Integrative Biology as a Framework for Education and Training

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I introduce the concept of "integrative biology" and education by paraphrasing key statements in the preamble to the description of the IUBS "Towards an Integrative Biology" program (Anon., 1999). That is to say, "Integrative Biology" at this point in its conceptual development means different things to different people. To some, it emphasizes multidisciplinary (cross-disciplinary, transdisciplinary; including the incorporation of physics, chemistry, engineering, sociology, economics, etc., as appropriate) research, especially through the bringing together of scientists with different, but specific, areas of expertise to address particular questions. To others, it means using a diversity of techniques and approaches in one's own research programme; and to yet others, the emphasis is on hierarchical approaches to questions and techniques. There are almost as many conceptions of "integrative biology" as there are people interested in the idea; this results in those people considering themselves to be "integrative biologists" without any clarification of or agreement upon the central themes of the concept.

What is "integrative biology?"

Traditionally, biologists are trained, and departments and institutes organized, in a manner characterized by specific approaches, techniques, working at a specific level of organization in the biological hierarchy, and/or organisms, investigating on model organisms or on one or a very few species. Integrative biology is both an approach to and an attitude about the practice of science. It seeks both diversity and incorporation. It deals with integration across all levels of biological organization, from molecules to the biosphere, and diversity across taxa, from viruses to plants and animals. It provides both a philosophy and a mechanism for facilitating science at the interfaces of "horizontally" arrayed disciplines, in both research and training. Work at interfaces involves discussion of significant problems among scientists with diverse expertise and perspectives. It finds appropriate techniques, often from unanticipated sources, and it makes appropriate, often novel, choices of taxa for observation and experimentation (so that it is not taxon-bound). It particularly stresses an approach to problems and questions from diverse perspectives, so that the explication of the research protocol has the potential to be both innovative and integrative, as appropriate to the question being addressed. Many of the questions now being addressed by biologists require both reductionistic and incorporative elements, but in a framework that allows resolution of the sub-elements of the question to contribute to an answer to a larger problem. This lays the framework for new models of investigation and of education.

In the context of a synthetic approach to problems, some investigators have referred to "integrative" and "integrated" biology, often indistinguishably. In my opinion, "integrative" and "integrated" are very different terms with reference to the concept. "Integrative" biology refers to the active development of integration through research and teaching across the hierarchy of biology and of science in general. "Integrative" biology is an on-going process, flexible and adaptive to the particular complex research issues being addressed; it emphasizes the training of students to be prepared to have that flexibility and adaptability, intellectually, philosophically, and technically. "Integrated" biology would be designed, or pre-designated -- it would have an output or product, rather than being open-ended and adaptive.

Many biologists are coming to the realization that our ability to deal with questions of biological complexity would benefit from a more integrative approach that spans the hierarchy of biological origin, and that includes techniques and theory from several subdisciplines, not just the biological. In my home department (which is called Integrative Biology) at the University of California at Berkeley, we are attempting to design a model for research and education in integrative biology; similarly, the IUBS is pioneering the presentation of integrative principles and practices in a diversity of ways.

I present as an exemplar a research- and education-based example of integrative biology as practiced in my department at Berkeley: the research and teaching of my colleague Bob Full and his associates, who study locomotion. They examine many animals--cockroaches, centipedes, crabs, salamanders, and other animals (e.g., Kram *et al.*, 1997; Martinez *et al.*, 1998; Queathem and Full, 1995). They have found that many animals (most animals that have limbs) use an alternating tripod gait, and they have analyzed its mechanical principles (Full and Koditschek, 1999). They have also examined the ways that gaits change, direction changes, and the differences in intermittent and sustained locomotion (e. g., Jindrich and Full, 1999; Kubow and Full, 1999). They study the cell, tissue, whole limb, and organismal bases of locomotion, and develop models that are testable in terms of principles. Understanding how animals locomote is allowing the development of muscle equivalents and of "walking" robots. They work on uneven substrates, including the bottoms of lakes and oceans. The tripod gait that characterizes most animal locomotion, and the "revelation" that animals don't move in straight lines at constant speeds, but must adjust in order to compensate for both external and internal factors, are principles that are revolutionizing robotics. Further, the adjustment can be simply a physical property of the appendages of a crab or a robot -- neural feedback is not required. Little needs to be programmed into these robots. Big and small robots are being developed that can explore oceans, go into terrestrial areas where humans can't or shouldn't, and miniaturized robots are being developed that can potentially be employed in blood vessels -- but making them able to move is the key. The key point is that functional morphology and biomechanics are informing engineering, and engineering and physics are informing morphology. The instrumentation that functional morphologists now have available is expanding the scope of the science--much better cameras, computer-aided analysis, treadmills, running tracks, flumes, wind tunnels, and others all make innovative new research possible. Many functional morphologists are becoming highly integrative, as they look at the feedback from the skeleton to the nervous system, and muscle fiber dynamics, at one level of understanding locomotion, and the mechanical properties provided by the environment at another; this was illustrated in a recent article in *Science* written by six of my colleagues who study animal locomotion from different but collaborative and complementary perspectives (Dickinson *et al.*, 2000).

New areas of biology are developing as a consequence of the kinds of questions and problems that require attention. The many manifestations of biocomplexity, from fundamental science to socioeconomic concerns, require approaches that transcend standard disciplinary lines in terms of research, funding, training, and dissemination. The problems now being addressed by many biologists require a diversity and range of expertise. It can be provided by bringing together experts in several areas, but may be better provided by biologists who are adaptable, flexible, and trained to address new questions that span levels of biological organization and extend to "non-biological" realms.

If, as I assert, integrative biology is more than the aggregation of workers with different expertise to consider complex problems, and new ways of approaching those problems are important, serious effort is needed to change the way that biologists, scientists in general, and even non-scientists, are educated and trained, as clearly delineated in the TAIB preamble (Anon., 1999). As stated there, the "separateness" of disciplines and sub-disciplines currently is structured by the identification of separate courses of instruction at all levels of the educational enterprise, and is reinforced at the university level by the discrete course offerings of departments of instruction and research. It is increasingly rare that a "department of biology" offers a full range of courses, from molecular biology to ecosystem biology, neontology and paleontology, and including members of all three domains of life, as well as the impact of non-biological domains of study. In fact, departments of biology are few, and their successors often focus rather narrowly, but with depth, on a small sub-set of biology. Even when taking courses in different sub-disciplines is encouraged, the course structure does not encourage an integration and synthesis of the information found in several such courses. This has several consequences: young biologists are well trained only in one sub-discipline; students who will become teachers in primary and secondary schools are not acquainted with the breadth of biology, let alone how to apply breadth to major questions; students who will enter other fields of endeavor, and become the educated public, and potentially policy makers, have only examples of parts of biology before them. Some institutions are attempting to develop cross-disciplinary programs, but they usually emphasize breadth of course work; the difficulty in effecting thinking synthetically is that most of the courses available to such programs are the traditionally structured ones.

How, then, can "integrative biologists" be educated?

We are trying a new model in my department at Berkeley; it is only one possibility, and is imperfect at this time, but we are trying. We consider ourselves to represent several dimensions of the hierarchy of organization of biology, and we try to integrate those dimensions in various ways. We characterize the "old" model of education as the "tunnel" approach; a student learns a limited scope, but learns it well. The current model of teaching at many places is what we call the "funnel" approach; students are exposed to a greater range of subdisciplines, but with emphasis on a specific kind of problem, especially in graduate training (see Wake, 1998). We now, however, are trying for a mode of education that emphasizes the cross-disciplinarity of both the entry-input and the output in terms of the student's facility with a broader scope of information and technique, in an integrative, problem-oriented framework.

How can this be achieved?

We have all the constraints of the status quo that most institutions do. Curriculum is difficult to change. Clearly, the current course structure cannot be abandoned; it serves many purposes well. However, the content of such courses can be expanded to draw on a greater breadth of information, and new courses can be implemented, probably using information technology, especially Internet communication and computer simulations, that emphasize integration and synthesis, and these can be coupled with field work. It cannot be stressed strongly enough that integrative biology is not just assimilating and synthesizing ever more information, but, rather, a way of approaching questions and being equipped with the resources to think broadly about their solutions. Several approaches to developing the curricular and training structure that would implement integrative biology by adding a greater range of resources are possible, and immediately:

1) the meeting of scientists with diverse expertise, but an interest in complex questions, to discuss ways of integrating their approaches (this is occurring with increasing frequency with the goal of good science, but rarely with the

goal of good education in addition, though this symposium is a notable exception);

2) the production of teaching materials as well as research publications by such aggregations of scientists;
3) greater breadth of examples in current courses, and especially a new emphasis in "traditional" courses of the relationship of course-specific material to other parts of biology and the current state of the world (this doesn't mean a separate, token lecture, but a common thread of interrelationship throughout the course);
4) the development of technical facilities (image analysis labs, gene sequencing labs, etc.) that are shared by people working on different kinds of biological questions, so that exchange of information, ideas, and questions is facilitated and common principles can be elucidated; and
5) at the level of graduate study, a real emphasis on transdisciplinary training in both theory and technique.

The process can be initiated by the development of new, non-traditional courses. My colleague Robert Full, whose research I discussed earlier, is not only a gifted researcher, but a gifted teacher. He was given an endowed professorship at Berkeley; there is one stipulation involved in the chair--the holder must design a new university course for non-biologists that meets the general education requirements in biological science. Full did this -- he designed a course on animal locomotion that integrates cellular, organismal, and robotic science. He gives a series of lectures (dynamic presentations using PowerPoint), and has laboratory/demonstration sections that work with models and computer simulations. He included one especially interesting aspect. Full wanted a logically consistent, adaptable course framework and design. Therefore, he structured his teaching plan so that his model would be applicable at different educational levels. He first tested the model with the school class of his twelve-year-old daughter -- they loved it, and learned a great deal from it. He then added some slightly more sophisticated examples and simulations for his University students, but within the same pedagogic framework. The students loved it, and learned a great deal from it as did the younger students. This is an ingenious example of integrative biology in evolution that demonstrates that such an education is indeed possible, and useful.

Developing such courses as first steps would allow the "next generation" to implement education and training with new ideas and approaches to integration, synthesis, depth and breadth. It should be our charge and our mission to facilitate those developments in every way possible--and immediately. At the same time, it is essential that scientists interested in an integrative approach to research and education should be in extensive communication, so that a common philosophy of integrative biology guides our efforts, though their expression should be flexible and as varied as our backgrounds and the questions that we are investigating permit.

References

Anon. 1999. Towards an Integrative Biology (TAIB) Program. *Biology International* 39: 1-9.

Dickinson, M. H., C. T. Farley, R. J. Full, M. A. R. Koehl, R. Kram, and S. Lehman. 2000. How animals move: an integrative view. *Science* 288: 100-106.

Full, R.J. and Koditschek, D.E. 1999. Templates and anchors: Neuromechanical hypotheses of legged locomotion on land. *J. Exp. Bio*. 202: 3325-3332.

Jindrich, D.L. and Full, R.J. 1999. Many-legged maneuverability: dynamics of turning in hexapods. *J. Exp. Bio.* 202: 1603-1623.

Kram, R., Wong, B. and Full, R.J. 1997. Three dimensional kinematics and limb kinetic energy of running cockroaches. *J. Exp. Bio*. 200: 1919-1929.

Kubow, T. M. and R.J. Full. 1999. The role of the mechanical system in control: A hypothesis of self-stabilization in hexapedal runners. *Phil. Trans. Roy. Soc*. London B. 354: 849-861.

Martinez, M. M., Full, R. J., and Koehl, M. A. R. 1998. Underwater punting by an intertidal crab: A novel gait revealed by the kinematics of pedestrian locomotion in air versus water. *J. Exp. Bio.* 201: 2609-2623.

Queathem, L. and Full, R.J. 1995. Variation in jump force production within an instar of the grasshopper *Schistocerca americana*. *J. Zool*. London 235: 605-620.

Wake, M.H. 1998. Integrative biology in biodiversity: an approach to questions, answers, and training. Pp. 35-40 In *Frontiers in Biology: The Challenges of Biodiversity, Biotechnology and Sustainable Agriculture*. C.-H. Chou and K.-T. Shao, eds. Academia Sinica, Taipei, Taiwan.