

TEACHING MIDDLE SCHOOL HUMAN BIOLOGY THROUGH BIOMEDICAL ENGINEERING-BASED PROJECT CONTEXTS

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Abstract—In this paper, we describe our design of a standards-based middle school science curriculum that promotes students' meaningful understanding of human biology. We aimed to have middle school students learn science by learning to use what they know to complete a challenging project. We wanted students' application of their knowledge of "how organs and organ systems, composed of specialized cells, work together to provide all cells with their basic needs" to be instrumental to completing the project we designed. Knowing that Biomedical Engineers often apply their knowledge of human biology to solving real-world problems, we explored how best to use a Biomedical Engineering problem as the focus for our project-based curriculum. We present a description of the curriculum we designed and the project at its core, as well as the lessons we learned along the way.

INTRODUCTION: SCIENCE CURRICULA THAT PROMOTE MEANINGFUL UNDERSTANDING

There are several challenges faced by students learning K-12 human biology, not the least of which is the scope of the content knowledge they are expected to master. The national standards suggest that by the end of 12th grade, students should know that human beings are composed of specialized cells grouped in organs that have special functions. Beyond the specifics of the anatomical and physiological systems, the national standards also ask that students understand how these systems work together to meet our essential requirements for life (e.g. obtaining food and deriving energy from it) [1]. In this way, the national standards not only emphasize a broad scope of human biology content knowledge but also aim to organize this content around big concepts in the service of improving students' conceptual understanding [2].

The goal of improving content knowledge and conceptual understanding is, of itself, challenging. Alternative conceptions held by elementary school students about, for example, the connections between the human circulatory and respiratory systems, persist in approximately two-thirds of college students [3]. But the problem does not end with what students do or do not know. One must further consider students' ability to apply this knowledge to real tasks. Knowledge that is relevant but can't be retrieved and subsequently applied remains "inert" [4]. In contrast, a

"meaningful understanding" of human biology is an understanding that enables students to use what they know to build relationships between ideas in order to explain and predict phenomena [5].

We expect that when students are not provided with curricula that help them build meaningful understandings, and are instead prompted to memorize facts and formulae, they lose interest in studying science. We know that as students transition to middle school, they lose the motivation to continue learning science [6]. Students who are not engaged in building meaningful science understandings may be more likely to develop such negative attitudes.

This paper describes our work designing a curriculum to foster middle school students' meaningful understanding of human biology, with the hope that such a curriculum might, in the long run, increase the number of middle school students who remain interested in studying science. In the "Project Ideas" section, below, we reflect on how we were best able to adapt Biomedical Engineering (BME) problems to meet the needs of this curriculum. But first, we discuss the evolution of the principled framework that guided our design of this curriculum, intended to promote students' meaningful understanding of human biology. We will also discuss the collaborative design process in which we engaged.

CURRICULAR FRAMEWORK: FROM INQUIRY TO PROJECT-BASED SCIENCE

One common approach to building meaningful science understanding is "inquiry". Inquiry curricula ask learners to apply scientific concepts and principles in order to solve problems and find solutions in the same way scientists do. Inquiry curricula advocate learners drawing from their base of science content knowledge to: generate a scientific question for study, design and implement the scientific investigation to best pursue their question, reflect on the implications of the results of their investigation, and communicate these results to others [7].

But how do we design an inquiry curriculum that takes into account the real constraints of real middle school classrooms? Project-based science provides a well-researched framework for curriculum design that has had some demonstrable success in promoting inquiry in K-12 classrooms [5]. The project-based science (PBS) framework

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guides the design of inquiry curricula. In PBS, students apply inquiry's problem solving to extended challenges or projects undertaken in collaborative classroom settings, i.e. students engage in a performance of understanding [8], equivalent to the "meaningful science understanding" we are targeting. PBS necessitates that a challenging question be the driver for the project. The project is broad enough to encompass the target content knowledge, but is authentic, personally relevant and engaging, and is anchored in the learners' own experiences. Learners collaborate to collect their own data and use evidence and examples to explain and generalize their new understanding. PBS provides task structures designed to assist the learners in negotiating these challenging investigative processes, and these supportive structures fade as learners gain proficiency. Lastly, PBS requires students to generate artifacts (such as designs, poster presentations of data and conclusions, working models, or journal entries) around which critique and revision can take place as students conduct their investigations. Technology often plays a supporting role in PBS, expanding the range of do-able projects, expanding the range of collectable data, or providing supports for the investigative process [9].

We aimed to use this design framework to develop a PBS curriculum to improve middle school students' meaningful understanding of human biology. However, the PBS framework can neither define the specific project that would work best for our purposes nor determine how best to guide students' work on this extended project. Our options as curriculum designers were vast. What project should we choose? And how should we structure how we ask students to work through this project? In the next section, we describe the design process in which we engaged.

CURRICULUM DESIGN PROCESS: COLLABORATIVE WORKCIRCLES

If educational researchers and content experts, unaided, were to design a PBS middle school human biology curriculum and offer it up to middle schools, we would likely find this curriculum adopted by very few teachers. Teachers might find the curriculum to be too theoretical or impractical for their classrooms or inconsistent with their views on how to teach science. We instead aimed to bridge this divide by engaging practitioners, education researchers, and content experts in a participatory design process in which the knowledge, experience, and expertise of all involved were valued. We call these collaborative teams that co-design and pilot curricula *workcircles* [10]. The workcircle we formed to design the PBS human biology curriculum consisted of several teachers from the Chicago Public School (CPS) system, one of whom assumed the role of the workcircle's teacher leader [EKK]. We were able to reach these teachers via the NSF-funded Center for Learning Technologies in Urban Schools (LeTUS) with whom we are

collaborating on this project. The workcircle also included a Learning Sciences faculty member [BJR] who was experienced in the design and development of PBS curricula, and a Biomedical Engineer with expertise in systems physiology and some training in education research [DEK]. This partnership ensured that the human biology curriculum we designed would be both useful to and usable by teachers and students and would account for the realities of day-to-day life in the classroom, while still embodying the PBS theory of instruction.

PBS PROJECT IDEAS: BIOMEDICAL ENGINEERING-BASED DESIGN

One of the most important decisions we had to make was the choice of the specific project or challenge around which the PBS curriculum would be focused. Certainly, the authentically engaging project we hoped to identify also had to be compatible with the other aspects of the PBS framework. But first and foremost, the project had to promote a meaningful understanding of human biology. This meant, as we discussed above, that utilizing the targeted human biology subject-matter had to be instrumental to doing the project. In middle school, the national standards recommend that students learn how organs and organ systems, composed of specialized cells, work together to provide all cells with their basic needs [1]. So, we needed to devise a middle school PBS project, the execution of which required students to apply their knowledge of the interactions of various human body systems.

We recognized that applying basic principles of human biology to authentic projects closely resembled the work Biomedical Engineers do. Biomedical Engineers apply basic biological and medical science to solving real-world problems. To what extent could we leverage this natural parallel between the work Biomedical Engineers do and the building of a meaningful understanding of human biology in order to develop an appropriate project context for our curriculum?

Biomedical Engineers' work applying scientific principles to practical ends is "design" work. Could the workcircle adapt BME design work as the project for the PBS curriculum? Beyond the potential fit between BME-based design and the practical application of the principles of human biology (the "meaningful understanding" we're targeting), a design project could readily support several other aspects of the PBS framework. Students could collaborate on teams to generate concrete artifacts as the outcome of their design efforts. Improving a design would require a team to engage in extensive testing: data collection and analysis. The results of such analyses, along with the designs themselves, would be artifacts for the class to scrutinize. As the class generalizes from these analyses the scientific principles that affected the performance of their designs, students would employ their new understanding to

revise their designs. In this way, it is easy to imagine a design task structure that would support the various aspects of the PBS framework.

Design is a subject that is itself explicitly targeted by the standards. “By participating in [design] activities, students should learn how to analyze situations and gather relevant information, define problems, generate and evaluate creative ideas, develop their ideas into tangible solutions, and assess and improve their solutions” [1]. In addition, learning about systems is also in the standards. The main goal of having students learn about systems is to enhance their ability to attend to inputs and outputs and interactions among system components as they attempt to understand and work with a whole system. A design project could support learning about systems to the extent to which design involves building and carefully linking subsystems together. Finally, design would provide opportunities for learners to get their hands on real phenomena. Such opportunities can help to anchor work on a project in learners’ own experiences...to make this work more authentic, more personally relevant and engaging. “Put students into contact with phenomena related to the area to be studied—the real thing, not books or lectures about it—and...help them notice what is interesting; to engage them so they will continue to think and wonder about it” [11]. Several other curricula have effectively used engineering-based design projects to support deep learning in K-12 science classrooms [12,13]. For all these reasons, BME-based design seemed an attractive idea around which to build our PBS curriculum.

However, the most obvious sort of BME-based design work, that done by Biomedical Engineers in the medical device industry, was deemed inadequate to promote students’ meaningful understanding of the human biology content and concepts we were targeting. A curriculum based on the design of a glucose sensor, pacemaker, catheter, or wheelchair would require students to apply their knowledge of chemistry, electricity, materials, or mechanics more so than their knowledge of how organs and organ systems work together to provide all cells with their basic needs. The human biology subject-matter would be insufficiently instrumental to a learner completing a project based on the design of a medical device.

Nevertheless, we did not think it was necessary to abandon the potential benefits of building our PBS curriculum around a BME-based design project. We simply needed to devise a design project, different than the design of medical devices, that would primarily require students to apply their knowledge of the integrated function of various body systems.

In the next section, we will describe the PBS curriculum we developed and the BME-based design project we ultimately placed at its core. We will also detail curricular structures we devised to guide students’ work on this extended project.

THE PBS HUMAN BIOLOGY CURRICULUM: *I,Bio*

At the heart of the *I, Bio* curriculum, middle school students complete a design project to explore how well their school lunch choices meet their bodies’ energy needs. Students design and redesign their school lunch choices until a measurement of the energy their school lunch choices add to their bodies’ energy stores is equivalent to the energy their bodies use up doing work. Completing this design project, students acquire and employ knowledge of how their bodies’ organs and organ systems interact to transform energy in food into energy used up doing work, how their bodies’ organs and organ systems interact to provide all cells’ energy needs.

Spiral One: Introduction to the School Lunch Project

I,Bio is structured into three spirals. Each spiral takes the student for a deeper pass through the same content and concepts, helping students gradually prepare themselves for the design project. Spiral One motivates the project. In addition, Spiral One presents the “generative question” that frames the design project: “How well do my school lunch choices meet my body’s energy needs?” This question is generative to the extent that, over the entire rest of the curriculum, students’ sub-questions (some of which are discussed below) derive naturally from this generative question and guide the learning that prepares the students to complete the design project. In Spiral One, we catch students’ attention by having them read excerpts from the book *Hatchet* by Gary Paulsen. *Hatchet* is a story about a boy their age surviving on his own in the woods, having no tools but his hatchet. *Hatchet* allows us to begin the curriculum with the concept of work. Students find that their bodies perform a variety of activities, all of which we call work. Students then brainstorm about what their bodies need to do this work and conclude that their bodies need energy that comes only from food. By posing the sub-question, “Why don’t we need to eat all the time?” students find that the body has stores of energy. Food adds to these energy stores and doing work depletes these stores. After learning why it is healthy to balance the amount of energy taken in with the amount of energy used up, students debate the different amounts of energy that certain foods and activities are “worth.” This is a point in the curriculum designed to reveal students’ prior conceptions. Students combine the results of their debate with a “body bottle” activity to tangibly mimic the ebb and flow of the body’s energy stores. By observing the level of energy in their body bottles over the course of a day, students address the sub-question they’ve been working toward: “How do my choices affect my energy stores?” They discover that they must measure the amount of energy they take in and the amount of energy they use up and compare these two numbers to know if they’re in energy balance. In this way,

Spiral One provides “project placeholders” for the two quantitative tools students will need to complete their design projects (measuring energy taken in via food and measuring energy used up doing work).

Spiral Two: The Tools to Conduct the School Lunch Project

Spiral Two helps students acquire the two quantitative tools essential to carrying out the design project: the ability to measure the energy taken in in the food one eats and the ability to measure the energy used up doing work. Each of Spiral Two’s halves is devoted to one of these two quantitative tools.

Measuring Energy Taken In By The Body— The first half of Spiral Two concerns itself with measuring the energy in the food we eat. Students begin the first half of Spiral Two with the sub-question, “How do I know there really is energy in food?” Students get more specific than they’d been in Spiral One about what it means for food to contain energy. They discuss transforming food’s stored energy into heat via burning to prove there is energy stored in food. As students do experiments using a gaseous oxygen sensor to compare their own exhalations to room air, they test how similar burning food is to how food energy is transformed in their bodies, and students find that oxygen is used up in both cases. Students return to the task of measuring the energy in food. Students find that food energy, transformed into heat, can be measured through calorimetry. Students conduct experiments with calorimeters to measure the energy stored in different foods. In order to answer the sub-question, “How much food energy do I take in?” students log the amount and types of foods they eat for lunch. Students then use their food logs along with the quantitative results of the their calorimetry experiments to calculate how much energy their bodies are taking in.

Measuring Energy Used Up By The Body— In the second half of Spiral Two, students learn to measure the energy expended by the body’s work. Now students get more specific about what it means to do work. As they debate about where the body’s work is performed, students learn that all work is a function of specialized body cells. Through hands-on experiments, students find that the complex work of multicellular organs is rooted in the work of single cells. Students make the connection that energy is used by the cells since that is where work is actually being done. Students learn about cellular respiration. Students explore the related issue of delivering foodstuffs and oxygen (the raw materials to transform food energy into cellular work) to the cells. Students conduct experiments and work with reference materials to figure out how foodstuffs and oxygen reach the working cells. In this way, students develop a basic understanding of how the digestive, respiratory, and circulatory systems work together to support the vital function of transport necessary for cellular

respiration. All together, the second half of Spiral Two supports students’ measuring via indirect calorimetry the amount of energy they use up doing work. Students will design experiments to collect their expired air while performing different types of work and will measure the difference between the quantity of oxygen they inhale and exhale using the gaseous oxygen sensor and related equipment. These indirect calorimetric measurements combined with students’ logs of their activities allow students to measure the amount of energy their bodies use up doing work. After completing both halves of Spiral Two, students are equipped with the tools to measure both the food energy taken in by their bodies and the amount of energy their bodies use up doing work.

Spiral Three: Completing the School Lunch Project

Students are now prepared for Spiral Three in which they complete the school lunch design project itself. Students design and redesign their school lunch choices— taking into consideration the constraints to which they typically adhere (these constraints reflect students’ personal choices about diet and exercise)— until a measurement of the food energy their lunch choices add to their bodies is equivalent to the energy their bodies use up doing work. During Spiral Three’s design process, students generalize the basic principles that affect the success of their designs, present these findings class-wide, and share and employ these ideas to further improve their designs.

DISCUSSION

I,Bio is a PBS curriculum that promotes middle schooler’s meaningful understanding of the human biology that is targeted by the standards for this grade level. A PBS curriculum is motivated by a challenge, and we’ve described the challenge that does this, namely “How do I redesign my school lunch choices to meet by body’s energy needs?” This project is personally relevant and engaging to the extent to which it deals with students’ own bodies and is based on students’ prior experiences eating, doing activities, etc. This is also a project that is broad enough to encompass much of the human biology content and concepts targeted by the middle school standards, including how organs and organ systems, composed of specialized cells, work together to provide all cells with their basic (energy) needs. Students design and redesign their school lunch choices based on analyses of data they’ve collected and critique takes place around the class-wide presentations of these designs. Technology supports the curriculum via various sensors and tools for data acquisition. Additionally, students’ path through this extended design project is guided by the generative question (which decomposes into sub-questions) and the project placeholders, both of which we believe support students seeing how the human biology content and

concepts are useful to completing the design project (i.e. the meaningful understanding we're targeting). In all these ways, *I,Bio* fits the PBS framework while providing students with the opportunity to build a meaningful understanding of human biology.

As we discussed above, *I,Bio*'s design project could not be based on medical device design and still meet our premiere goal of promoting a meaningful understanding of the human biology content and concepts targeted by the middle school standards. For example, designing an artificial heart would require students to apply a knowledge of some physiological systems, but would not require them to apply a knowledge of how organs and organ systems work together to provide all cells with their basic needs, as does *I,Bio*'s "school lunch choices" design project for cells' energy needs. Other investigators' design-based K-12 human biology curricula look more like medical device design—students design a working model of the lungs [14] or a working model of an elbow joint [15]—but these curricula do not directly target the meaningful understanding of standards-based middle school human biology that was our objective. However, *I,Bio*'s "school lunch choices" design project still ends up being very much a BME-based design project. Students use technology to collect quantitative data, including physiological data they collect from their own bodies; students' principled design and redesign of their school lunch choices is based on their analysis of this quantitative data. In these ways, the design project at *I,Bio*'s core is BME-based.

I,Bio's design project still supports many aspects of the PBS framework, as we'd discussed was the case for design projects in general. Improving the design of their school lunch choices requires teams of students to engage in extensive data collection and analysis, and the results of these analyses, along with the designed diets themselves, are the artifacts the class scrutinizes. As the class generalizes from these analyses the scientific principles that lead to improved diet designs, students employ this new understanding to revise their own diets. In this way, design learning is explicitly addressed. Systems learning remains explicit in *I,Bio* only to the extent to which we highlight the integrated operation of various body systems...and the organ sub-systems which comprise these systems...and the cells which comprise these sub-systems. Since students do not design a physical object, some explicit systems learning opportunities are lost.

All this being said, perhaps we could have developed a computer-based instructional environment in which students use their knowledge of the integrated function of body systems to design a virtual physiology, which provides for the needs of all the virtual cells in a virtual body. We did not pursue this type of design project due to our desire to put students in direct contact with real physiological phenomena. By building *I,Bio* around a design project that requires students to collect and analyze data from their own

bodies and behaviors, we believed we were anchoring this project in learners' own experiences, making this work more authentic, and more personally relevant and engaging.

Finally, PBS curricula designed to promote meaningful understanding may also be valuable in undergraduate engineering education. The Accreditation Board for Engineering and Technology's EC-2000 criteria support this focus on learning to *apply* basic knowledge in relevant situations [16]. New initiatives to promote project-based engineering learning in universities and colleges are slowly winning ground [17].

FUTURE WORK

We will pilot the completed *I,Bio* curriculum in two Chicago public middle school classrooms beginning in January 2001. We will subsequently evaluate the success of this curriculum based on student growth in three student-learning variables: understanding science concepts, doing science, and communicating scientific information. Student growth in these three variables will be determined from assessments embedded within the curriculum (e.g. journal entries, oral presentations, design reports), class-wide pre- and post-tests, clinical interview protocols conducted with subsets of students, and video records of student performance in the pilot classrooms.

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