# Development of a virtual cell and molecular biology laboratory environment for StarCellBio, an experiment simulator

## Abstract

StarCellBio is a new inquiry-based cell and molecular biology experiment simulator that is currently under development. StarCellBio's goal is to enhance student learning of core biology concepts and procedural knowledge in traditional and online courses by providing students with the opportunity to participate in all aspects of experimental design and process in a simulated lab environment. The funds requested for this project will be used to design and develop visualizations, animations and videos to create a virtual laboratory environment that enhances the learning experience of students using StarCellBio. Currently, StarCellBio allows students to design and execute simulated cell and molecular biology experiments, producing realistic results that students then analyze and interpret. In its current state, the program focuses on allowing students to conduct experiments virtually. The additional multi-media resources that we propose to incorporate into StarCellBio will serve to illustrate all aspects of experimental design, process and analysis for complex biology experiments. The development of the basic StarCellBio software is funded with an NSF TUES 3-year grant and with limited additional support from Graham Walker's HHMI Professorship, but these funds do not cover the additional, but essential, work of developing a virtual laboratory environment and help features for StarCellBio. The addition of visualizations, animations, and videos to StarCellBio will more faithfully represent the processes of scientific inquiry, which is one of StarCellBio's primary educational goals, and will play a vital role in enhancing the program's educational experience, particularly for students at MIT and elsewhere who have not had significant first-hand experience with experimental science. StarCellBio will be implemented in undergraduate cell biology education at MIT and other institutions, and is being developed for future implementation in MITx online courses, thereby reaching a wide audience worldwide.

## Background

### StarCellBio: A powerful new biology education tool being built through a collaboration of experienced MIT teams

We are developing, implementing and evaluating a freely available, inquiry-based educational software program called StarCellBio to enhance the teaching of core biology concepts and competencies at MIT and other institutions worldwide. The goal of StarCellBio is to enhance conceptual understanding as well as teach experimental design and reasoning by providing students with firsthand opportunities to participate in all aspects of experimental design and analysis. Therefore, StarCellBio aims to introduce the sensibility of actual research into cell and molecular course assignments due to the dearth of experimental laboratory components in traditional cell and molecular biology courses at most undergraduate institutions. In addition, StarCellBio will enable instructors to expand the use of active, inquiry-based approaches to other areas of the biology curriculum. StarCellBio is a collaboration between MIT faculty members, Professor Graham Walker and Provost Chris A. Kaiser; research scientists, Lourdes Alemán, Ph.D. and Alison Brauneis, Ph.D., who are core members of Professor Graham Walker's MIT HHMI Education Group; and a developer, Ivica Ceraj, from the Software Tools for Academics and Researchers (STAR) team within the Office of Educational Innovation and Technology (OEIT) at MIT. To develop, implement, and assess StarCellBio, this collaborative team was awarded a three-year NSF TUES (Transforming Undergraduate Education in STEM) grant in 2011.

This same collaboration between faculty members, the MIT-HHMI Education Group and OEIT's STAR team has already resulted in the successful development and implementation of StarBiochem (http://star.mit.edu/biochem/) and StarGenetics (http://star.mit.edu/genetics/), two powerful, freely available biology education visualization and simulation software programs that have been incorporated in to multiple MIT courses and are being widely used around the world. StarBiochem is a molecular 3-D visualizer designed specifically for education to enable the visualization and manipulation of any Protein Data Bank structure, while StarGenetics is a customizable genetics virtual laboratory that allows students to perform genetic crosses with model organisms, such as Mendel's peas, fruit flies, and yeast, as well as non-model organisms such as cows.

**The educational goals of StarCellBio**

By embodying the principles that underlie the success of StarBiochem and StarGenetics, StarCellBio will enrich the teaching and learning of experimental design and reasoning by providing students with the opportunity to propose hypotheses, perform experiments, and interpret the generated data from their own simulated cell and molecular biology experiments. Within an assignment in StarCellBio, students are first prompted to propose a biological question they would like to investigate or a hypothesis they would like to test. Then, students design an experiment to address a specific question or hypothesis. While setting up their simulated experiments in StarCellBio, students can vary many experimental conditions such as: single or multiplex treatment combinations, treatment concentration(s), time of treatment(s) initiation, duration of treatment(s), and collection time points. This allows for a great deal of flexibility in the degree of experimental complexity presented to a student within a StarCellBio assignment, which is similar to real laboratory experimentation. Once students have set up an experiment, they will be able to analyze their samples through three different experimental techniques: (1) western blotting, (2) flow cytometry, and (3) microscopy. StarCellBio uses simulated and real data to provide realistic experimental results. We believe that exposing students to realistic experimental results, even in courses that do not have a laboratory component, will introduce them to the notion that experimental variability often results as a direct consequence of the stochastic nature of biological processes, a concept that is often overlooked in most biology courses. As a consequence, students will be required to think about the meaning of reproducibility when justifying their assumptions and explaining their results. Currently, we generate experimental variation within StarCellBio by using probabilistic, randomized models for all the computations performed by the software to generate results.

**Progress to date**

During the first NSF TUES grant funding year, we (i) assembled a team of experts, (ii) developed a StarCellBio prototype, (iii) obtained feedback on StarCellBio's usability and functionality from MIT undergraduates students, scientists and instructors, (iv) enhanced its usability and functionality through work with user interface and graphical designers, and (v) began implementing an assessment plan. StarCellBio will be used for the first time in cell biology courses at MIT (7.06) and Tufts University this spring.

**Feedback on the StarCellBio prototype**

Following the development of a StarCellBio prototype, we collected feedback through a focus group composed of MIT HHMI Education Group members who have strong interests in education innovation and through a prototype test with MIT undergraduates taking MIT's Experimental Biology & Communication course (7.02). In both cases, users were asked to evaluate (i) the qualitative look-and-feel of StarCellBio's graphical user interface; (ii) ease of usability of StarCellBio; (iii) StarCellBio's ability to simulate meaningful cell biology experiments; and (iv) the tool's ability to support learning of core biological concepts and experimental inquiry. Among the focus group participants, the most consistent improvements and new

features that were suggested were to add "*visual representations of what is being done*", "*animations of experiments*," "*a roadmap of the process*", and "*a visual representation of [the] experimental setup to prevent mistakes*". When we asked 7.02 students to rank the features that should be considered during future development of StarCellBio, the two most important features were (a) the ability to perform experiments in multiple sessions (30.9% of students, n=56) and (b) incorporation of visual representations of experimental details and help features (26.8% of students, n=56). Feedback from scientists and students clarified that developing an authentic experimental experience will require not just realistic representations of experimental results, which we believe the current StarCellBio prototype does well, but also the creation of a more complete laboratory environment and experience.

## Proposed work

When properly executed, the role of visualizations, animations and virtual environments is well known to enhance the learning experience, particularly of concepts and procedures that do not translate well with traditional methods of learning (de Jong, 2006; De Jong and Van Joolingen, 1998; Garrison and Anderson, 2003). Our experience with the StarCellBio prototype has convinced us that creating a realistic experimental environment in StarCellBio will require the addition of visualizations, animations, and videos to the current prototype. We are therefore requesting Alumni Class Funds to address the critical need of developing and incorporating visualizations, animations, and videos in StarCellBio so that StarCellBio can most effectively achieve its two main educational objectives: (i) to enhance the learning of basic cell biology concepts and (ii) to teach students about experimental design and logic. The work proposed here will be focused into three different and complementary projects:

1) *Development of an experimental set-up summary feature*. The experiment set up in StarCellBio is very complex, containing numerous options regarding variables and conditions. Currently, the various experimental choices available to students are represented in text form with a series of dropdown menus because it allows students to design complex experiments without utilizing a lot of space within the program's user interface (Figure 1). To better communicate and relate real-life laboratory set-ups, we will design a new feature that will visually summarize a student's experimental set-up. This feature will simulate how scientists plan and execute experimental set-up in the lab by utilizing simple drawings that symbolize samples and drug treatments in conjunction with calendar-like features to indicate complex time variables such as treatments, treatment duration, and collection times. This visual summary feature will present the experimental set-up in a simple visual manner to help students identify the experimental controls and parameters missing within their experiments.

2) *Development of a virtual lab notebook within StarCellBio*. An important component of performing experiments in the lab is learning how to document the experimental process: generating a hypothesis, designing a well-controlled experiment, analyzing and interpreting data, generating conclusions and trouble shooting experiments. In the current prototype of StarCellBio, students conduct experiments within the software program, but produce their reflections on the experimental process, data analysis and conclusions on paper. In addition, students must submit a paper version of their assignment and experimental results to their instructors. To allow for students to easily document, annotate and reflect on their experiments in a completely electronic manner, we will develop a virtual lab notebook for StarCellBio. The lab notebook feature will contain the actual assignment, as well as background material and readings, and a complete record of a student's experimental processes and results (Figure 2). In the lab notebook feature, students will be able to annotate their lab notebooks with their analyses, interpretations and conclusions of their experiments, just like in a real laboratory. The lab notebook will not only serve as a record of students' experimental design and process but will also contain a feature that will allow students to submit a report electronically to their instructors.

3) *Illustration of relevant concepts, experimental techniques and experimental processes*. To help students understand the core biology concepts and the techniques within the program as well as teach experimental design and logic, we will develop detailed visualizations, animations, and videos for the program. The primary users of StarCellBio will be undergraduate students in introductory cell and molecular biology lecture courses. Some of these students, particularly those in the more advanced cell and molecular biology courses, will have a strong biology background, but most will not have prior hands-on cell and molecular biology laboratory experience. As a result, illustrating core concepts, experimental design and relevant techniques is of utmost importance for an effective learning experience when completing a virtual laboratory assignment. This spring in 7.06, StarCellBio will include a primarily text-based reference library on experimental design and techniques. The necessary visualizations and animations to better communicate and illustrate complex concepts and steps within experimental procedures that are impossible to observe by eye and difficult to convey through text-based or other traditional media will be lacking in the first reference library prototype. Examples of visualizations and animations that will be developed include proteins moving through a three-dimensional gel matrix in western blotting or the amount of DNA content detected inside individual cells in flow cytometry. To illustrate how these techniques are performed in a real laboratory environment, we will create short videos documenting MIT undergraduate and graduate students conducting these techniques. These videos, termed "In the Lab" videos, will be featured in various locations throughout StarCellBio, including the experimental set up and technique pages (Figure 3). In addition, these videos will also serve to illustrate experimental design and process in a real laboratory, by showcasing components of experimental design, including how to design well-controlled experiments, specific controls required for specific techniques, common operator errors, and strategies for troubleshooting experiments, amongst others. The visualizations, animations and videos will all reside within the reference library resource in StarCellBio, which can easily be accessed on every page of the program.

## Assessment

It is of utmost importance to us to assess the effectiveness of StarCellBio at enhancing students' learning of cell biology and experimental science concepts. With assistance from the Teaching and Learning Laboratory, we designed an assessment plan to evaluate impacts and outcomes of StarCellBio development and deployment on the learning and educational experiences of students. The assessment plan for StarCellBio consists of collecting both pre- and post-implementation data using a mixed-method approach and is guided by the following questions:

> (1) To what extent does StarCellBio provide a virtual learning environment that simulates aspects of biology experiments and is intuitive, easy and fun to use?
> (2) To what extent does StarCellBio improve student learning, with specific focus on the ability to design, conduct, and interpret hypothesis-driven experiments?
> (3) To what extent does StarCellBio provide a positive educational experience and promote student interest in the biological sciences?

Of particular interest in relationship to the work proposed in our Alumni Class Funds proposal is question 1. With this in mind we have modified our assessment plan to include items that will directly assess the proposed work. What follows is a summary of the assessment plan for StarCellBio, with the modifications that we have made to this plan to address question 1 more specifically in relationship to the proposed work.

*Pre-implementation.* The first StarCellBio implementation in 7.06 this spring will focus on one cell biology topic, the cell cycle. In spring 2012, in collaboration with the professors who teach MIT's cell biology course

(7.06) and with assistance from Dr. Glenda Stump, we collected pre-implementation baseline data while StarCellBio was still under development by administering a concept quiz, which consists of a diagnostic experimental question focused on this cell biology concept, the cell cycle, before and after learning about this cell biology concept in the course. This same concept quiz will be administered in the same manner this spring 2013, in which StarCellBio will be implemented. By comparing the results from 7.06 students this spring 2013 with those of students who took 7.06 last spring, we will be able to quantify learning gains in critical cell biology experimental reasoning and logic that are the result of experience with StarCellBio. As previously mentioned, we also obtained feedback on the StarCellBio prototype from undergraduate students, scientists and instructors, which served as the impetus for the proposed work.

*Post-implementation.* In addition to administering the concept quiz, we will also collect additional post-implementation data during this spring to assess StarCellBio's effectiveness at enhancing student learning of experimental design, process and analysis. This additional data will be collected through direct and indirect instruments: (i) homework exercises, (ii) exam questions, (iii) student interviews, and (iv) student surveys. Any increase in students' mastery of cell biology concepts and growth in experimental thinking before and after StarCellBio implementation this spring will be taken as indicators that StarCellBio has successfully met its stated educational goals.

To assess the effectiveness of the illustration work proposed in this grant (visualizations, animations and videos), we will incorporate questions within the student interviews and student surveys that addresses the ability of the proposed work to provide a virtual laboratory environment that more closely simulates the experience of performing experiments and that guides students through experimental design and process. A corresponding survey instrument will be administered to 7.06 graduate student teaching fellows to assess the implementation process, locate any needed improvements for future StarCellBio implementation efforts, and collect feedback on the ability of the proposed work to provide a more real-life laboratory experience, and adequate resources on experimental techniques and experimental process to students. In addition, we will continue to employ our focus group to provide feedback throughout the implementation of the proposed work.

## Resources

To develop the experimental set-up summary and the virtual notebook features detailed in projects 1 and 2, we will work with user interface and graphic designers, both of whom we have prior working relationships. To develop the complex biological visualizations and animations detailed in project 3, we will work with a graphic designer who has a background in biomedical illustration. The videos included in project 3 will be filmed in MIT biology labs, with the assistance of undergraduate and graduate student volunteers, and the Academic Media Production Services (AMPS) office at MIT.

Coordination and project management of these three projects will be conducted by MIT-HHMI Education Group members, Drs. Lourdes Alemán and Alison Brauneis, with guidance and feedback from 7.06 professors, Professor Terry Orr-Weaver and Professor Iain Cheeseman, Provost Chris Kaiser, and supervision from Professor Graham Walker.

## Impact

The advancement and rapid growth of online capabilities and courses is revolutionizing how undergraduates are taught, both at MIT and globally, and will continue to mold learning altogether in the future. Since StarCellBio is a completely web-based educational experiment simulator, StarCellBio will suit many educational endeavors, whether in a traditional course with an online component or an entirely online course, such as an MITx course on the edX platform. The creation of customizable software tools,

such as StarCellBio, that allow students to conduct experiments virtually will become an important component of delivering high-quality instruction in engineering and science courses at MIT and other institutions. We anticipate that the number of students without that could benefit from the proposed work will increase dramatically once StarCellBio is incorporated into an MITx course, increasing from approximately hundreds to hundreds of thousands of students each year.

We believe that simulating a realistic laboratory environment and explaining complicated biology concepts, laboratory techniques, and teaching about experimental design and logic through the proposed work will be vital for enhancing the program's educational experience for students at MIT and elsewhere. In particular, these visualizations and animations will be crucial for students who have not been previously exposed to experimental design and cell biology experimental techniques and for courses that are devoid of a real-life lab component and are relying upon StarCellBio to provide students with an accurate representation of experimental science.

## References

De Jong, T. (2006). Computer simulations. Technological advances in inquiry learning. Science *312*, 532-533.

De Jong, T., and Van Joolingen, W.R. (1998). Scientific Discovery Learning with Computer Simulations of Conceptual Domains. Review of Educational Research *68*, 179-201.

Garrison, D.R., and Anderson, T. (2003). E-learning in the 21st Century. A Framework for Research and Practice. Routledge.

## Figures

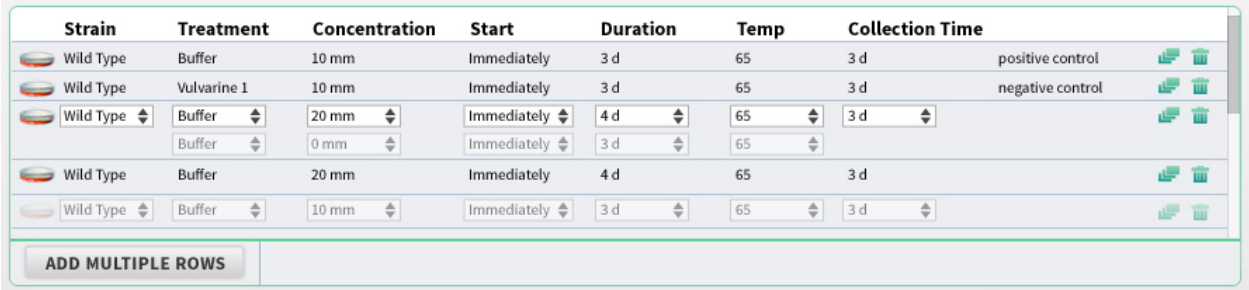


**Figure 1.** *Experiment Set-Up Window*. The experiment set-up window is currently text-based. Students use a series of dropdown menus to select all the conditions for their experimental treatments.

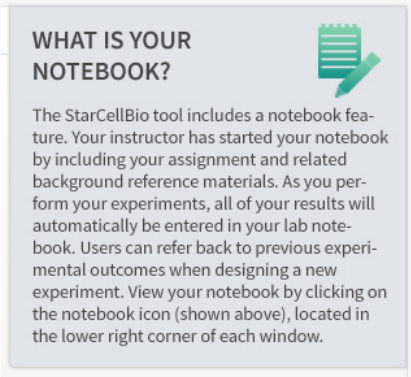


**Figure 2.** *Lab Notebook Feature*. The introduction to the lab notebook feature and icon within StarCellBio.


**Figure 3**. *In the Lab Feature*. The current graphic design plan to feature the "In the Lab" resources, including videos, visualizations and other media, to inform students of how experimental processes occur in a real laboratory environment.