

## Teaching and Learning Biology at the Undergraduate Level

### Michigan State University

Effective teaching of biology requires that we have cognitive snapshots of typical students sitting in our classes, be it in the introductory general biology course or in an advanced (but still undergraduate) genetics course. Our goal as instructors is to foster changes in those snapshots as a student progresses from being able to supply narratives and models when asked, to being able to reason from and apply them in appropriate ways. What follows is what we think we know about students as they enter our classes and what our expectations are following instruction.

1) **Who's in our classes and what do they know?** The answer is somewhat dependent on whether we are talking about intro students or those with some instruction entering advanced classes. However, all students bring with them knowledge accumulated from experiences about biology (as a shorthand we call this **accumulated experience**). Some of this accumulated experience is from previous instruction, K-12 and whatever university science courses they have taken. However, often little instruction has been firmly incorporated into the body of experience that they reason from. Instead accumulated experiences are largely "informal": for example, what they know from watching *House*, *Mythbusters* and other TV programs, taking care of pets and plants, sex ed, playing *SimCity* and its clones, Scouts, camping, fishing, etc. As these examples indicate, students have some experiences that they can apply (correctly or not) to biology learning at the organismal level; some may have a bit they can use at the level of ecosystems. However, generally there is precious little accumulated experience they can use to explain phenomena at the atomic/molecular and cellular/subcellular levels (unless they happen to catch a really good episode of *House*). Our primary goal as instructors is to have students incorporate formal ideas of biology into their accumulated experience.

2) **What do we want them to know?** Ultimately, we want our students to be like us: to be able to use appropriate models, principles and ideas of biology to reason about the living world. A shorter way to say this would be that we expect them to use **principled reasoning**, that is reasoning based on models, ideas, principles, etc., when approaching a new problem. We would like them to have incorporated standard biology ideas at all scales (atomic/molecular, cellular/subcellular, organisms, and ecosystems) into their **accumulated experience** and apply it appropriately. This is the goal of graduate education in which dedicated students in an extended "apprenticeship" learn to use their accumulated experience to solve problems, but what are reasonable expectations at the undergraduate level? We have started to frame the answer to this question as wanting students to see that much of biology, at the four scales, can be mastered by reasoning from three basic principles shown below. As students move through the curriculum, we would like them to elaborate relevant explanations and models and expand the principles.

a. **keeping track of matter:** monitoring the inputs and outputs of matter between and among the four scales (for example, food and molecules). What goes in has to come out. Where does it come from and where does it go? How is it utilized in biological systems? This applies not only to matter in general (conservation of mass) but to individual atoms or elements in the matter (e.g., the carbon cycle). At the cellular level, tracing matter is the basis for making sense of metabolic pathways. For example, Calvin and Benson used reactants where particular atoms were labeled with radioactivity to study the steps of the pathway that bears their name. Moving up in scale, tracing matter in organisms provides a systematic approach to nutrition, digestion, circulation, and nitrogenous waste disposal. For example in the case of digestion, it is useful to trace the fate of each type of macromolecule (carbohydrates, lipids, proteins, etc) and its subunits. At the level of ecosystems, studying the cycling of carbon, nitrogen, phosphorus, and water through the biotic and abiotic components is one lens for making sense of the interactions among organisms, as well as understanding the effects of some forms of pollution.

b. **keeping track of energy and energy transformations:** “stuff” is happening to matter in biological systems. What makes it happen? Since energy is conserved, where does it come from and how is it transferred and transformed? How does this help us understand biological systems? Biologists expect the energy that goes into any process at any scale to balance the energy that comes out, with some loss of useful energy to entropy. The “energy budget” of an ecosystem, i.e. the primary production of its plants, is a key factor in determining the quantity and diversity of organisms. At the cellular and molecular levels, living things manipulate compounds containing reduced carbons, oxidizing them when they need useful chemical potential energy and making ATP.

c. **keeping track of information flow.** Biological systems interact at all levels. These interactions require feedback, which is accomplished by the flow of information, whether it be mitosis (subcellular), hormones (cell-cell), pheromones and birdsong (organism) or mimicry (ecosystem). Biologists also work hard to understand how living systems maintain equilibrium conditions and sustain their complexity and organization in the face of entropy. Cells are relatively stable environments where the concentrations of many substances are kept within particular ranges and substances are made only when needed. To accomplish this, information about the internal or external environment in the form of concentrations (of metabolites, ions, or signal molecules) affects enzyme activity or the activity of other proteins such as pumps. Information about the amino acid sequence of proteins is stored in the DNA of the cell. This information is carefully maintained and duplicated during the cell cycle, used as needed in protein production, and distributed to the next generation. Multicellular organisms coordinate specialized parts by passing information between them in the form of hormones. At the ecosystem level, the information for building a species exists in its genome and natural selection acts on the genome. Evolutionary reasoning involves studying how the organization of living systems, from genes to ecosystems, changes over time.

The response of some might be: don't they know to do this already? If they don't, isn't this simply an information transmission problem? However much work has been done that shows that students do not “automatically” keep track of atoms, molecules and energy when learning about, for example, cellular respiration. We argue that this requires explicit instruction and an appropriate framework. Keeping track of information is a new idea, but we believe that doing so will help students with some difficult ideas (meiosis, for example).

3) **How do we get students moving on the path toward principled reasoning?** At the introductory level, using the principles above as an overall, explicit framework, the students should be able to “tell the story” of phenomena at their fundamental level appropriately using standard models and representations. We include in this being able to give an accurate (though probably simplified) description of phenomena from the perspective of the basic principles and to use the principles and patterns to reason about new phenomena. Conversations with instructors of upper level courses indicate that this would be a terrific basis (which they don't usually see) for more sophisticated teaching/learning. This implies that students after completing introductory biology have properly incorporated simple standard models, ideas, and principles into their accumulated experience. Assuming that students have this knowledge permits instructors of upper level courses to teach basic principles (above) using more sophisticated models, representations and ideas.

To put students on the road to reasoning from basic principles, we must find ways to help them see biological principles as **useful**, that is, as a way to properly describe and explain the living world. They must see that proper, research-based ideas and models better explain what they observe than does their sometimes incorrect, often incomplete, accumulated experience. For us to have any hope of students reasoning from their biological knowledge, they have to see that the postulates, facts, hypothesis and processes are **connected** with one another across all scales.

4) **What are the problems? What makes teaching so hard?** Students come (and unfortunately, also leave) classes with strong, but incorrect explanations of what they see in living

systems. These explanations are based on their accumulated experience that seems logical to them. These **robust misconceptions** are hard to dislodge; only when the correct explanation is seen as more useful or makes more sense than does the misconception, do students incorporate it into their accumulated experience. Changing students' conception of the world is a daunting task for instructors. It requires finding out how students explain phenomena before coming into class, providing innovative and relevant instruction, developing ways for students to work with the material and writing questions that accurately reflect fundamental changes in their thinking.

Instruction in all disciplines is plagued by misconceptions. However there is another type of problematic thinking that we believe is more prevalent. Students don't have any explanations either before or after instruction. When students encounter new material that does not link to their accumulated experience, they may make erroneous connections or analogies to what they think they know or they may attempt to memorize facts, terms, or algorithms for working particular types of problems separate from their accumulated experiences. Rather than developing explanations, they have at hand a "fruit salad" of factoids that doesn't really allow them to explain anything. They can't bring ideas together, can't explain models, can't apply their knowledge and certainly are a very long way from reasoning based on a set of principles. Instead they can do what we call **procedural display** of their **fragmented** and **disconnected knowledge**, that is they can produce (or display) isolated facts when asked directly for them or they can reproduce the algorithms. However, many questions will not trigger appropriate parts of their accumulated experience and they will produce an incorrect answer.

**What are the implications for assessment?** If our goal for undergraduate learning is principled reasoning, then our assessment needs to ask students to do principled reasoning. This simple approach has several advantages. Framing biology around principled reasoning reduces the seeming complexity of trying to "cover" all of biology giving us some patterns to focus on. We have chosen to focus on a small number of organizing principles. We recognize that this creates a simplified, perhaps over-simplified, view of biology compared to biologists' understand. However we believe that the simplification is necessary, because principled reasoning is not the norm for students. Also while there are alternative principles, the three we have chosen allow us to organize most of the biology traditionally taught.

In addition this approach gives us a way of framing questions that hopefully will reveal both misconceptions AND procedural display. We predict that when looking at students' responses to such questions, we will see students who respond to a cluster of questions with consistent wrong answers indicative of a misconception or erroneous principle (matter and energy can be interconverted). We also expect to see students who respond to a cluster of questions with wrong, but seemingly random responses which we take as being indicative of understanding limited to procedural display.

It might appear that students' procedural display is simply a transmission problem. We haven't transmitted the principled reasoning that we want students to attain well enough for them to learn it. However it is not clear that procedural display is a type of understanding that will eventually yield to instructional pressure and become principled reasoning. We do not know if procedural display is on a possible path that eventually leads to principled reasoning or if it is a dead end. Therefore identifying and understanding students' procedural display more completely using assessment tools is one of our goals.