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Interactive and Adaptable Cloud-based Virtual Equipment and Laboratories for 21st Century Science and Engineering Education

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Abstract

This paper presents and discusses the use of simulation-based customizable online learning activities, virtual laboratories, and comprehensive e-Learning environments for teaching subjects such as materials science, chemistry, and biomanufacturing. The virtual equipment and lab assignments have been used for: (i) authentic online experimentation, (ii) homework and control assignments with traditional and blended courses, (iii) preparing students for hands-on work in real labs, (iv) lecture demonstrations, and (v) performance-based assessment of students' ability to apply gained theoretical knowledge for operating actual equipment and solving practical problems. Using the associated learning and content management system (LCMS) and authoring tools, instructors kept track of student performance and designed new virtual experiments and more personalized *learning assignments for students. Virtual X-Ray Laboratory and Web-based Environment for Single-Use Upstream Bioprocessing have been used to illustrate the implementation of the concept of Interactive and Adjustable Cloud-based e-Learning Tools. The paper discusses the implementation of virtual labs and e-learning environments at two-year and four-year colleges and universities in the USA, UK, Russia and some other countries. The virtual X-Ray lab has also been integrated with the MITx course delivered via the MOOC (massive open online course) edX platform for Massachusetts Institute of Technology undergraduate students.*

Today, online courses in natural sciences, engineering, and technology offered by many colleges and universities around the world lack hands-on practice that is an essential part of any conventional science or engineering curricula. Interactive virtual laboratories (v-Labs) and comprehensive e-learning modules and environments can facilitate authentic online experimentation and partially substitute actual equipment. V-Labs can also supplement and extend physical labs and address some educational drawbacks and limitations of real, fully computerized equipment. In addition, realistic virtual copies of contemporary research and production equipment can address the shortage of such equipment in developing countries and increase the inclusiveness of quality education.

The presented interactive virtual laboratories and e-learning environments developed by ATeL [1] are grounded in educational research findings and meet the learning habits of today's students. Highly interactive simulations that form the core of virtual labs and environments incorporate a solid science/math model that accurately reproduces the design and operation of actual devices/systems, natural processes, or learning situations. Simulations facilitate online experimentation and exploration and enable students to theoretical concepts and principles in the context of their practical applications. Extendable sets of customizable self-directed online assignments (or virtual experiments) included in the system are used to achieve particular learning or training objectives. Each assignment in addition to a one or several simulations comprises instructional, assessment and educational resources that can be adapted to student levels and backgrounds. Associated learning and teaching resources for 'just-in-time' learning are based on the uniform constructivist pedagogical approach and conceptually organized in such a way that they complement and reinforce each other allowing students to tackle the leaning subject from several directions. Synchronized auxiliary simulations that extend the functionality of the main simulation (e.g. visualize hidden processes or explore phenomena from different perspectives) may also be included.

v-Labs could be easily integrated with various offline and online courses including those delivered via MOOC (massive open online course) platforms. The complimentary authoring tool enables an instructor to tailor an online activity to specific learning objectives, students' levels and backgrounds.

Simulation-based online modules can run in four different modes.

- *Tutorial* mode introduces students to the major processes and equipment design and operation.
- In *Practice* mode students, following scenario and step-by-step instruction, performs interactive virtual assignments that perfectly mirror common workplace tasks.
- In *Assessment mode*, performance-based and sequential tests provide faculty with reliable data on student skills and understanding and help students self-evaluate their knowledge and progress.
- *Interactive Manual* mode sequentially visualizes procedures and steps demonstrating how to perform them to accomplish a required task.

Virtual X-Ray Laboratory

The virtual X-Ray Laboratory (v-XRLab) [2] has been designed as a flexible and adaptable e-learning tool for academic education and skills training. It enables undergraduate and graduate students and industry trainees: (i) to become familiar with nondestructive research and testing methods widely used in science and industry, (ii) to explore the design and operation of X-Ray equipment and its major parts, (iii) to perform authentic laboratory experiments and workplace tasks online, using fully functional virtual X-ray equipment, and (iv) to contextually learn underlying scientific and engineering principles and laws. Through on-line and blended activities, students gain practical skills required for conducting actual experiments, collecting, analyzing and interpreting experimental data, and examining the instrumental factors affecting data accuracy.

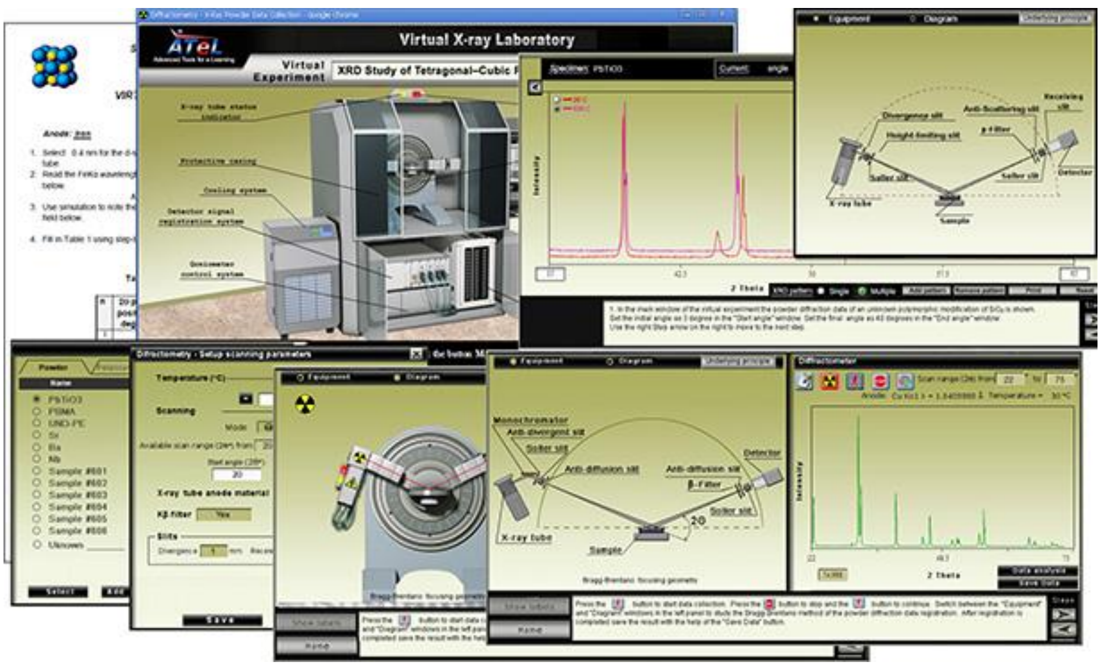

Figure 1. The *Virtual XRD Powder Diffractometer:* Screenshots of a virtual experiment

The v-XRLab includes highly interactive virtual X-ray equipment that realistically reproduces the generalized design and operation of actual equipment. Associated simulations accurately model the relevant physical processes. Over the course of an online experiment, following the detailed instruction, the student sequentially executes all standard procedures performed in a similar actual experiment.

Figure 2. Screenshots of a virtual experiment (left); Students and faculty of the U.S. and Russian universities jointly perform an online experiment using the v-XRLab and communicating via WebEx (right); v-XRLab embedded into the MITx course running on the edX MOOC platform (far right).

A complementary authoring tool enabled instructors to easily create new experiments and modify the existing ones to better match specific course objectives or training needs. The experiments could be substantially different to match the great diversity of course subjects, student majors, educational goals and settings. The collection of virtual samples available for online experimentation included alloys, ceramics, polymers, nanostructured materials, and thin films. Instructors were able to add their own virtual samples to the collection.

Virtual Single-use Biomanufacturing Learning Environment

Virtual learning environments and v-Labs are especially useful in teaching students the fundamentals of processes with long timescales. Cell culture operations in biopharmaceutical manufacturing operations are one example of this. Typical mammalian cell culture processes in a laboratory environment take 7+ days to complete. Because of this timescale, learning opportunities must follow well established protocols. Additionally, there is minimal feedback on the status of the culture during operation. Therefore, it is practically impossible for a student to operate a bioreactor in such a way as to develop an understanding of key relationships between critical parameters. Conversely performing similar experiments in a virtual environment allows students to perform multiple repetitions, while changing important parameters, in less time than it takes to physically set up a bioreactor in a lab. Such rapid experimentation and feedback cycles allows students to better cement key concepts and relationships in their minds driving understanding.

The cloud-based interactive and comprehensive virtual Single-use Biomanufacturing Learning Environment has been developed and implemented to address the needs of biopharmaceutical education and professional training. It includes a set of simulation-based v-Labs, virtual production line, as well as online lessons, assessments, a glossary, and supporting materials.

Figure 3. Screenshots of the Cell Growth lab, where a student can virtually assemble a disposable bioreactor and related production system and calculate an initial amount of buffer and cell culture. Then, he/she loads the system and controls the cell growth and performs the required procedures such as calibrating sensors, taking and analyzing probes, maintaining the appropriate temperature and atmosphere, etc. The system imitates abnormal situations involving the student in troubleshooting. The microscopic view visualizes the processes occurring in-side the bioreactor.

The v-Labs enable students to gain skills in performing typical workplace procedures, master the aseptic techniques of cell culture, and enhance their understanding of precautions and requirements to prevent cross contamination.

To help students build the ultimate “big picture” of upstream processing, the virtual Biomanufacturing includes an interactive upstream process flowchart diagram that allows students to explore all upstream processing procedures in detail, learn the requirements for executing the procedures, view relevant video clips, graphs, tables, and other relevant multimedia resources.

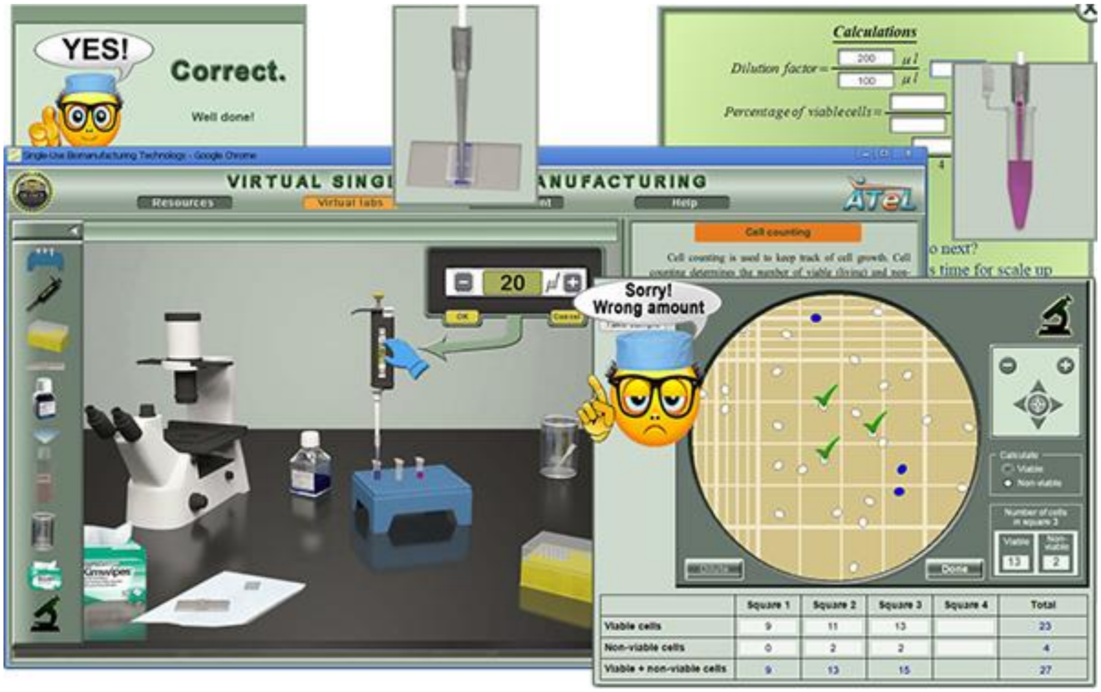

Figure 4. The virtual Cell Counting Lab helps students develop skills for accurate and consistent cell counts. The student is required to assemble his/her workplace, prepare a sample and count the number of viable and non-viable cells. Calculated data must be placed into the equations to calculate the cell processing parameters. An animated avatar provides immediate feedback, tips and comments.

The use of the latest Web technologies made it possible, in addition to self-directed asynchronous learning, to facilitate most advanced and innovative learning and teaching techniques such as synchronous collaborative learning when remote students perform an experiment together executing task procedures on peer's devices in real time. An instructor can monitor, how students carry out a virtual task and instantly intervene when necessary. An embedded authoring tool enables the instructor to modify the experiment scenario on the fly.

Results

Several online experiments using virtual diffractometer were incorporated into the undergraduate MITx course "Introduction to Solid State Chemistry" as home assignments. Students had to perform all procedures required in the actual hands-on experiment: set up scanning parameters, operate X-ray diffractometer, and analyze the obtained pattern to determine the peak position and Miller indices. Only after that, they were able to calculate the required structural parameters. Before the integration of v-XRLab students were just provided with the diffraction peak positions already ready to be used for calculations.

The virtual labs and e-learning environments have been used at two-year and four-year colleges and universities in the USA, UK, Russia and some other countries as follows:

1. As the only practice on the relevant subjects for students enrolled in large-scale lecture classes or in distance learning courses;
2. For preparing students for hands-on practice in actual laboratories;
3. For performance-based assessment of students' ability to operate the equipment and apply gained knowledge for solving practical tasks;
4. For lecture demonstrations;
5. In conjunction with real equipment as an interactive manual and for hybrid experimentation.

Students' and faculty's feedback

Students reveal that interactive v-Labs environments provided helpful process visualization accompanied by a useful overview of equipment and methods. This helped students develop a deep conceptual understanding. Students appreciated being able to perform assignments from home at their own pace at a convenient time. Students also pointed out that the combination of interactive simulations with synchronized online multimedia resources associated with experiments enabled them to perform the following actual experiment tasks faster and more meaningfully.

The described e-learning tools allowed instructors to create educational content of a greater quality, and enhance their teaching efficacy. The instructors were able to offer students a greater number of varied exercises, challenge students with practical assignments that otherwise were difficult or even impossible to offer due to the lack of time for hands-on practice and unavailability or limited availability of physical equipment. It also became possible to expand the tasks of some experiments, e.g., explore troubleshooting scenarios in biomanufacturing.

The deployment of virtual biomanufacturing laboratories at Quincy College (MA, USA) for training two-year college students and biopharma technicians enrolled in professional development programs made them comfortable to perform actual laboratory tasks, and enabled faculty to cut conventional hands-on training time by up to 40%.

The embedded LCMS allowed instructors to split students into small collaborative groups and personalized assignments.

Overall, virtual experimentation enhanced the students' confidence and fostered their self-reliant research capacity. It also helped students bridge the gap between theoretical knowledge and its practical application to analyzing and comparing diffraction data.

[1] ATeL Virtual e-Learning Laboratories, *https://atelearning.com/en-us/publications.htm*

[2] Y.E.Cherner, M.M. Kuklja, M.J. Cima, A.I. Rusakov et al., 'The Use of Web-based Virtual X-Ray Diffraction Laboratory for Teaching Materials Science and Engineering", MRS Advances, 2017, pp. 1–6.