Virtual laboratories as a tool to support learning

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Abstract: When university instructors face the need to train students on an experimental science, it means there should be a strong load of learning how to work in a laboratory, to understand the techniques, and to interpret results. However, it is often the case that there are difficulties associated e.g. to the lack of laboratory space, instrumentation or time in the course schedule. This article presents some guidance that may help in choosing, designing and particularly implementing practices around virtual laboratories and other simulations of experimental environments and techniques. The objectives are to provide a more active and significant learning, by engaging students in the process, to support and facilitate the practical sessions and, in cases where real experiments are not feasible, to provide some alternative exposure of the students to the laboratory work.

Keywords: active learning; education; laboratory; practicals; simulations; techniques; training; virtual labs.

Introduction: the challenge

This article aims to reflect on some challenges related to the practical part of science courses. When university instructors are facing the need to train students on an experimental science, it means there should be a strong load of learning how to work in a laboratory, to understand the techniques, and to interpret results. A significant part of this deals with the students gaining knowledge as well as hands-on practice with both classical and more recent techniques, like molecular analyses and genetic diagnoses, which are perhaps among the most difficult to implement in a real practical laboratory.

The most common limitations that hamper this task include the need for laboratory infrastructure—and often the lack of it—, like space for large groups and access to specialised, sophisticated, expensive instrumentation. One may also add the difficulties associated with obtaining biological samples and the precautions to be taken regarding biohazards, in the hands of inexperienced students. Finally, time limitations in the course schedule, together with a high number of students, may also complicate or prevent the implementation of practical laboratory sessions.

We will not try to offer a list of resources or solutions, but rather to bring some reflections and thoughts, to apply some critical analysis and to suggest what to watch for when searching for teaching and learning resources and when designing strategies for their use.

Methods: before coming to the lab

One approach that may help improve the learning in the experimental part of a course deals with thinking about...
offering the students some pre-laboratory materials. One should elaborate such materials, or select among available ones, then follow a careful planning in offering them to the students and, importantly, formulate assignments to encourage or even force the students to work with the material before attending the laboratory.

Among the benefits of using pre-lab material we may list: to help become familiar with the techniques before actually using them, to gain knowledge about the fundamentals of the experimental procedures and techniques, and to get acquainted with the instrumentation and how to use it.

Experience shows that explanation by the instructor, in front of a group of students in the lab, of how to assemble and prepare an SDS-PAGE gel is more time-consuming and ineffective than having the students watch a selected 4 min video that explains and displays the procedure, before coming to the laboratory. This is particularly so when the video uses the same brand and model of gel casting device and electrophoresis apparatus that will be used in the practical.

Moreover, the length of time required in the laboratory is reduced, which benefits logistics and helps reduce student stress brought by long sessions. Finally, and most relevant, the stay in the laboratory is likely to be more profitable, favouring more independent work, a better concentration on the meaning of the experiments rather than on trying to find out which is the next step to follow in a recipe-style procedure, and, ultimately, a better assimilation of the underlying concepts involved in the experimental technique.

Materials: first approaches and concerns

Among the most obvious strategy for designing this pre-lab experience is the selection and inclusion of online resources like videos, animated diagrams and simulations. There are plenty of them nowadays, but a careful selection by the instructor is needed to achieve efficiency in learning. Some important questions to pose while making this selection are discussed next.

Is the resource truly interactive?

Many multimedia items are attractive and useful, but for more significant contribution to comprehension and productive learning it is preferable that the learner is not a passive recipient of information but instead must get involved in the experience e. g. clicking, choosing among options, etc. The more interaction and flexibility, the better; advancing along slides in a presentation is not bad, but not the best. There is no need to expand on this here, since there is a lot of bibliography about the benefits of active learning.

Can you change conditions?

Is the process flexible? Can you pick different samples, or change conditions of the assay or technique, and obtain results accordingly? This makes for a more significant and enriching exposure, closer to real practice. It also opens the way for autonomous exploration which, again, is a well-known path to more productive learning. Finally, is it possible to get different results, even negative results? Simulations that always proceed correctly all the way up to the expected end are less valuable.

The proliferation of television series where the chromatographic analysis or the DNA tests produce, in a matter of hours, an indisputable conclusion is not helping the concept that science is not absolute certainty and laboratory tests are sometimes not conclusive.

When to use it?

One should consider, depending on the features of the resource, whether it is best applied for training before coming to the laboratory, as a complement during the practical session (maybe using idle time in the experiment) or as reinforcement after finishing the practical work. All of those moments are possible and useful. Furthermore, depending on the already mentioned limitations, it may be a question of either complementing or wholly replacing the actual hands-on experimentation in the wet lab. It is best that the resources are used to reinforce the actual experimentation, such as going again through the procedure, or repeating the assays in a simulator but employing different conditions or samples. Yet, when the actual laboratory is not feasible, at least the students may be exposed to the techniques in a simulated or virtual way, which will certainly be better than no experience at all beyond a theoretical explanation.

Features to aim at

Without pretending a comprehensive listing, which is a difficult task for the diversity of subject areas in (bio)molecular sciences and given the continuously evolving
landscape of the web, we will mention just two illustrative examples, to showcase the principles and critical analyses that we want to convey.

The first one is a collection of pre-lab interactive simulations (Figure 1) developed by Learning Science™; you can find out details in their website [1], ask for guest access to explore them, or visit a small set of free examples by becoming a user in the FEBS Network [2]. There is also a recent article [3] that not only presents the use of these, but ponders on wider goals and ways to enhance the laboratory experience.

The second set of examples is the techniques and virtual labs section at Biomodel.UAH [4] which has been developed with these principles in mind. Some examples with more details are presented below.

**Results: make it a learning experience**

To avoid the possibility that the student just browses the resources, playing them forward up to the end without really getting involved, it is paramount that any learning resource is offered with some accompanying activities. Instructors—whether the resource is their own or borrowed from somewhere else—should prepare a challenge, a task, an activity, or some questions, so that the student is forced to get engaged in the resource as an active participant. The resource should then be just the tool to solve some conceptual problem designed by the instructors according to the particular learning objectives in their course and group of students. The focus is not the technology, the informatics, the media, the visual effects … but the concepts, the ability to find solutions, to investigate. This is the path to learning by doing and to deep understanding.

As an example, apparently of a low complexity but which serves to illustrate the point, let’s examine a simulated SDS-PAGE electrophoresis of proteins [5] (Figure 2).

First of all, the actual simulation is displayed side by side with several sections that provide context: Presentation, Instructions, Analysis of results, Practice, and Terminology.

The Practice section contains four exercises:

A. **Influence of the applied voltage** proposes to run four experiments selecting in turn the different potentials available in the power source, and then to answer the question: *Which is the effect of an increase in the voltage applied between both electrodes?*

B. **Influence of the acrylamide concentration** proposes to run the simulation with each of the four concentrations of acrylamide in the gel, capture the results or write down the mobility of the standard proteins and answer the following questions: *Which is the effect of an increase in the acrylamide concentration that forms the gel? and How can you interpret the result, in terms of the mechanism of separation?*

C. **Self-assessment of results for molecular mass** requests to analyse one or more of the unknown samples provided, measure mobilities of each band and estimate the molecular masses by interpolating in the calibration line made with the standards.

D. **Determination of quaternary structure** proposes some numerical problems, related to multi-subunit sample proteins, which need the calibration curve to be solved.

All those activities may be performed by students without supervision, at their own pace, since they are assessed automatically.

**Figure 1:** Two virtual activities related to the proper use of pipettes and a calibration curve. Taken from ref. [3], Creative Commons BY-ND Licence.
Another example is a simulation of column chromatography for resolving protein mixtures \[6\] (Figure 3). This allows to select among 13 types of matrix (covering size exclusion, ion exchange and affinity) and 10 elution buffers (with different values of pH) to analyse mixtures of three proteins, either from a predefined list, or providing their custom mass and pI values, or from preset unknown samples. Apart from watching the animated separation and the plotting of the chromatogram, several activities are included in the form of questions that need running simulations in order to be solved (Figure 4).

**Discussion: for the best experience, open experimentation rather than a guided tour**

Taking into consideration the already presented rationales, one of the best solutions is to have a virtual laboratory that allows the user to choose samples and conditions, as wide as possible, and that after a proper procedure provides a simulated result that changes according to the options followed. While still permitting the use of preset protocols (particularly for less experienced users), this also allows to have users act freely and explore in a situation much closer to reality. The experiment may fail or work, but always responding to the effect of the actual conditions used.

A set of samples must have been preprogrammed inside the system, but their identities or properties are hidden to the user. They may also be randomised every time an experiment is started, providing different results for each user and so avoiding any knowledge in advance of the expected results (as it happens in real life). The user is allowed, within reasonable and technical limits, to choose any conditions, amounts, combinations of samples, reagents and procedures. Importantly, there are plenty of opportunities for repeating experiments while exploring the effect of changes in the variables. There is hence a chance for training professional abilities like experiment design, observation and analysis of diverse results.
Access to modern techniques that are not always feasible in the real teaching laboratory allows for exposing students to such important methods that may well be faced every day in their future profession.

The sources for such virtual environments are not so wide, but still there are some and more will quickly emerge in the coming years. Some are of high quality but commercial and have the drawback of financial limitations when trying to implement them; still, they are worth the investment. Others are free, and even though usually less sophisticated one can make good profit if the activities are planned carefully.

We can mention eBioLabs [7], developed at the University of Bristol and described as a ‘Comprehensive online laboratory resource for bioscience students’. The dynamic laboratory manual includes simulations, videos and instructional text, accompanied by self-help resources. But they include as well integrated quizzes, coursework submission, automated marking, feedback and tracking of activity, therefore implementing a complete environment for the students to perform their whole training in laboratory pre-, post- and during the physical practical sessions.

We can obtain good advice for our own planning by reading about their experience in running eBioLabs (quoted [8] from their site):

The primary purpose is to teach skills that cannot be taught elsewhere.

Professional, high quality material inspires confidence. … if so, students have no problem working online.

All knowledge needed to succeed in the laboratory should be in the online experimental information.

Concentrate effort on practicals run at the start of the course.

It is not necessary to fill the laboratory with computers … good achievement does not need the pre-lab material during the lab.

To balance theory and technical knowledge … it’s most valuable to teach the technical aspects of practical science.

Quiz writers must possess clarity of purpose, know the experiments.

Have well-designed questions and use question banks … so every student will see a different set of questions.

Not too much, not too little information in the printed lab book … pays close attention to student feedback.

More preparation work leads to less post-lab work. The post-lab should not ask questions that may be answered without doing the practical.

Maths and data handling are most challenging … provide contextualised support material.

Difficulties were actually more with basic computer operations such as saving and retrieving a file.

Students are the best quality controllers … Give them every opportunity to provide feedback.

Cybertory [9] is another example of a simulated environment that provides ample flexibility for choosing conditions while designing experiments and yields a realistic result (Figure 5). It is focused on molecular biology assays based on DNA sequence: restriction enzyme digestion, fragment length polymorphism, multiplex polymerase chain reaction for amplifying specific polymorphic targets, gel electrophoresis, and DNA sequencing by the dideoxy method with four fluorochromes. Other applications may be designed in addition to those currently implemented, which include diagnosis of sickle cell disease, genotyping of celiac disease, criminal scene forensics, paternity test, polymorphism in CYP450 (with relevance in pharmacogenomics), detection of coronavirus infection, and adulteration of dairy products or vegetable oils detected through mitochondrial or chloroplast DNA.

This virtual laboratory has been available for free since 2007 (2010 in English) and has been later expanded with more kinds of assay. Since then, over 200 people have

Figure 4: A partial view of activities designed to be solved using the simulation of column chromatography.

Taken from ref. [6], Creative Commons BY-NC-SA Licence.

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This virtual laboratory has been available for free since 2007 (2010 in English) and has been later expanded with more kinds of assay. Since then, over 200 people have
registered for using it with their students (January 2017 to March 2019, including yearly renovations).

Conclusions

We have presented some guidance that may help in choosing, designing and particularly implementing practices around virtual laboratories and other simulations of experimental environments and techniques. The objectives are to provide a more active and significant learning, by engaging students in the process, to support and facilitate the practical sessions and, in cases where real experiments are not feasible, to provide some alternative exposure of the students to the laboratory work.

The author is open to collaboration with interested readers in developing new resources or applications following the principles presented in this article.

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