A Systems Physiology Instructional Environment for Biomedical Engineers: a Design Grounded in the Learning Sciences

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Abstract

To the extent that Biomedical Engineering (BME) is rooted in the biological and medical sciences, a core Systems Physiology course provides undergraduates with an important learning opportunity. However, the rapid evolution of BME's biological and medical foundations necessitates that beyond learning systems physiology's content and concepts, pre-professionals must learn to apply relevant aspects of systems physiology to unanticipated new tasks. The Accreditation Board for Engineering and Technology's EC-2000 criteria similarly support engineers learning to apply their knowledge. This paper describes a principled approach by which we are designing a BME instructional environment in which students learn systems physiology subject matter coupled to its application. We explain how our design principles for this instructional environment evolved from the Project-based Science pedagogical framework and a modern understanding of how people learn, and further discuss our process of participatory design, which involves individuals from both BME and the Learning Sciences. We present our progress to date, and the ideas we have distilled from this experience.

1. Introduction

Grounded in the biological and medical sciences, Biomedical Engineering (BME) uses systems physiology as a core component of its undergraduate curriculum. The fact that this is so is reflected by the extent to which most undergraduate BME curricula include formal training in systems physiology. Systems physiology is one of few places in the curriculum where undergraduate BME students can develop a specialized vocabulary in biology or medicine, a specialized knowledge of the problem-solving techniques of biology or medicine, a capacity to deal effectively with the uncertain behavior of biological systems, and a generalized knowledge of the application of engineering techniques to biological or medical topics [1]. At the end of their training, Biomedical Engineers should uniquely possess such competencies. But beyond the agreed-upon merit of teaching systems physiology, there is little consensus on how best for BME students to learn systems physiology, and what of this material to emphasize.

As the knowledge base of biology and medicine changes with ever increasing speed— evolving so rapidly as to require unprecedented on-the-job training by Biomedical Engineers— one could argue that BME pre-professionals are best served by learning to apply systems physiology's governing principles facilely to addressing unforeseen challenges. The Accreditation Board for Engineering and Technology's (ABET) "new" EC-2000 criteria support this focus on learning to *apply* knowledge in relevant situations. EC-2000 goes well beyond the knowledge acquisition on which universities have traditionally focused [2] to emphasize higher-order cognitive skills

Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition

("An ability to identify, formulate, and solve engineering problems"), procedural skills ("An ability to use the techniques, skills, and modern engineering tools"), and combinations of these two kinds of knowledge as applied to investigating problems ("An ability to design and conduct experiments as well as to analyze and interpret data") [3]. In fact, the perception that engineering graduates are unable to apply their knowledge to solve novel problems is part of the motivation for the new engineering instructional paradigm embodied by EC-2000 [4].

We set out to tackle the unmet challenge of closely coupling systems physiology subject matter learning and its application in hopes of facilitating the next generation of Biomedical Engineers' problem solving. To do this, we aimed to apply a framework for classroom instruction called Project-based Science (PBS), which has been used successfully, primarily in K-12 classrooms, to design and develop effective instructional environments that meet such goals [5].

1.1 The PBS Pedagogical Framework

The PBS framework helps learners develop a deep understanding of scientific concepts and inquiry strategies via their performance on extended challenges or projects undertaken in collaborative classroom settings. Learners engage in a "performance of understanding" [6]. PBS necessitates that a challenging question be the driver for the project. The challenge is broad enough to encompass the targeted content. Learners collaborate to use evidence and examples to explain and generalize their new understanding. PBS provides task structures designed to assist learners in negotiating these challenging processes, and these supportive structures fade as learners gain proficiency. Lastly, PBS requires students to generate, as they conduct their investigations, artifacts (e.g. journal entries, working models, or poster presentations of data) around which critique and revision can take place. PBS projects that teach basic science in the context of its application might, for example, have students learning the basic principles of cellular growth kinetics and protein transcription by applying these concepts to determining specifications for a bioreactor [7]. Based on the set of basic attributes of the PBS framework, we aimed to design an instructional environment to teach systems physiology to Biomedical Engineers in a way that would couple this knowledge and its application.

1.2 Research from the Learning Sciences

Implementing PBS effectively requires considering how people learn, and how best to support that learning. The recent National Research Council publication, "How People Learn," summarizes into four attributes its implications for the design of effective instructional environments. A well-designed instructional environment must be learner-centered, knowledge-centered, community-centered, and assessment-centered. Taking these ideas into account has ramifications for how we design our PBS instructional environment [8].

Learner-centeredness tells us that in order to build bridges to new understandings, an instructional environment's teaching and learning activities must be based on the relevant conceptual knowledge that students bring to the classroom, and must take into account what interests students. This is in contrast to a notion of teaching as telling, organized by the structure of the discipline. We must incorporate what students care about and want to do, and additionally what students know and are able to do. Applied to PBS, this translates into our first two design principles: 1.) the PBS challenge must be grounded in the learner's prior knowledge, based on the learner's own conceptions and experiences; and 2.) the PBS challenge must be motivating and relevant to the learner.

Knowledge-centeredness says that improving students' problem solving requires emphasizing using what you know, and conveying a well-organized body of knowledge that is easily retrievable in the appropriate situations. For us, this means that 3.) addressing the PBS challenge must require learners to apply the target content, 4.) tackling the PBS challenge must serve to reorganize the body of knowledge for learners and thereby promote future problem solving, and 5.) the evidence learners invoke must be underpinned by target concepts.

Community-centeredness says that learning is enhanced by social norms that encourage discourse, and by connections to a broader community of practice. Another design principle emerges: 6.) the PBS investigation must require discourse of learners that mimics that in which practitioners engage.

Lastly, assessment-centeredness requires instructional environments to define clearly what will pass as evidence of the learning that's been targeted. For evidence of the ability to apply knowledge, 7.) the artifacts learners generate pursuing the PBS challenge must themselves serve as relevant assessments.

We expected that adhering to these principles would help us design a PBS instructional environment that supports Biomedical Engineers' acquiring systems physiology content knowledge in the context of its application. However, we still needed to figure out what specific PBS challenge would work best for our purposes, and what we should prescribe of how students carry out their investigations. In the following section, we describe the design process in which we engaged to design the instructional environment, and then in the subsequent section we share the details of the instructional environment itself.

2. Our Design Process

While education researchers possess an extensive knowledge of what comprises effective instruction and how to facilitate it, education researchers' systems physiology content knowledge is undoubtedly insufficient for them alone to design an improved BME systems physiology instructional environment. Unaided, BME faculty's extensive content knowledge and experience teaching systems physiology would be similarly insufficient. We bridge the divide by engaging both education researchers and BME faculty in participatory design teams that value the knowledge, experience, and expertise of all involved. In effect, participatory design becomes a mechanism for education researchers and BME faculty to learn through interaction with one another [9]. We call these collaborative teams that co-design and pilot instructional environments *workcircles*. The workcircle charged with designing the systems physiology PBS challenge (based on the aforementioned seven design principles) consisted of one BME faculty member who contributed as both an experienced systems physiology educator and a systems physiology content expert, and two education researchers, one an expert in the Learning Sciences (LS), the other contributing some expertise in BME and systems physiology. The BME and LS communities were able to collaborate in this way via the National Science Foundation-funded

Engineering Research Center for Bioengineering Educational Technologies (VaNTH- named for its partner institutions Vanderbilt, Northwestern, U. Texas, and Harvard/MIT), whose mission it is to take the principled and collaborative approach to designing instructional environments we are describing.

3. A Project-based Design for Systems Physiology

We are currently using the workcircle process to design a PBS instructional environment that supports Biomedical Engineers learning systems physiology in the context of its application. We are in the midst of this process. Our goal here is to sketch for the reader, in broad strokes, the envisioned PBS instructional environment. We will first present an overview of our design-in-progress, and then describe how the seven design principles are achieved by this design.

3.1 Prologue

The learner is introduced to the extended challenge of "wiring up" a network of retinal neurons to address the challenge of "efficient seeing." After an introduction to the basic functionality of the eye, the behaviors of the various retinal cell types, and some general constraints on the manner in which these cell types interconnect, students work with the instructor to better define the challenge. A reasonable idea at which students might first arrive is that "efficient seeing" is about faithfully and efficiently transducing light into bio-electric signals passed to the brain, and that this is simply a function of using photoreceptors to sample the light cast upon the retina. Sampling an image using the smallest possible population of photoreceptors reduces the biological cost to the body, and might thus be construed as "efficient seeing."

3.2 Sampling Sub-challenge

So the learner enters the first sub-challenge, a computer-based experimental space, expecting to array photoreceptors in such a manner as to "sufficiently resolve" a natural image for the lowest possible biological cost. At this point the learner is without a clear definition of what comprises "sufficient resolution." The learner is given tools with which to choose the density and geometry of a two-dimensional array of photoreceptors (for the sake of this challenge, we confine learners to using only cone cells), and the learner initially receives only qualitative image data and an index of biological cost as feedback. As learners investigate this first sub-challenge, their choices for the density and geometry parameters are circumscribed, allowing them to entertain any of a multitude of options, but not an infinite solution space.

The learner's use of this experimental space is structured. The learner is first required to predict, in writing, the results of using the chosen density and geometry parameters to sample the image. Then the learner observes and annotates the results [the learner receives both the sampled image itself and the index of biological cost (number of cells) as feedback]. Finally, the learner explains how these results relate to their initial prediction, and justifies any changes they would make. These are predict/observe/explain or POE cycles. The learner continues through these cycles until satisfied with their choices for the density and geometry of a photoreceptor array that yields a sufficiently resolved image for the lowest biological cost. At this point, the learner presents their design decision to the entire class, to be critiqued against others' solutions. The results of these class-wide design critiques might prompt the learner to return to the experimental space for additional POE cycles followed again by class-wide design critiques.

Along the way to completing the sampling challenge, learners uncover the phenomenon by which undersampling causes high-resolution information in the initial image to be lost in the sampled image. This phenomenon, aliasing, is explored in greater depth as learners detour into a module on aliasing. It is here that students learn to identify aliasing qualitatively by directly comparing the initial to the sampled image, and quantitatively by comparing the power spectrum of the initial to that of the sampled image. Returning to the sampling sub-challenge (and its POE cycles and design critiques), learners compare both the initial and sampled images, and the power spectra of the initial and sampled images, to design an array of photoreceptors that, for the lowest biological cost, resolves the image without aliasing. This is a significant refinement of the initial criteria of "sufficiently resolving" the image.

3.3 Noise Reduction Sub-challenge

Completing the sampling sub-challenge, learners encounter another problem to resolve. They are prompted by the instructor to scrutinize the ability of their array of photoreceptors to process an image that is noisy (this would be the case in low light levels where a stray photon would add significant noise to the initial image). Learners find that as they've designed it, their array of photoreceptors performs poorly, sampling and reproducing the noise. It will pass the noisy information on to the brain, also passing on the biological cost of attenuating the noise. The learner is left with the problem of redesigning their neural network to significantly reduce the noise level while still sampling without aliasing, all for the lowest biological cost. The learner is inspired to draw from their remaining arsenal of retinal neurons to modify their network.

Learners now work in a second computer-based experimental space, networking other retinal cell types (bipolar cells, amacrine cells, horizontal cells, and ganglion cells) on top of their array of photoreceptors, then applying the completed network to the noisy image. Initially, the learner receives only qualitative data, sampled and filtered images, as feedback; but learners quickly realize they do not know how to analyze even this qualitative data to determine how successfully their networks have attenuated the noise. Learners are motivated to detour into a module on noise in which they learn to evaluate noise levels qualitatively by examining sampled, filtered images, as well as qualitatively by comparing the power spectra of the initial noisy images to that of sampled, filtered images. Learners re-enter the noise reduction sub-challenge, armed with these new tools for analysis.

As they complete the noise reduction sub-challenge, learners are required by the same POE task structures and design critiques as described for the sampling sub-challenge, to explain how they interpret the feedback they receive (the images and the power spectra, as well as the index of biological cost), and justify the changes they make to their retinal neural network designs. Learners iteratively redesign their networks until they pass the least amount of sampled noise for the lowest biological cost.

3.4 Redundancy Reduction Sub-challenge

Successfully completing the noise reduction sub-challenge, learners are presented with one final problem: what if the ganglion cells (the output cells of the retina that extend into the brain) that are ultimately wired-up to adjacent swatches of photoreceptors pass identical, or redundant, information? Learner's find that their retinal neural networks as designed pass redundant information on to the brain. Processing this redundant information is an unnecessary biological cost.

Learners now have the final sub-challenge of designing networks that reduce redundancy while maintaining a significant reduction in noise, all for the lowest biological cost. They return to the computer-based experimental space used in the noise reduction sub-challenge to continue their network design work. Unfortunately, learners quickly find that the analysis tools at their disposal are insufficient to determine the redundancy that remains in an image sampled and filtered by the retinal neural network. Learners detour into a module to learn to determine how much redundancy remains, both qualitatively (visual inspection) and quantitatively (autocorrellogram). Incorporating these new feedback measures of redundancy, learners again engage in POE task structures and design critiques to, in the end, complete a retinal neural network design that passes the least amount of sampled noise and the least amount of redundant information for the lowest biological cost.

3.5 Epilogue

As a final experience, the learner probes (virtually) the receptive field of the ganglion cells of the retinal neural network he or she has designed, and uncovers a systems-level behavior of this network of cells that is nearly identical to a systems-level property (center/surround) exhibited by real retina.

4. Instructional Principles in the Design

How does using this instructional environment embody the design principles with which we intended to comply? We have created an extended PBS challenge with supportive structures that help break this larger investigation down into sub-challenges, and prompt learners to engage in critique and revision. In this section, we review our design principles, and consider how these are achieved.

Permitting us to proceed out of order…knowledge-centeredness gave us our third, fourth, and fifth design principles: 3.) addressing the PBS challenge must require learners to apply the target content, 4.) tackling the PBS challenge must serve to re-organize the body of knowledge for learners and thereby promote future problem solving, and 5.) the evidence learners invoke must be underpinned by target content concepts. Adherence to the fourth design principle was what led us to target the big-picture concept from systems physiology that we did, namely the notion of how the systems-level properties of ensembles of cells differ markedly from the properties of individual cells. That is to say: how could it be that systems of cells have emergent properties that do not belong to individual cells in the system? We call this concept "from cells to systems." The "wiring up" challenge we chose (in this particular case for the neurons in the retina) required a re-organization of what a learner knows about cells' properties and the properties of a system of cells to emphasize that the properties of a system of cells emerge from both the individual cells' properties and the nature and number of their linkages. The "from cells to systems" focus emphasized by the "wiring up" challenge served to re-organize the traditional content into a framework that supported strategic thinking, a framework that learners could later apply to understanding and/or diagnosing any of the body's other multicellular systems. To restate: pursuing the "wiring up" challenge that focused on understanding the links "from cells to systems," transformed the traditional content base into a conceptual tool for reasoning and problem solving. In addition, tackling the challenge itself, and completing the requisite POE tasks and design critiques along the way, clearly required learners to employ the target content's technical concepts to make sense of how individual cells' properties and the number and nature of cell-to-cell linkages gave rise to the emergent systems-level properties the learner observed, thus addressing our third and fifth design principles.

Learner-centeredness told us that: 1.) the PBS challenge must be grounded in the learner's prior knowledge in order to bridge to new understanding, and 2.) the PBS challenge must be motivating and relevant to the learner. Each of the sub-challenges as we have designed them asks learners to begin investigations into concepts (e.g. aliasing, noise, or redundancy) in which they have received no direct prior instruction. Therefore, new learning is necessarily based on either the prior conceptions and experiences students bring with them, or on conceptions and experiences students have built up during their work in the instructional environment. In this way, the overall challenge we designed adhered to the first design principle. We also devised the instructional environment such that the unsatisfactory performance of a learner's neural network was what motivated entering each additional sub-challenge. In this way, the learner was motivated to improve her or his own neural network design, adhering to the second design principle.

A desire to be community-centered established that the PBS problem-solving process require learners' discourse to mimic that in which practicing Biomedical Engineers engage (design principle 6). This was accomplished by including the aforementioned design critique task structures. In the design critiques and the experimentation that leads up to these critiques, learners participate as would members of the BME researcher community. Learners iteratively advance to the class-at-large claims about how a retinal neural network might best function; they collaborate in teams, share information, and draw from target subject-matter to resolve conflicting claims.

Lastly, assessment-centeredness required that the artifacts learners generate must themselves serve as relevant assessments to evaluate student performance. It was our intention that the written artifacts from the POE and design critique tasks, generated while addressing the challenge, would serve this purpose. We designed our challenge to require a target level of learning and the application of a base of knowledge in order to succeed in the challenge, and the assessment of the target learning is imbedded in the quality of the learner's solution. This is in contrast to using a separate examination to evaluate what students learned.

In conclusion, have attempted to craft an effective project-based challenge that teaches sophisticated neural systems physiology and embodies the seven design principles we targeted.

We will continue in the next section with a discussion of the generally applicable ideas we have extracted from this design experience.

5. Lessons Learned

We believe that the PBS framework as informed by a theoretical understanding of how people learn, has adequately guided the design of our instructional environment. Within the workcircle environment, our design principles have guided our development of a challenge-based approach to learning broad systems physiology concepts in a way that emphasizes the application of this knowledge.

Using PBS to teach systems physiology to Biomedical Engineers in a challenge-based format seems quite consistent with an overarching goal of engineering education: learning to apply basic science content in problem-solving contexts. For this reason, we feel that our approach is not only appropriately grounded in education theory, but is conducive to supporting the modern paradigm of engineering education represented by ABET's EC-2000 criteria [3].

Indeed, we believe that the principled approach we have taken to designing our instructional environment could just as well be applied to improving instructional environments for other science subjects at the core of the BME curriculum. We hope that the reader would see this approach to be generally applicable to teaching other such subjects in a project- or challenge-based manner. However, although the challenge we designed is in some ways very much an engineering design challenge (learners design a retinal neural network to meet certain criteria and constraints), it is not at all the sort of design challenge one would think of a Biomedical Engineer undertaking in industry. Since we are explicitly targeting broad conceptual understanding and cognitive skills in systems physiology, the nature of the design challenge was adapted accordingly. Learners are not, for example, designing an artificial retina. Pursuing the design of an artificial retina wouldn't necessarily have required the learner to wrestle with and apply the broad systems physiology concepts (e.g. "from cells to systems") we had targeted as our primary learning goals. From this observation, we wish to point out that appropriate challenges need not necessarily be "real" engineering design problems to well promote learning in the context of the application of the knowledge, and in some cases "real" engineering design problems would directly conflict with this goal.

We will also mention that an obvious tension exists between engaging learners in an extended investigation and maintaining sufficient depth and breadth of content coverage. We were challenged to design a task that did not under-develop the content or over-simplify the science. Although there is no easy solution to this dilemma, we will point out that the challenge we designed ended up incorporating concepts from Electrical Engineering, an intended part of these students' training that we would not typically have addressed in a Systems Physiology course and had not expected to emphasize to the degree we did in the challenge we set out to design. So we would encourage the reader to note that while the one might believe the extended challenge approach we are advocating to <u>reduce</u> opportunities for sufficient content coverage, we did not find this to be the case. Challenges, like the one we have designed <u>provide new opportunities</u> to integrate e.g. engineering and life science content. Emphasizing links between seemingly disparate subjects insofar as their synergy in solving problems is known to promote a learner's later ability to apply their knowledge in novel situations, and is more like the knowledge possessed by expert problem-solvers [10].

Finally, we wish emphasize the role technology plays in our instructional environment. In the end, the challenge we designed was untenable without technology. The kinds of learning conversations we hoped this challenge to foster within a learner's own mind or among learners would not have been possible without the computer technology to provide the appropriate experimental space within which learners could explore their ideas[11]. This is a view of technology very different than as a way to deliver the usual content in a new (multimedia) format.

6. Future Plans

We plan to pilot the completed instructional environment at Northwestern University in an undergraduate BME Neural Systems Physiology course in the Fall Quarter of 2001, and subsequently evaluate the success of this enactment.

7. Acknowledgment

This work was supported by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9876363 and the Postdoctoral Fellowships in Science, Math, Engineering, and Technology Education Program of the National Science Foundation under award number DGE-9906515.

Bibliography

1. Johnson, A.T. and W.M. Phillips (1995), "Philosophical Foundations of Biological Engineering." Journal of Engineering Education, October, 311-8.
2. Krotseng, M. and G. Pike (1995), "Cognitive assessment instruments: Availability and utilization," in *A Practitioner's Handbook for Institutional Effectiveness and Students Outcomes Assessment Implementation*, J. Nichols, Ed. New York: Agathon.
3. "Engineering criteria 2000 third edition," in *Criteria for Accrediting Programs in Engineering in the United States*. Baltimore, MD: The Accreditation Board for Engineering and Technology (ABET).
4. "Assessment criteria" in *How Do You Measure Success?* Washington, DC: American Society for Engineering Education (ASEE), 1998.
5. Krajcik, J., C. Czerniak, and C. Berger (1999), *Teaching Children Science: a Project-based Approach*. Boston: McGraw-Hill College.
6. Singer, J., R.W. Marx, J. Krajcik, and J.C. Chambers (2000). "Constructing extended inquiry projects: Curriculum materials for science education reform." Educational Psychologist, 35(3), 165-78.
7. Giorgio, T.D. and S.P. Brophy, "Challenge-based learning in biomedical engineering: A legacy cycle for biotechnology," in *ASEE Annual Conference Proceedings*. Washington, DC: American Society for Engineering Education (ASEE), 2001.
8. "The design of learning environments," in *How People Learn: Brain, Mind, Experience, and School*, J.D. Bransford, A.L. Brown, and R.R. Cocking, Eds. Washington, DC: National Academy Press, 1999.
9. Shrader, G., K. Williams, J. Lachance-Whitcomb, L.E. Finn, L. Walker, and G.M. Gomez (1999). "Work in the work circle: Collaborative design to improve teaching practice." Paper presented at the Spencer Foundation Conference on Collaborative Research for Practice, New Orleans.
10. Lesgold, A.M. (1988). "Problem Solving," in *The Psychology of Human Thoughts*, R.J. Sternberg and E.E. Smith, Eds. New York: Cambridge University Press.
11. Pea, R.D. and L.M. Gomez (1992). "Distributed multimedia learning environments: Why and how?" Interactive Learning Environments, 2, 73-109.

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