Democratizing Bioinformatics Research in a High School Biology Classroom

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> I remarked incidentally that the philosophy in question is, to paraphrase the saying of Lincoln about democracy, one of education of, by, and for experience. No one of these words, *of, by,* or *for,* names anything which is self-evident. Each of them is a challenge to discover and put into operation a principle of order and organization which follows from understanding what educative experience signifies. (Dewey, 1938, p. 29, original emphasis).

John Dewey's idea for a philosophy of experience has long challenged us to consider *how* to democratize education and scientific research practices so that students can have a variety of everyday opportunities to participate in discoveries and create new knowledge instead of passively receiving it. According to Dewey, such democratic learning requires four dimensions, which are aligned to the intrinsic interests of the learner: (1) communication (e.g., the opportunity to discuss); (2) inquiry (e.g., the opportunity to ask questions); (3) construction (e.g., the opportunity to create things); and (4) artistic expression (e.g., the opportunity to express) (Dewey, 1990, p. 47).

In pursuing Dewey's challenge in more recent years, many educators have considered how information technology can contribute to democratization. For example, Bruce and Levin's (1997) taxonomy classifies a variety of modern technology uses that align with Dewey's four-interest framework. In this taxonomy, Bruce and Levin's stated purposes were to explore the ways in which applications currently supported integrated, inquiry-based learning and teaching and to highlight potential uses of technology, as well. In addition, Hill (1999) provides a general overview of open-ended information systems, such as the World Wide Web, which allow users access to an ever-expanding, vast amount of data that could be used to solve a variety of problems. According to Hill, open-ended information systems are also characterized by shared authorship. Thus, users are not only consumers of information, but also creators of the system. Although open-ended information systems may be moderated for quality control purposes, users have opportunities to add content, data, or tools as they participate in the open-ended information systems.

In this paper, we attempt to move beyond descriptions of how such technologies *might* be useful to enact Dewey's principles to providing a concrete example of how one high school biology class actually did so using Biology Workbench.[2] As expected, the story illustrates how information technology can help realize democracy in education on a level that would be very difficult to achieve without it. However, the case also illustrates how educators need to work with inquiry-based approaches to help students realize the potential of these open systems. Environments such as the Inquiry Page[3] help to contextualize the use of tools such as Biology Workbench.

Biology Workbench

Biology, frequently referred to as an "information-driven" science, is concerned with constructing knowledge from vast amounts of complex information derived from experiments and field observations. The application of information technology is leading molecular biology to evolve into an entirely new discipline, *bioinformatics* (e.g., Gibas and Jambeck, 2001). Just as astronomy was transformed through the invention of the optical telescope, and later the radio telescope, biology is transforming into a new science, one which links studies of biochemistry, genetics, cellular processes, anatomy, physiology, and evolution through the structure and properties of macromolecules. A major tool in this transformation is Biology Workbench (Subramaniam, 1998). Biology Workbench organizes a diverse set of sequence and structure analysis tools with access to multiple and enormous biological databases into a single web-based graphical interface.[4]

Biology Workbench has been publicly available since June 1996, and it has steadily grown in the number of users and the amount of use. Presently there are more than 63,000 registered users worldwide. Biology Workbench also allows users to store data from their accounts. Such users with account data are referred to as "active" users. Any data of active users that has not been accessed in a given time period (e.g., up to 10 months) is automatically deleted. For instance, from January to October 2002, Biology Workbench had over 23,000 active users.[5] On an average, Biology Workbench has over 1000 users per week.

Biology Workbench is developed for use by scientists and for scientists everyday (e.g., Chicurel, 2002). By providing both rich research quality data and powerful computation, this tool presents an important opportunity to engage researchers at all levels in meaningful investigations into biological questions (Jakobsson, 2000). As an example, a researcher can search through the evolving collection of protein databases for all entries related to myoglobin, a protein that carries oxygen in the muscle tissue of all vertebrates. The researcher can then use a molecular visualization program within the Biology Workbench tool suite to view the myoglobin molecular structure for a given species. Via this process, the researcher can compare a particular molecular structure with comparable structures from other species.

While initially designed for the molecular biology research community, Biology Workbench has the potential to become a powerful tool for biology education. A report from the National Science Foundation (NSF) workshop on information technology recommends that educational experiences of students should include curriculum integration of learning tools that are "open-ended, inquiry-based, group/teamwork-oriented, and relevant to professional career requirements" (NSF, 1998, p. 33). Many experts and recent national reports concur that that inquiry-based projects successfully facilitate learning. One considers "peer Inquiry Groups" as a valuable professional resource for teachers (National Commission on Mathematics and Science Teaching, 2000, p. 26), which can be envisioned as communities of learning. Another report on technology and inquiry has suggested that inquiry-based instruction "allows students to engage in practices of scientists and to construct their own scientific knowledge through investigation rather than memorization" (Linn, Slotta, and

Baumgartner, 2000, p. 2). Yet another report has called for an emphasis on inquiry in teaching and learning in classrooms across K-12 (National Research Council, 2000).

One way to accomplish a more relevant, democratic, experienced-based curriculum is to provide students with access to the same tools that scientists' use, while at the same time addressing the needs, interests, and skills of students. Since tools such as Biology Workbench are changing how biologists do their work, providing students with access to that tool enables them to experience how biologists conduct their research, form inquiry questions, connect with the work of other biologists, and build knowledge in the field (e.g., Jones, Jordan, and Stillings, 2001). For example, virtually every protein and protein fragment, every gene and gene fragment, found in the databases has close relatives in many different organisms, often in several different kingdoms. In understanding the basis for a genetic disease such as the sickle cell anemia, the students can use Biology Workbench to explore the relationship between the genetic mutation in hemoglobin, the molecular structure of hemoglobin, and the pathology of the disease itself.

In such contexts, the Biology Workbench especially holds potential for using information technology to provide an *open world* of learning and exploration. Previous approaches to using computers in education have focused on the creation of closed-worlds in which students could navigate and explore. Many of these computational environments are excellent and useful, but they are limited. Students are not encouraged to investigate the unknown. The open environment of Biology Workbench is fundamentally different. By providing access to essentially all that is known about biomolecular sequences and structures, it makes it possible for students to learn more than what their mentors and teachers know, and even to generate new scientific knowledge.

In addition to providing a window to the entire world of molecular biology, Biology Workbench is open in a second sense. This is that it is continually growing, adding new features that extend its capabilities and domain of applicability. Biology Workbench will continue to grow as the whole field of molecular biology grows, because it is more than a computer program. Researchers are not only users, but also creators of the system, as they add their research results to the available corpus of articles or other modifications of the databases.

Biology Workbench is not an alternative tool for teaching biological concepts, although students who work with it can expand their understanding of biology significantly. Rather, it is an exemplar of a venue for learning, one in which students explore genetics, protein structure and function, physics, chemistry, and other domains of inquiry, invoking processes of pattern-matching, probabilistic reasoning, and both inductive and deductive analysis. The significance of Biology Workbench relates to three major ways in which it is an open world system: open data and problems, open computational environment, and open community. Aspects such as these provide new affordances for public science and opportunities for democratizing education. In this paper, we explore those characteristics and the way they operated in a high school biology classroom.

A High School Biology Classroom

During the two-week period from January 29 to February 9, 2001, we visited Paul Lock's advanced placement biology classroom five times. The class had 20 students (8 men, 12 women). We had two reasons for these visits. One was to understand how Mr. Lock was incorporating bioinformatics into his high school biology curriculum, and another was related in part to a doctoral dissertation focusing on how teachers mediate instructional change in their own classrooms and in broader arenas, as well (Williamson, 2002).[6]

We gathered a variety of data during our visits, such as through field notes, videotaping of classroom interactions, and interviews and surveys of Mr. Lock and his students. Mr. Lock has been teaching biology from 9th to 12th grades at this high school for over 10 years. The story follows:

An Inquiry unit: How are different organisms related?

> 'Now remember,' [Mr. Lock] announced to his students, 'We are using a professional-type tool that people use to do their research—not just some designer game or simulation that is making money for a particular Web designer. So, you might be first person to look at how these particular things are actually related. There is a limited number of people and almost an infinite amount of information out there, so maybe your idea is something new. Maybe no one has actually looked at this thing or looked at it in this way' " (Williamson, 2002, p. 204).

On this day in the school's computer lab, Mr. Lock launched an activity he had designed to help his students understand evolutionary history. The students' task was to use Biology Workbench to explore how a group of plants or animals were related to one another. After his introduction, he directed his students to form groups of two to four, and he demonstrated how to create an account and start a session in Biology Workbench. Mr. Lock also gave students an overview on how to use the protein toolset and search through a database within Biology Workbench for a protein. Next, he showed his students how to import and align sequences. Finally, Mr. Lock demonstrated how to generate phylogenic trees to show relationships between species.

After the short introduction and demonstration, Mr. Lock instructed the students to form questions that would guide their inquiry. He modeled the process by posing two general questions: (1) How are different organisms related? and (2) How can we show their evolutionary history in a way that is easy to understand?

Students were left to decide what types of organisms they would investigate and how they would represent their findings to the class using rooted and/or un-rooted phylogenic trees. For those who needed further guidance, Mr. Lock distributed a sheet of suggestions, such as canines, dolphins, felines, and ferns, which would serve as suitable topics for study.

Two young women in the class chose to study marine mammals for their investigation and began to conduct queries in Biology workbench. As they progressed, they were surprised to find that dolphins and killer whales were closely related in spite of their different size and appearance (see Figure 1). In pursuing their investigation, the students' discourse resembled how practicing biologists might make meaning during their own investigations:

Student A (while using Biology Workbench): Okay, import those.
Student B: There are too many. Let's narrow them down.
A: Okay. I like seals, otters, whales, and dolphins. That's good. Great, let's choose a tree.

(Students pause as the computer renders the diagram. Students study it quietly and independently for a few moments after it appears.)

B (as she looks at the diagram): Whoa! What's that killer whale doing over there with the dolphins.
Ae: Where?
B: Right there!
A: We must have done something wrong. Do it again. Choose myoglobin this time.

After several trials, they were convinced that, in spite of the differences in names and appearance, that the killer whales were more closely related to dolphins than to the other whales. Later that same day, one of us [EGJ], a computational biologist, reviewed the tape of the students working. "They are *toothed* mammals! That's why they are closer together," he explained to rest of us. He drafted a short explanation for the students and sent it to one of us (UT), who forwarded it to Mr. Lock, who in turn shared the email with the two students and rest of the class the next day.

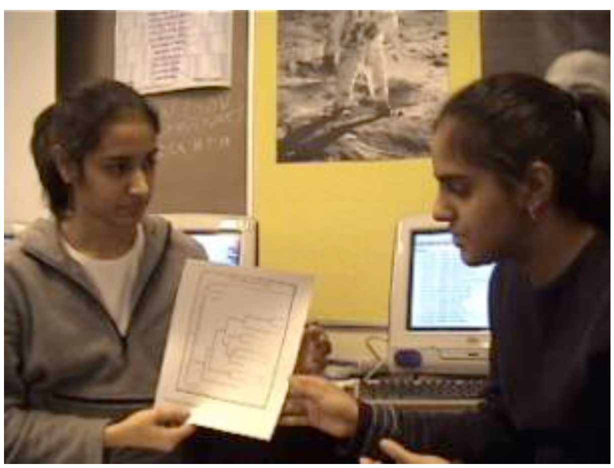

Figure 1: Interpreting and analyzing relatedness between dolphins and killer whales

In similar ways as this marine mammals group, other students in the class investigated the animals or plants they chose to study. After two days in the computer lab, students returned to their class to prepare posters representing their findings (see Figure 2). These posters served as visual aids during formal presentations to their teacher and to fellow classmates a few days later.

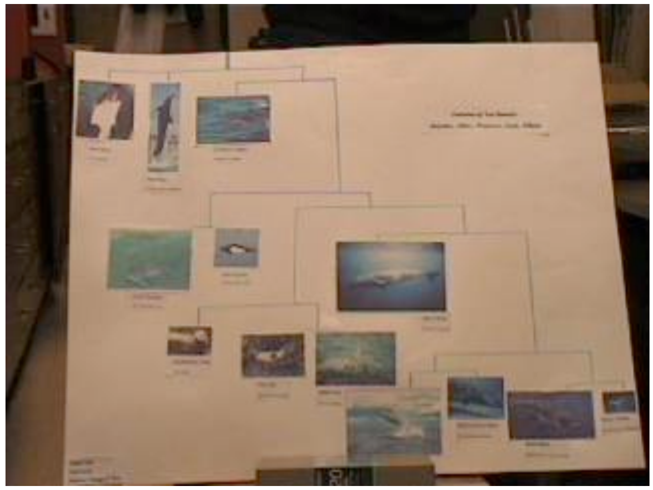

Figure 2: Student findings

As students reflected on the learning activity using Biology Workbench, their responses were positive. Through this activity they found themselves connected to a larger, open community by using the data and tools of practicing scientists. At least in the case of the marine mammal group, students were even able to communicate with a university scientist about their investigation. Such access gave students a sense of self-worth and responsibility. It helped them to assume the roles of a computational biologist and to experience the work, cognitive patterns, and discourse of a professional. The students were also attracted to the many paths they could take to learn and to the opportunity to direct their own learning. One student commented:

> We got to work on our own and choose our protein, animals, and trees, and I like that. We usually learn through the text, worksheets, and lectures. This was different in the sense that we did a visual and oral project that wasn't directly related to the text.

Support for open world systems: The Inquiry Page

We believe the lesson described in this paper illustrates the potential for Biology Workbench and similar open world systems to support the democratizing of science education. Yet, since the tool does not exist for the purpose of education per se, Biology Workbench is likely to pose challenges for most high school teachers. First, it does not fit conveniently within a curriculum. Second, non-experts cannot easily comprehend it. Third, the underlying data and the analysis/visualization tools change rapidly. While, on one hand, these are the very features make Biology Workbench an alluring learning tool for inquiry, these qualities may also deter teachers from actually using it. Therefore, the current challenge to the Biology Workbench team is to learn how to increase the accessibility to scientists' tools without diminishing their inherent openness. In addition, getting teachers interested and familiar with inquiry is challenging (Thakkar, Bruce, Hogan, and Williamson, 2003).

To address such challenges, our efforts have focused on developing Biology Student Workbench, a growing collection of enhancements to the Biology Workbench, including tutorials and inquiry based materials, all of which help students and teachers to conduct open-ended investigations in molecular biology.[7] As a portion of the development process, Mr. Lock serves with two other area high school biology teachers to advise the workbench team and to design and pilot activities in their classes. In addition, we have also partnered with the Inquiry Page.

Like the Biology Workbench, the Inquiry Page is an open world system that connects students, teachers, and scientists to support inquiry-based learning and teaching (Bruce, 2001).[8] The Inquiry Page performs two key roles. First, it helps to build a community of inquiry by involving all those interested in democratizing education. Second, it helps to foster the creation and adaptation of inquiry units. The Inquiry Page allows teachers and students to create their units using a web-based inquiry unit generator. In addition, if a teacher or student wants to adapt an existing unit, he or she can easily do this by using the Inquiry Page's "spin-off" feature.

The Inquiry framework, on which the unit generator is based, suggests that there are at least five phases associated with high-quality, inquiry cycle (see Figure 3 and Table1).

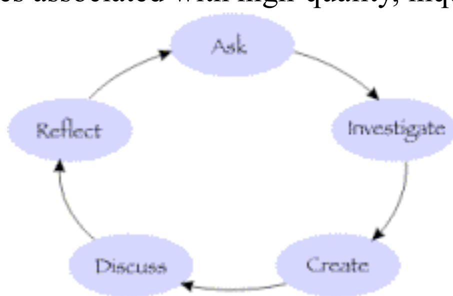

Figure 3: The Inquiry Cycle

Table 1: Components of the Inquiry Cycle

Ask	This stage, and the entire inquiry cycle, begins with the desire to discover. Meaningful questions are inspired by genuine curiosity about real-world experiences. A question or a problem comes into focus at this stage, and the learner begins to define or describe what it is. Of course, questions are redefined throughout the learning process. We never fully leave one stage and go neatly to the next. Questions naturally lead to the next stage in the process: investigation.
Investigate	As the information gathered in the investigation stage begins to coalesce, the learner begins to make connections. The ability at this stage to synthesize meaning is the creative spark that forms all new knowledge. The learner now undertakes the creative task of shaping significant new thoughts, ideas, and theories outside of his/her prior experience.
Create	As the information gathered in the investigation stage begins to coalesce, the learner begins to make connections. The ability at this stage to synthesize

	meaning is the creative spark that forms all new knowledge. The learner now undertakes the creative task of shaping significant new thoughts, ideas, and theories outside of his/her prior experience.
Discuss	At this point in the circle of inquiry, learners share their new ideas with others. The learner begins to ask others about their own experiences and investigations. Shared knowledge is a community-building process, and the meaning of their investigation begins to take on greater relevance in the context of the learner's society. Comparing notes, discussing conclusions, and sharing experiences are all examples of this process in action.
Reflect	Reflection is just that: taking the time to look back at the question, the research path, and the conclusions made. The learner steps back, takes inventory, makes observations, and possibly makes new decisions. Has a solution been found? Do new questions come into light? What might those questions be?

At this time, the Inquiry Page is serving two important functions in the Biology Workbench project. First, As Mr. Lock engages in the very complex task of contextualizing new technology tools for local purposes (Nardi and O'Day, 1999), the Inquiry community provides him with an instructional framework and an even larger, open community of support for designing inquiry-based learning. While scientists involved with the Biology Workbench project can provide Mr. Lock with content expertise and the few teachers in the Biology Workbench project provide a limited amount of peer, instructional support, the Inquiry community connects him to even more like-minded educators pursuing similar classroom goals.

However, perhaps more importantly, the Inquiry Page serves as a way to disseminate the lessons that Mr. Lock and others write. Currently-published Biology Workbench-related units include: "How do I use the Biology Workbench?," "How are different organisms related?," "How can cystic fibrosis be explored with the Biology Workbench?," and "How can bioinformatics be used by students to research and visualize the genetic disease process?" (To review these and other such units, please search for "Biology Workbench" units on the Inquiry Units Search Page.)[9] By publishing these lessons, the authors provide models for others to follow, sets standards for use, and establishes tangible artifacts around which discussion of inquiry-based, Biology Workbench can occur.

Future Directions

Paul Lock claims that his successful use of Biology Workbench has co-developed with his understanding of inquiry-based learning. He believes that each of his attempts have progressively become more open and more democratic and he constantly seeks the next evolution. Now, his quest is to help students contribute information to the Biology Workbench databases and to have even more contact with practicing scientists.

At a conference, a fellow Inquiry Page teammate met a scientist who was collecting information on whales and submitting the data to the Workbench. Mr. Lock found this idea intriguing. While he has not yet worked out the logistics, he seeks to find a way to help his students participate in this process.

In the meantime, the Biology Workbench team is trying to increase Mr. Lock's and the students' opportunities to work with practicing scientists. With support from NSF, we recently initiated the Graduate Teaching Fellows in K-12 Education (GK-12) program.[10] In this GK-12 program, graduate fellows in science, technology, engineering, and mathematics (STEM) disciplines work with STEM and Education faculty and K-12 teachers to integrate the use of computer-based modeling and scientific visualization in science and mathematics education. The responsibilities of such graduate fellows include visiting classrooms to observe, offering assistance to the collaborating teachers, and co-teaching courses with these teachers, and the responsibilities of the participating faculty include mentoring the fellows and their cooperating teachers. For instance, one of the GK-12 fellows has been assigned to work with Mr. Lock for over a year.

Such partnerships have benefited STEM graduate fellows, as well as students and teachers (Harnisch et al, 2003). By connecting teachers and students to practicing scientists in the field, students can understand how real-life open learning environments operate instead of relying only on closed-world systems of completely specified problems, static and restricted databases, predetermined answers, and walled classrooms that limit learning opportunities.

Continued and expanded involvement with the Inquiry Page is also a critical component for the Biology Workbench project. As we have seen, teachers' access to an open learning environment that supports their learning is as important as students' access. The closed-world approach to learning has persisted in part because of educatorss understandable reluctance to engage in experimental situations that demand change, yet do not guarantee clear learning outcomes. Open-world learning is inherently different from traditional instruction. In open-world learning, the distinction between researcher/teacher/student blurs, and the loss of authority and structure can be disorienting. However, teacher access to open-world systems for educators can ease tension and raise comfort levels. As teachers learn how to participate in an open culture, they feel more confident in creating a similar culture in their classrooms. Open-world systems also have the power to capture and disseminate educator successes so that others can build upon them. Therefore, we believe programs that connect teachers to other teachers, as well as practicing scientists, will be the most successful. Addressing both content, as accomplished in this project via the Biology Workbench project, and pedagogy, as accomplished via the Inquiry page, is necessary to promote the democratization of elementary and secondary education.

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[2] http://workbench.sdsc.edu

[3] http://www.inquiry.uiuc.edu

[4] Eric G. Jakobsson, the second author, is the co-developer of Biology Workbench and holds a patent on it.

[5] Biology Workbench allows up to 31,000 active users at a time due to software limitations.

[6] Bertram C. Bruce, the first author, directed the doctoral dissertation by Jo E. Williamson, who graduated from the Department of Curriculum and Instruction at the University of Illinois at Urbana-Champaign.

[7] http://bsw.ncsa.uiuc.edu

[8] http://www.inquiry.uiuc.edu

[9] http://www.inquiry.uiuc.edu/php/units.php3

[10] http://gk12.ncsa.uiuc.edu