Constructing Computer Models to Provide Accurate Visualizations and Authentic Online Laboratory Experiences in an Introductory Biochemistry Course.

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Abstract: The goal of science courses is to aid the students in understanding the underlying physical laws that are responsible for observed phenomena. Meeting this goal is especially challenging in biology courses due to the complexity of the systems involved and the spatial and temporal nature of many biochemical processes. In the case of our introductory biochemistry course, we have designed a number of technology-based enhancements to assist students in developing more complete understanding of many fundamental processes in biochemistry. Our paper describes the process and pedagogic goals followed in creating these animations, tutorials, simulations and other dynamic models; and how they can be deployed in a hybrid lecture based course.

Introduction

According to the National Research Council, there needs to be greater emphasis on quantitative, inquiry based learning science education: "… in which mathematics and computing serve as essential tools in framing experimental questions, analyzing experimental data, generating models, and making predictions that can be tested."(National Academy Report, 2003). The complexity of the systems involved and the spatial and temporal nature of many biological processes make it difficult for students to understand the underlying physical laws that are responsible for observed phenomena. In the case of our introductory biochemistry course, we have designed a number of technology-based enhancements to provide students with this enquiry-based approach. For a number of years we have been offering a blended course with the students attending lectures three times a week and using a course text enhanced with various online materials and assessments.

These enhancements can be divided into two main categories: The **first category** can be described as a series of **animated tutorials** that provide a detailed description of the series of events that occur in biological processes, ranging from enzyme catalysis to DNA replication. These tutorials are easily integrated into a traditional lecture course, and greatly enhance a students understanding of the processes. They are publicly available at http://telstar.ote.cmu.edu/biology/.

The **second category** generates **authentic laboratory experiences** for students via the simulation of various processes, such as equilibrium, osmosis, protein purification, protein denaturation, ligand binding, and enzyme kinetics. These simulations have hidden mathematical models that provide the students with data, so they can experiment and construct their own models for the behavior of biochemical systems. The simulations provide significant context and feedback to the students, while letting them experience the changes in a system's behavior caused by their own modification of the parameters of the system. Consequently, these laboratory experiences provide quantitative, inquiry based learning in the physical sciences.

These authentic laboratory experiences and dynamic models provide the students with experiences, data and models so that they can construct their own learning. It is this type of learning experience that was referred to by Nobel prize winning cognitive Psychologist, Herb Simon when he insisted that "Learning takes place in the head of the learner, and only in the head of the learner." (Simon 1999) In addition to enhancing the initial learning experience of the student, the assessment of the student after the exploratory process using exactly the same simulated environment is significantly more effective than using traditional, quiz based questions.

The Process for creating these interactive materials

The construction of both classes of interactive materials requires a great deal of effort along a number of dimensions. The approximate sequence of events is as follows:

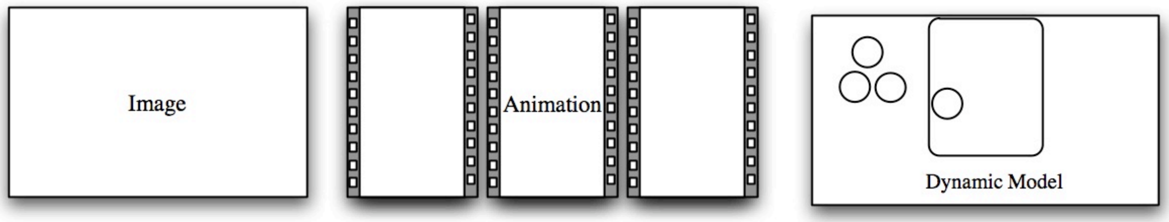
- *Analysis of the issues in helping the students understand the materials* – Instructors with experience teaching the concepts in previous semesters, are great candidates for analyzing gaps in student preparation & understanding and mental model flaws.
- *Analysis of the informational requirements* – Experienced instructors are also best prepared to judge what level of detail should be included in the animation/model
- *Construction of detailed storyboards* – The instructors construct precise storyboards of the processes to be included within the tutorial or simulation. These storyboards become the basis for communicating within the team.
- *Study of the state of the art research* – Creating these detailed tutorials sometimes requires checking with current research to add any new developments or correct any details of current understanding by the scientific community.
- *Construction of visual and computer models* – The design of the visual elements requires an artistic balance between simplifying models to focus on the important issues yet not fostering student misconceptions. For example, if one were designing an animation to describe how a car engine functioned it would be important to include the component that times the firing of the spark plugs, otherwise the student may not realize that careful timing is essential to the proper function of the engine. The design of the computer models requires a blend of the computational science and it's implementation as a student tool.
- *Testing with students* – Given the nature of the classroom environment, there are few opportunities to properly test the materials. Using the animations one semester in an evaluative mode, followed by integration into the course content is usually the best that a teaching environment can provide. In our opinion, our carefully designed animations are an excellent resource for explaining course material, thus evaluations based on withholding the animation from part of the class are a disservice to that particular segment of students. Nevertheless, it is essential to collect retrospective feedback from the students to further improve the impact of the animations. However, the ability of an instructor to collect this data may be limited by institutional resources.
- *Constructing activities* – An essential part in the deployment of these learning materials are the activities and assessment questions the instructor uses to make the students use the materials, and to force them to think more deeply about the processes they are studying. It is important that instructors continually improve the integration of these materials into student assignments.

Production Team and University Infrastructure

Our work to create these materials is part of a collaboration effort that has been growing for about ten years. It now consists of a team of five biologists teaching various levels of the domain, a computer animator with an advanced degree in biology, as well an educational multimedia software developer. The latter individual is part of the Office of Technology for Education (OTE), one of Carnegie Mellon's organizations that supports the appropriate use of technology in education on campus. Together with the Eberly Center for Teaching Excellence, they collaborate to help faculty make best use of technology and sound teaching strategies, based upon cognitive research on how people learn. They work with departments on campus to continually improve the learning opportunities of our students.

Our Tutorials and Simulation Models

To help us teach complicated biological processes, we rely heavily on visualizing the concepts. These visualizations begin with static images, which are then expanded into either animations, or dynamic models, depending on the process that is being illustrated.



Images - students can look for interactions and count static objects, but lose site of equilibrium and other dynamic processes.

Animations illustrate the dynamic concepts and can be expanded to more concepts but still only provide glimpses of pre-determined visualizations.

Dynamic models: The instructor can vary the model to illustrate different concepts. The student can vary the parameters to help them develop an understanding of the underlying model. The instructor can vary the parameters as well as model based on student last name to provide individualized, authentic assessments to students.

Figure 1: Each of the various visualization techniques serves a different function. Applied as needed, they provide the student with the information and experiences that let the them construct their own meaning from the online materials.

Animations: There are two main goals of the animations. The first is to provide a clear message to the student that the process is series of events with well-defined temporal and spatial characteristics. Although it is possible to convey these characteristics using a series of still images, an animation is a more effective mechanism to show that the process involves a number of changes over time. Secondly, the animation allows the student to gain an understanding of how a system progresses from one intermediate state to another.

Virtual Labs: After more than four years of constructing animations, we began constructing dynamic models to represent various interactions in biological systems at the molecular level. We started by constructing authentic laboratory experiences that embedded mathematical models into visual simulations. These laboratory experiences allowed the student to manipulate some parameter of the system (e.g. temperature) and to observe the effect of that change on the state of the system. After completion of the experiment the student then either perform a simple quantitative analysis of their data or use their data to draw conclusions regarding the underlying mathematical behavior of the system. These activities serve a useful role in the learning experience: they teach the students to practice the methods of learning science: to observe, draw conclusions, test their hypotheses to see if they support their conclusions (Rule, G., & Bajzek, D., 2005).

These lab environments have consisted of a computational model embedded into the system that provides accurate data for the students to use to practice their science. This environment facilitates student ownership of the data by encouraging the student to develop their own approach to solve the problem that has been assigned to them by the instructor. In addition, we have coupled a visual model to the simulation that allows us to visually express the concepts we want the students to learn. In most cases, the physical model cannot be used to directly generate the visual model due to limitations of processor speed. Even if we could visually render what is happening within the model, there are often too many molecules and too much detail for the student to focus on to see what is happening. Consequently, we generally simplify the visual model, however we are very careful to insure that it accurately represents the important elements of the concept, even if it does not quite accurately depict the reality of the experiment.

One of the most significant outcomes of our earlier work has been the construction of a robust and flexible platform that can be used to easily simulate a wide variety of molecular phenomena. The features of this platform are illustrated in Fig. 1. The primary element of the platform, which is present in all virtual labs, is the visual display of the molecular process. An underlying molecular simulator drives the images on this display. The instructor can specify the selection of molecules and their initial behaviors in the simulator. Within an XML description file, the author assembles a number of optional pre-built tools such as background images and animations, text-display boxes, value displays, sliders, and graphers (Bajzek, D., Burnette, J., & Brown, W., 2005). The flexibility of this platform allows the same underlying simulator to be used:

- As a simple in-class demonstration with no adjustable parameters, i.e. just the visual display is used.
- As a more complex in-class demonstration with instructor manipulated parameters, i.e. the visual display with a slider.
- As an online (or in-line) animation to be used for retrospective feedback by students.
- As an online assessment, in which the student would vary a parameter using a slider and record data from the value display. This data can be analyzed using pre-defined mathematical models or the student can be asked to develop a model from the data. In this case the text display box is often used to define the problem and the students name that is entered into the input dialog box may be used to set one or more parameters for the molecular simulator. In this way it is possible to give different types of problems to different students.
- As a tutorial, in this case the text display box is used to guide the student through the different steps of the tutorial.

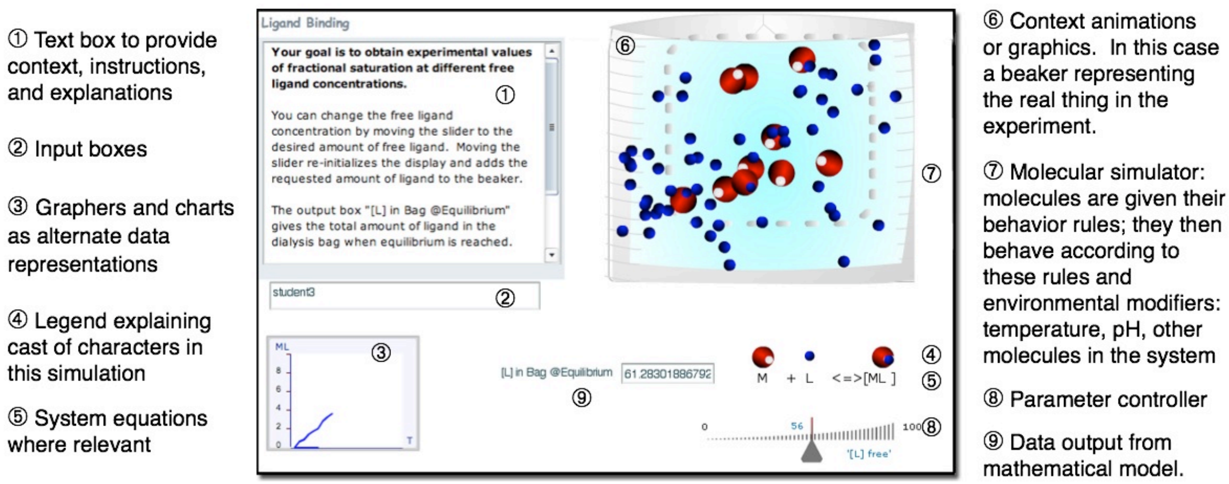
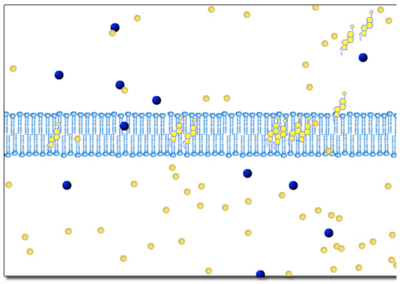


Figure 2: The assembly presented in Figure 1 uses many of the tools currently available to an instructor and would typically be used for student assessment. Figure 2 shows a much simpler presentation in which only the visual display is used. This simple form would be suitable for an in-class demonstration or for retrospective feedback. It is important to note that the underlying code that was used to generate Figure 1 is essentially identical to that used to generate the display in Figure 2.

How do these models differ from the interactive animations of the past? Animations are to simulations what multiple choice questions are to essay questions. In the case of an animation, the author predefines some sequences and branch points. The student moves through the animation using the navigation tools provided, but can only make the predetermined choices of results that the author has previously animated; the role of the student can be quite passive. In the case of our simulation models, the instructor describes the rules and behaviors of the objects in the model and the objects animate themselves based on their pre-described characteristics in response to the student directed changes in the environment of the molecules. In this way, the simulation will react to the changes in the environment that the instructor allows the students to control. Visualizations constructed in this way become interactive learning opportunities for the student and provide an opportunity to explore the behavior of a physical system at a much deeper level than previously possible. (National Research Council, 2003)



Constructed as a dynamic model, the illustration at the left can allow students to speculate on the probabilities that the cholesterol molecules in this moving simulation will become trapped within the cell membrane. As they watch the resulting behavior, they can be prompted to explain the behavior or allowed to modify their previous prediction and allow the illustration to restart.

Figure 3: This model could be used as a classroom demo, or embedded in a text explaining membrane permeability.

While our models do not come close to matching the capabilities of discreet object simulation that state of the art computational science is capable of, the number of potential physical processes that can be easily portrayed using the simulator platform is quite exciting. Our models are providing visual interactions that illustrate the concepts we are teaching in our courses.

In addition to setting the behavior of the molecules, the instructor can also assemble a series of steps in the tutorial, usually an overview, some instructions or explanations to the student, perhaps some initial displays, and then the simulation. By using dynamic models in the animations/simulations that we are building, the instructor can quickly create another example by modifying the behaviors of the model or some other parameter within the environment; i.e. the permeability of a membrane to a specific molecule, the affinity of one molecule to bind with another, the pH of the solution. If these models contain accurate computational data models underneath, the simulator can provide and grade unique computational exercises to each student. Depending upon the script provided by the instructor the simulation may provide lots or little opportunity for control by the student.

From the student's perspective, they are presented with an open-ended, relatively unscripted, opportunity to investigate a physical process. Since the manipulation of the system can be student driven, it is not necessary for the instructor to provide specific positive or negative feedback to the student as they progress through the tutorial since the students can use the behavior of the molecules within the system for guidance. If they predict a certain behavior and do not get that behavior, then as true scientists they must re-evaluate the initial conditions for the experiment, their hypotheses and their results. They can then redo the experiment or try to explain their results. Consequently, students will take a more active role in learning.

Future Work

There are several challenges that still need to be addressed. First, we recognize the need to develop our expertise as instructors in authoring more effective uses of these model-based visualizations as well as doing more assessment of the effectiveness of these learning materials. The second is to facilitate dissemination of this material for use by other instructors, in particular those at other institutions. One of the key challenges here is to make the use of existing materials seamless by packing the animations and virtual labs so that they can simply be transferred to other servers.

Summary

Providing students with opportunities to acquire concepts in a way that they can immediately relate to real situations helps them in constructing their own knowledge. Immediate practical application of concepts allows them to make correlations, or draw conclusions, much faster than they would if only given textual information. Stimulating scientific discovery through contextualized "real world" simulations, with hidden models, generates opportunities for students to manipulate these simulations in order to discover and validate their own mental models. By constructing a collection of dynamic models for use with our students, we are providing authentic activities with built-in feedback. These dynamic visualizations have compelling implications for online learning where the timeliness and nature of the feedback provided to the student is critical to his or her learning.

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