Connecting the "Big Ideas" in Biology with Those of Other Disciplines

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In the extensive email dialog that ensued after the first CAB meeting in Boulder last March, a particularly intriguing exchange was recorded in May between Mike Klymkowski, Kathleen Fisher, and Joel Michael regarding the chemistry of bond-breaking and formation and whether such concepts are appropriate or even necessary concepts to include in the teaching of introductory biology. In his email on this particular matter, Mike raised some provocative points that I think are extremely relevant to the dialog that will (should) occur at the upcoming CAB II meeting. As to the "issues of bond-breaking and formation, and energy," Mike questioned whether (these concepts) are "biology," noting that if "chemistry did its job, we would not have to worry about it." Next he posed the provocative idea that it "may well be possible to teach introductory 'biological reaction dynamics' without even mentioning deltaG or equilibrium constants."

This was a shocking idea to someone like me who teaches biochemistry and who anticipates (even expects) that incoming students will be versed (if not well-versed) in basic chemical concepts such as these, especially considering that entering students have already completed required courses in introductory chemistry and biology as well as organic chemistry. Of course, I agree with Mike's point that "if chemistry did its job" we wouldn't have to worry about it. I also agree with his insinuation that chemistry doesn't do its job and that we do have to worry about this, based on my own experiences. Thus, it is my practice to give students "pre-instruction" assessment quizzes during the first week of classes just when they are starting out in our year-long General Biochemistry lecture series. In these assessments, they are asked to solve "chemically-related" problems based on fundamental chemical concepts. What we have found is that a surprising number of students lack a functional understanding of equilibrium reactions and their associated constants, and many have little or no understanding of how such reactions and constants relate to "biological reactions dynamics" (to quote Mike). Even after having the problems posted for a week, only <u>half</u> of the 208 students entering my Fall 2005 biochemistry course, for example, were able to arrive at a suitable quantitative answer for the following problem:

> "Calculate the pK_{dn} for a 0.01 M weak acid solution in pure water if conductivity measurements show that it is 1.16% dissociated at equilibrium." (Ans. pK_{dn} = 5.87 +/- 0.05)

Likewise, only <u>third</u> of these students (again having the problem posted for a week) where able to find an adequate solution for the following problem:

> "Calculate the pH of a solution containing 1.0 M glycine and 0.5 M HCl with the pK_{dn} values for Gly being $pK_{dn}(\alpha\text{–}NH_3^+) = 9.8$ and $pK_{dn}(\alpha\text{–}COO^-) = 2.4$." (Ans. pH = 2.4 +/- 0.05)

I could easily describe many other related examples but the bottom line here is that we have noted similar difficulties with approximately the same percentages of students in other academic years (1). Thus, it seems that many students start out their junior or senior years in upper level biology courses with significant "chemical" conceptual difficulties. We have made some effort to identify the underlying causes, as discussed in a previous publication (2), but it is still clear to us that many biology students are challenged in terms of understanding the chemistry of <u>reversible</u> equilibrium reactions. I would argue that understanding fundamental "chemical" concepts, such as those needed to solve the problems above, is key to understanding important biological concepts in general. In fact, I would argue that the Gibbs free energy (deltaG) of <u>steady-state</u>, <u>irreversible</u> reactions is a "big idea" in biology because the related concepts (which took years for biochemists to fully appreciate) allow for thermodynamic explanations of how energy flows and drives most dynamic biological processes. The significance of zero free energy change for <u>reversible</u> equilibrium reactions and, hence, the underlying concept behind the equilibrium constant, are topics that typically are not covered well in introductory chemistry courses while the topic of steady state thermodynamics is usually approached only in biochemistry courses, if at all. However, "biological reaction dynamics" (again, to quote Mike) – help explain the ability of an organism or a cell to respond <u>reversibly</u> and usually immediately to chemical changes in its environment and also resist the inevitable pull of entropy that accompanies all natural processes. One can only understand these concepts in terms of the reversibility of non-equilibrium reactions. Thus, I would argue that such concepts embody "big ideas" in biology and need to be embedded in any biological concept inventory (BCI). I would also argue strongly <u>against</u> eliminating discussions of detaG and equilibrium constants in introductory biology courses and would recommend extending these concepts to include irreversible, steady reactions.

In order to construct and assess a meaningful BCI, we need to keep in mind that biology is really a complex amalgam of other scientific disciplines. While the highly successful Force Concept Inventory (FCI) developed by Hestenes and others (3) seems like a natural starting point and template for formulating a BCI, we must keep in mind that the FCI is much more narrowly defined in terms of concepts strictly derived from Newtonian mechanics, electricity, and magnetism. Biology's conceptual base is much broader by comparison. One cannot truly understand evolution without some knowledge of the geological history of the earth. One cannot understand evolution without knowledge of genetics. One cannot understand the mechanisms of genetics without knowledge of the "information carriers" of biology – DNA, RNA, and proteins. And, one cannot understand the chemical dynamics of biological processes without understanding the chemistry of reversible reactions, one form of chemical bond breaking and formation.

Thus, in facing the task of constructing a BCI, we face the challenge of adequately articulating the blend between concepts that are considered to be strictly in the domain of "biology" and those that draw from other fields of science. As a biochemist, I am highly interested in the development of a biochemistry concept inventory, but one that is firmly anchored in a broader Biology Concept Inventory. Ideally, the latter will logically underpin all of the major areas of biological specialization – biochemistry, genetics, cell biology, physiology, etc. In this way, the development of a BCI provides those of us who teach biology courses with a wonderful opportunity to add unprecedented coherence to the unwieldy and extremely vast body of knowledge we call biology. As Bill Bryson so neatly illustrates many times over in his "A Short History of Nearly Everything" (4), there is wonderful coherence in the natural world where trilobites, perhaps the most ancient of known forms of life, ultimately gave rise to australopithecines, among the earliest known hominid fossils, eventually leading to the appearance of modern man, whose entire genome has now been the decoded along with many other forms of life. With this kind of coherence, the BCI should connect living things and living processes in ways the help our students understand how the world was, how it is now as we know it, and how it likely will become given what we know now.

(1) Scott E. Thompson‡, Nathan J. Barrows S. Robin Saxon, and Duane W. Sears (2007) "Identifying Student Misconceptions in the Development of a Biochemistry Concept Inventory" (in preparation)
(2) D. W. Sears, S. E. Thompson and R. S. Saxon (2007) **"**Reversible Ligand Binding Reactions: Why Do Biochemistry Students Have Trouble Connecting the Dots?" *Bio. Mol. Biol. Ed. 35:*105-118.
(3) D. Hestenes, M. Wells, & G. Swackhamer (1992). Force Concept Inventory. The Physics Teacher" *30:*141–158.
(4) Bill Bryson (2003) "A Short History of Nearly Everything." Broadway Books, NY.