational concepts of the discipline, should be proficient in understanding foundational concepts from other disciplines, and should possess the skills needed to practice as professionals. If students understand core principles and theoretical constructs of their field, they can use them to make sense of new information to tackle novel problems.

After the meetings, to validate both our consensus of general concept areas and our unpacking of these areas, the "allied fields" working group (the authors of this article) decided on the following strategy:

a) Allow for further comment and, as appropriate, refine the list, and b) start to align learning goals with the consensus allied field concept areas. A survey was

TABLE I *Essential Concepts from the Allied Fields*

Foundational Mechanical Concepts from Physics
1: Laws of motion and molecular structure and dynamics
2: Force laws and molecular structure and interactions
3: Waves, light, optics, and imaging
4: Statistical mechanics, diffusion, and interactions
5: Quantum mechanics and biological systems
6: Conservation laws and global constraints
Foundational Energy and Thermodynamic Concepts from Physics and Chemistry
1: Energy and order in biological macromolecules
2: Macroscopic and microscopic views of energy in biology
3: Coulomb's Law at work in the molecular life sciences
4: The second law of thermodynamics and the molecular life sciences
5: Systems far from equilibrium
6: Thermal processes at the molecular level
Foundational Concepts of Structure from Chemistry
1: Covalent bonds and polarity
2: The hydrophobic effect
3: Hydrogen bonds and other non-covalent interactions
4: Bond rotations and vibrations
5: Dynamic aspects of molecular structure
Foundational Concepts of Reactions from Chemistry
1: Collision theory
2: Transition state theory
3: Rate laws and equilibria
4: The effects of temperature
5: Structure and reactivity
Essential Mathematics
1: Using equations to define biological and chemical processes
2: Linear functions in the molecular life sciences
3: Exponential functions in the molecular life sciences
4: Saturation (hyperbolic) functions in the molecular life sciences
5: Sigmoidal functions in the molecular life sciences
6: Assessing whether the right type of function has been used
7: Using the predictive power of equations

constructed, Table II, where the general areas (referred to in the survey as "Core Concepts and Underlying Theories") were listed and participants asked to comment and suggest unpacking into "subcore principles." Respondents were not provided with the working group's unpacking of the general areas to give maximum flexibility for respondents to suggest appropriate unpacking.

The survey was sent to all the faculties who had attended one or more of the regional workshops.

This article reports on an analysis of the results from the survey by the allied fields working group to validate the list of foundational concepts and underlying theories from physics, chemistry, and mathematics. Two other working groups identified essential concepts in biochemistry and molecular biology and the skills required to have a complete and thorough understanding of biochemistry and molecular biology.

One-hundred and twenty ASBMB members responded to the survey and 68% agreed the essential concepts and underlying theories from physics, chemistry, and mathematics list was complete. Thirty-six respondents suggested the list was not complete and provided suggestions for revisions of the list. For instance, there were several suggestions that energy and thermodynamics were redundant concepts. Twenty-five percent of respondents thought thermodynamic and kinetic concepts should be taught from a chemical context or physical chemistry not a physics context. Many of the responses added sub-foundational concepts to answer the question, such as "Thermodynamic and Kinetic concepts from Physics should include Fluctuation/Dissipation and Random Thermal Processes." Many of the respondents thought the list should be more specific and stated that the Foundational Concepts were too broad. This was illustrated in the following statement: "Although I answered yes (list is complete), the list is not very specific as to what critical concepts are and what essential is. Depending on what is in those categories, the list could be complete or incomplete. In addition, energy and thermodynamics are taught in chemistry courses required for biochemistry students, such as general chemistry and physical chemistry." Several respondents suggested computer science core concepts regarding complex systems and emergent properties should be included in the list. Overall, the results from the survey indicate the list of foundational concepts and underlying theories from physics, chemistry, and mathematics is complete.

It is important for the ASBMB community to recognize that every foundational concept that has been identified as a "big idea" includes many smaller component ideas useful in teaching, learning, and assessment. The "general areas" of what we are calling the foundational concepts must be unpacked into their component ideas. Foundational concepts are broad and general since they encompass many constituent subconcepts. These component ideas serve as tools for applying the foundational concepts to specific

TABLE II *Questions from the survey*

The following is a list of the broad areas we think constitute the Core Concepts and Underlying Theories from Physics, Chemistry and Mathematics that biochemistry majors or molecular biology majors need to understand after they complete their major courses.
a. Mechanical Concepts from Physics
b. Energy and Thermodynamic Concepts from Physics
c. Critical Concepts of Structure from Chemistry
d. Critical Concepts of Reactions from Chemistry
e. Essential Mathematics
In the box below answer the following question. Is this list COMPLETE?
If you do not think it is complete explain what is missing, or what should be deleted, or should the wording be changed.
Do you think there is a hierarchy in the Core Principles and if so, what is the hierarchy?
Because the Core Principles are broad, we would like to know what are Sub-Core Principles of each of these Core Principles.
a. In the box below list no more than six Sub-Core Principles of Mechanical Concepts from Physics. If you think it is appropriate, what is the hierarchy of your Sub-Core Principles?
b. In the box below list no more than six Sub-Core Principles of Energy and Thermodynamic Concepts from Physics. If you think it is appropriate, what is the hierarchy of your Sub-Core Principles?
c. In the box below list no more than six Sub-Core Principles of Critical Concepts of Structure from Chemistry. If you think it is appropriate, what is the hierarchy of your Sub-Core Principles?
d. In the box below list no more than six Sub-Core Principles of Critical Concepts of Reactions from Chemistry. If you think it is appropriate, what is the hierarchy of your Sub-Core Principles?
e. In the box below list no more than six Sub-Core Principles of Essential Mathematics. If you think it is appropriate, what is the hierarchy of your Sub-Core Principles?

areas of BMB at suitable levels of difficulty. The component ideas must match expected learning goals, learning objectives, and outcomes and assessments [10]. By defining all the foundational concepts and skills in biochemistry and molecular biology, ASBMB can discuss how to disseminate the information and assess students' knowledge and skills. The next question on the survey asked, "Is there a hierarchy to the foundational concepts and if so, what is the hierarchy?" About 30% of the survey participants stated there was no hierarchy, and over 50% of the respondents who replied there was a hierarchy, stated mathematics was the most important foundational concept. The response suggested essential mathematics was at the top followed by either foundational concepts of structure from chemistry, or foundational concepts of reactions from chemistry. For example, a common response was "Math comes first, physics, and chem(sic) either concurrent or subsequent" indicated the importance of mathematics. The following respondent's statement is similar to how the survey respondents answered the question about hierarchy: "It is hard to fit them into a single hierarchy. Mathematics seems fundamental to understanding both chemistry and physics concepts, but that depends on what level of math is implied. Structure and reactions from chemistry are clearly interrelated; I would say you need to know some structure before you can understand reactions, but then it would make more sense to interweave those concepts than to teach all of structure first and then all reactions." It is important to remember that about one third of the respondents thought there was no hierarchy and all foundational concepts were equally important.

The survey participants listed no more than six subfoundational concepts for each foundational concept from physics, chemistry, and mathematics, and they gave a hierarchy of their subfoundational concepts or stated there was no hierarchy. After reviewing the results from the surveys, the subfoundational concepts were found to be very similar to the subfoundational concepts from the workshops. The following paragraphs will give an overview of the results from the survey. Common suggestions for subfoundational concepts of mechanical concepts from physics were the following: Newtonian physics, wave behavior, and electromagnetic forms of energy. This is similar to what is listed in Table I under the heading Foundational Mechanical Concepts from Physics. One respondent suggested the following subfoundational concepts: "1: Newton's Laws; 2: Work-energy theorem; 3: Conservation of energy; 4: Hookian spring and SHM; 5: Force fields and potential functions; and 6: Molecular dynamics." Even though the wording is different, there is alignment between this list and the list above in Table I, the subfoundational mechanical concepts from physics.

Foundational energy and thermodynamic concepts from physics and chemistry were the next foundational concepts. A participant suggested the following list for subfoundational concepts from energy and thermodynamics: "First Law of Thermodynamics; Second Law of Thermodynamics; Free energy and spontaneity; Chemical equilibrium; Thermodynamics of solutions." This does a great job of unpacking the foundational concepts. Once a subfoundational concept list is generated, a curriculum can be developed, department or major learning goals can be defined, and assessments can be designed to accurately measure the learning goals. For instance, students at a 100 level will have a conceptual understanding of the first law of thermodynamics or, in other words, the law of conservation of energy where energy of an isolated system is constant. For a course in thermodynamics, a learning objective should include a demonstration of one's understanding of the first law of thermodynamics by completing a case study. When the case study is completed, it can be used as an assessment.

To the question "In the space provided, please list no more than six subcore principles of critical concepts of reactions from chemistry. If you think it is appropriate, please rank these subcore principles according to hierarchy" respondents' answers were similar to the subfoundational concepts of structure from chemistry in Table I. In fact, the participants' responses were more similar to the subfoundational concepts in Table I except for the responses to subfoundational concepts of reactions from chemistry.

The respondents' six subfoundational concepts of reactions from chemistry were very diverse. The following are examples of the way the respondents answered the question.

The first two examples state similar answers (semantics) but in two different ways.

- "Acid–base chemistry and thermodynamics."
- "Transition state and transition state complementarity; transition state stabilization; leaving group (and ability); pH dependence, and covalent catalysis."

The following answers were very specific answers and illustrate the diversity of answers:

- "General/specific acids and bases; dehydration synthesis, hydration, redox reactions; free energy; bond energy; equilibrium; law of mass action."
- "(1) Be able to "push arrows" to show the mechanism of a given biochemical reaction. Understand how organic chemistry actually makes biochem easier to understand. (2) Be able to do standard basic kinetics and equilibrium calculations for a given chemical reaction."
- "Acid–base chemistry; understanding pKa and pH; understanding water as a solvent and a reactant; reactions of carbonyl compounds; different mechanistic paths for reactivity (heterolytic, homolytic, and pericyclic); curved arrow notation for reaction mechanisms."

Since the answers in the realm of "structure and reactivity" from Table I were so diverse as to what should be included in the list of subfoundation concepts, it is important to re-evaluate whether this subfoundational concept requires further unpacking.

Finally, the last question asks for the subfoundational concepts of essential mathematics. Unit conversion was one subfoundational concept that was often cited. This was not specified in the list of subfoundational concepts of essential mathematics in Table I. Unit conversions is included in subfoundational concept "Assessing whether the right type of function has been used" even though it is not explicitly stated. Here are two lists of subfoundational concepts of essential mathematics.

"Use of logarithms (both ln and log); Exponents and exponential functions; Prefixes (nano, micro, milli, etc.); Converting between units; Use of simple derivatives (relationship to change over time); Graphing and analyzing hyperbolic, exponential, and linear functions."

"Solution calculations; dilution calculations; Beer's law calculations; Standard curve;Data fitting; thermodynamics; simulations."

It seemed that the participants' answers are very closely aligned with the subfoundational concepts of essential mathematics given in Table I even though the language was different. Since some responses included comments about "computer science" concepts it is important that future discussion and consideration be given to including an additional category, perhaps "essential computer science concepts."

Vision and Change [6] states that undergraduate curriculum must be grounded in the "traditional terminology while still reflecting the growing interdisciplinary nature of the numerous life sciences." Vision and Change explains that the "emerging interdisciplinary fields" includes biochemistry and we add molecular biology. Disciplines, such as biochemistry and molecular biology, deal with nature of science issues and increasingly depend upon interdisciplinary conceptual understanding particularly with physics and mathematics/computer sciences. Vision and change discusses the integrated Allied Fields, which "spread across the diversity" of biochemistry and molecular biology, and opens a vast array of practical applications. The following is a quote from Vision and Change [2].

"Core Competencies and Disciplinary Practice 4. Ability to tap into the interdisciplinary Nature of Science: Integration among subfields in biology, as well as integration between biology and other disciplines, has advanced our fundamental understanding of living systems and raised a number of new questions (pg. 15)."

As a result we suggest this consensus list as a focal point for the future development of appropriate assessment tools that focus on conceptual understanding rather than specific factual knowledge of the key concepts from the allied fields in the context of Biochemistry and Molecular Biology.

We believe that given the essential interdisciplinary aspects of the molecular life sciences (biochemistry and molecular biology) there is a strong dependence on foundational understanding of the conceptual links with the allied fields of chemistry, physics, and mathematics. We must make these connections explicit in our teaching and include the connections as an integral part of our assessment of student understanding. This is the only way to ensure that students can make such vital interdisciplinary connections. For example it is hard to understand the nature of dynamic aspects of macromolecular structure without a sound linkage to the appropriate concepts from physics and chemistry. A major purpose of the work undertaken and reported here is to develop a consensus of the key foundational concepts from the allied fields to provide a guide for the integration of these concepts explicitly into biochemistry and molecular biology courses and assessments. In the next phase of the project our focus will be on translating these concepts into learning objectives that can be incorporated into course design along with those identified in the other two white papers [11, 12] in the area of skills and disciplinary concepts.

The foundational concepts from the allied fields summarized in Table I fall into groups that can be aligned with either skills or concepts of biochemistry and molecular biology discussed in the accompanying papers [11, 12], which suggests natural linkages in both instruction and assessment, as well as ways to develop context relevant assessments. Essential mathematics concepts clearly fall into line with the three learning objectives outlined in the necessary skills paper [11] as well as into the homeostasis, and biological information areas of the disciplinary concepts paper [12] while the foundational concepts from chemistry align with three overarching conceptual areas that map to the "Macromolecular structure and function" section in the foundational concepts paper [12]: macromolecular structure and dynamics, rates and equilibria, and chemical mechanism of enzyme action. These might be expressed in learning objectives such as "students should be able to compare and contrast the contributions of covalent and noncovalent interactions to macromolecular structure and dynamics," "Students should be able to explain the chemical basis for the kinetics of enzymes and relate terms in the rate equation for a typical enzyme to both experimental observation and foundational concepts in chemistry" and "students should be able to suggest a chemical mechanism of action for an enzyme and design and rationalize appropriate experiments to test their hypothesis." Likewise the concept areas from physics can be put into three broad areas that could be described as related to conceptual areas identified in either the skills (experimental design) or biochemistry and molecular biology content (macromolecular structure and function, or Matter, and energy transformation), lending themselves to further "blended" learning objectives such as "students should be able to compare and contrast deterministic and stochastic approaches to biological processes such as signaling pathways" or "students should be able to apply basic concepts of physics to analyze the dynamic nature of molecular interactions." Finally, in the arena of "Essential Mathematics" learning objectives such as "students should be able select and apply appropriate equations for the analysis of kinetic or thermodynamic data and be able to relate the equations to experimentally observed parameters" would appropriately match some of the "process of science" skills discussed in the accompanying paper [11].

As has been suggested by Anderson [13], foundational concepts can be unpacked into subfoundational concepts, the subfoundational concepts can become course objectives, curriculum objectives, or program objectives. Such thinking results in a direct guide to inform teaching and, therefore, assessment. It is necessary to make sure that assessments are indeed measuring students' achievement of the specified objectives. The essential foundational concepts [12], skills [11] as well as the critical concepts from the allied fields described here can provide an organizational structure for the acquisition of new knowledge. Understanding the foundational concepts and engaging in the biochemical and molecular biology practices will prepare students for comprehensive understanding and deeper levels of investigation during their undergraduate career.

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