Technical and didactic problems of virtual lab exercises in biochemistry and biotechnology education

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INTRODUCTION

It is well-known that “cook-book exercises” in science and engineering education do not fully realize the learning objectives ascribed to them. Students *do* learn basic lab skills, but highly instructed exercises do not (by themselves) support theoretical understanding or appreciation of scientific methods. With web technologies we can now design exercises for remote or virtual labs, but we should not expect to improve student learning simply by recreating old didactic problems in new media. Unfortunately studies of the efficiency of different lab types (hands-on, virtual, and remote labs) suffer from a lack of conceptual analysis of what actually constitutes *virtual labs*. A clarification of these conceptual issues is suggested as part of a Danish research and development project on virtual lab exercises in biochemistry, molecular biology and biotechnology education. The main outcome of this clarification is that *specific didactic problems of biochemistry education* can now be addressed through the design of exercises in the virtual lab environment.

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1 THE FUNDAMENTAL PROBLEM OF TRADITIONAL LAB EXERCISES

1.1 The didactic dilemma of instructional scaffolding

There seems to be a common set of problems associated with laboratory exercises and experimental work in general across different domains of science and technology education (e.g. physics, chemistry, engineering) as well as across different levels of the educational system (schools, high schools and universities). Students do not always understand the purpose of the lab exercises they perform, they do not always link exercises with underlying theory, and they do not necessarily obtain an improved conceptual understanding from doing experimental work or an appreciation of general scientific methods [1, 2, 3].

In chemical education research it has been confirmed that the main problem is the expository instructional style of “cook book” exercises [4, 5], where the experimental procedure as well as the expected results are given in advance. Students do generally not take ownership of the exercises, because they were not involved in their design. Students might not even read exercise manuals in advance, because the detailed instructions do not make much sense outside the laboratory context.

In a biochemical lab students will furthermore be supported by lab assistants that prepare materials and instruments to be used and help groups of students when they are confused about procedures or results. Sometimes lab assistants can even take over part a procedure in order to “save time”. D. Domin provides a good chemical analogy, i.e. that *instruction functions as a catalyst*: “Just as a catalyst speeds up a chemical reaction by providing an alternative lower energy pathway, the laboratory manual reduces the amount of time necessary to complete a laboratory activity by providing an instructional pathway that does not require the utilization of higher-order thinking skills. The laboratory manual has become an instrument that maximizes laboratory efficiency at the expense of fostering higher-order cognition.” [6]

Instructional support of exercises thus constitutes a real *didactic dilemma*: to some extend *cognitive scaffolding* of experimental work through instruction in concepts and procedures is necessary – even with problem-based approaches – but on the other hand, it can be a hindrance to students’ assumption of responsibility [7]. Some students report that they saw links between lab experiment and underlying theory in the later phase of report writing, but sometimes even data handling and report writing is reduced to a “fill-in-the-blanks” exercise, because of the elaborate scaffolding provided by detailed lab manuals. In a follow-up study to their original 1982-study of the role of the laboratory in science teaching, Hofstein and Lunetta concluded that despite 20 years of increased focus on active learning, collaborative learning, and inquiry-based methods, in lab instruction… ”students are seldom given opportunities to use higher-level cognitive skills or to discuss substantive scientific knowledge associated with the investigation, and many of the tasks presented to them continue to follow a “cookbook” approach” [8].

1.2 The potential of virtual lab exercises

Model-based simulations already play an important and increasing role in modern science and engineering education, and with the development of web-based technologies for 3D graphics and virtual reality we can now design exercises for online virtual labs. It is therefore natural to explore the potential of virtual labs for improving student learning and supporting student motivation and home work. On the other hand we should not naively expect virtual labs to improve student learning in and by themselves, i.e. independent of how we implement them or how they are designed. Many virtual labs are in fact highly instructed and thus follow the instructional design pattern of traditional exercises, and in this way we are probably just recreating old problems in new media.

Looking for indications about the *effectiveness of different lab types* through the research in higher education, we are however confronted with a meta-problem: comparative studies of different lab types, i.e. *hands-on labs, virtual labs, and remote labs*, are generally inconclusive [9]. One reason for this is the lack of a prior conceptual analysis of what should count as a virtual lab: in some studies a virtual lab is online animations of experiments, in other studies it is java applets running a simulation, and in other studies yet a virtual lab would require some form of 3D virtual world for implementing an online interactive laboratory environment. Ignoring such differences in empirical studies of lab types renders them useless.

2 CONCEPTUAL ANALYSIS OF VIRTUAL LABS

2.1 Formal Concept Analysis (FCA)

The key problem is that “virtual labs” is neither a well-defined concept nor a prototype concept with a consistent set of examples, but rather an umbrella-like concept covering many conceptual types. This is not as unusual as it might appear at first. In everyday language we are used to handle concepts that are both vague and flexible as demonstrated by the concepts we form of artefacts [10]. A “chair” for example does not really correspond to a single prototype artefact with a particular physical appearance (say a wooden chair with four legs), since many things may serve as chairs, e.g. an office chair on wheels, an armchair, or even a tree chunk in the garden, as long as they afford sitting, i.e. the function we collectively associate with chairs. In the case of “virtual labs”, however, we have a series of *functional properties that can be combined in different ways*. Rather than a conceptual hierarchy of different types of virtual labs we should conceive “virtual labs” as a *concept lattice* organized by the functional properties or features that can be expressed in the concrete objects (i.e. the virtual lab examples) in different ways. This provides what in Formal Concept Analysis (FCA) is called a formal context for the concept [11].

FCA is a method for exploration, analysis and visualization of knowledge and data based on the *relations* expressed by knowledge and data between particular *sets of objects* and particular *sets of attributes*. A concept lattice is a collection of *formal concepts* which are ordered by sub-concept and super-concept relations. The formal concepts arise from the construction of a *formal context* for a given domain of knowledge or data set, where the formal context is basically a cross-table of objects and attributes with an indication of the properties associated with each of the objects. A formal context K is a triple (G, M, I) where G is a set of objects, M is a set of attributes, and I is a binary relation between G and M called the incidence relation.

The idea of a *formal concept* can be seen as a mathematical expression of a well-known notion from philosophical logic, i.e. that a concept is determined by a collection of objects (its extension) which “fall under” the concept and a collection of attributes (its intension) “covered by” the concepts. The intension of a concept can be understood as its *meaning*, whereas its extension can be understood as its domain of application, i.e. the objects to which the concept applies. FCA is useful as a methodology because the formal context constructed for a data set can be seen as *a hypothesis to be explored*: once a concept lattice is generated from a formal context the examples and attributes can be explored, visualized and revised utilizing their logical relations.

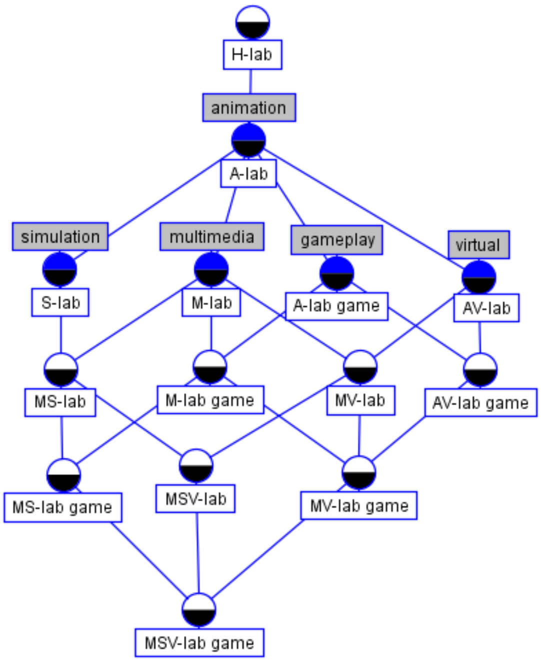
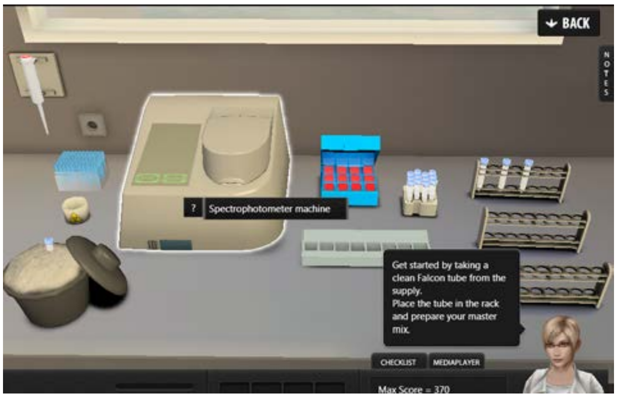


*Fig.1.*The concept lattice of virtual lab types. The features expressed at the top (hypermedia, animation) are inherited to the conceptual lab types below.



Get started by taking a clean Falcon tube from the supply.
Place the tube in the rack and prepare your master mix.

Fig. 2. A scene from the enzyme kinetics exercise of the Labster Virtual Lab. This is an example of an “AV-lab” type based mainly on hypermedia, animation and virtual reality.

2.2 The differentiating features of different virtual lab types

So what are the relevant *media features* that can be used to understand the internal variation of virtual lab types? In our preliminary studies [12] we found that the examples (the objects of the formal context) could be understood as combinations of six media features (the attributes of the formal context): *hypermedia, animation, simulation, multimedia, gameplay, and virtual reality*. All online “virtual labs” in fact utilize hypermedia features (e.g. hyperlinks) and they are therefore seen as *inherited* from the top of the concept lattice to all sub-concepts below. The use of animation is an additional specification, and this was also used by most of the examples. Simple wikis illustrating lab exercises might be an example where *only* hypermedia is used. We call this limit case “H-lab”, and the combined examples using both hypermedia and animated graphics we have called “A-lab” (“Animation lab”), cf. Fig. 1.

The main separation of the virtual lab types turned out to be effected by the utilization of model-based *simulation* (called “S-lab”, leaving out the inherited H and A), in the utilization of *multimedia* (“M-lab”), and in the utilization of *gameplay* (for readability we termed these animated lab games for “A-lab game”) and 3D *virtual reality* (for readability we termed these animated virtual reality labs “AV-lab”, cf. the example in Fig. 2). These four features can be included in virtual labs independent of each other, but they can also be combined, e.g. an “AV lab game” would be a virtual lab combining hypermedia, animation, gameplay, and virtual reality, but without model-based simulation, whereas e.g. a “MSV lab” would be a virtual lab combining hypermedia, animation, multimedia, and virtual reality, but without the element of game play. The bottom of the concept lattice defines the potential of a virtual lab combining all features in a “MSV lab game”.

2.3 Didactic properties of media features – the case of animation

But what is the significance of such a classification of virtual lab types? The importance of the different media features is that they *impose different affordances and constraints on the learning activities they support* and they therefore create different problems for the design of the didactic situations in which they are to be used [12]. Since we can know about media features and their differential cognitive support in advance, we can articulate knowledge-based arguments for the choice of different lab types in higher education independent of the empirical studies of their efficiency. We can only give a short exemplification here. Let us take the case of animation since it is used in almost all virtual labs.

"Animation" is often confused with "simulation" in a way that obscures interactive model-based simulation and data visualization in science learning [13]. The problem is that non-interactive animations are often called "simulations" even though students cannot access the underlying model, and even graphical visualizations without any underlying model (relating to the content of learning) can be called a "simulation". Animated graphics can be used as a part of a virtual lab (in biochemistry in could be to visualize a process such as an enzymatic reaction at the molecular level), but this is not in itself a model-based simulation unless students can access the underlying model and change its variables and parameters.

Discussions about animation tend to focus on a technical level of how animations are designed and transmitted rather than on characteristics of animations that are relevant to their learning potential, i.e. *the semiotic and cognitive levels involved in supporting conceptual meaning and scientific reasoning* [14]. From the didactic point of view animations do not only provide visualization of phenomena [15]. Basically we can distinguish four learning potentials of animations:

- Animations can provide visualizations of dynamic phenomena that cannot easily be observed directly and the temporal dimension can be manipulated (e.g. when representation of natural processes are slowed down or speeded up to make them observable).
- Animations can provide graphical abstractions of dynamic phenomena by schematization of abstract objects (e.g. models), relations and events as observable spatial objects, relations and events.
- Animations can support conceptual change by creating a conflict between the represented models and the mental models and expectations of students.
- Animations can (when combined with interactive model-based simulations) support thought experiments and exploration of models.

Graphical abstraction can however also have unintended effects like misplaced concreteness and fake realism, i.e. students might believe that molecules are "really" like the ball-and-stick simplifications of represented molecules or they might be seduced by colourful creative visualizations of physical and chemical phenomena into believing that this is what the world "really looks like" at a molecular level. Generally animations should – like all graphics – be designed as simple as possible, i.e. avoiding any additional features (e.g. false colours that are not used to carry information) that are not necessary for the learning objective. "Less is more" so to speak. Animations can in the worst case create an illusion of understanding, if the dynamic visualization leads to shallow processing of the animated content [15].

Another problem associated with complex visualizations (and in particular animations that are also model simulations) is that novice learners in a scientific domain will have difficulties in distinguishing relevant and irrelevant features of an animation. Too many things might happen at the same time, and novice students do not know where to look, what to look for, and what information to extract from what they see. In that sense animations can be overwhelming and paradoxically lead to superficial learning, and in the end animations might not be superior to static graphics!

A possible solution to this problem might be to provide scaffolding for the knowledge integration of students by guiding their observations through different sequential parts of an animation, and by selectively focussing their attention on different part of the represented schematic content. Alternatively a series of static graphic diagrams or images might prove to be more effective for learning because they would support students in doing the work of knowledge integration at their own pace.

Alongside these didactic properties of animations, we similarly have to consider the didactic properties of hypermedia, simulation, multimedia, gameplay and virtual reality – as well as the effects of their combinations. Given such a theoretical work, however, we can arrive at the real design issue of virtual labs in biochemistry, molecular biology and biotechnology education, namely the question of *how we can specifically support student learning through supplementary online lab exercises*.

3 VIRTUAL LAB EXERCISES AND SPECIFIC LEARNING DIFFICULTIES

3.1 Technical and didactic issues

Let us first recapitulate. We have three main types of *technical organization* of lab exercises, i.e. hands-on labs, virtual labs, and remote labs. Within the online virtual labs we have specified a set of *media features* that can account for the variability of virtual lab types. These media features are part of the technical specification of lab types. They all raise didactically relevant questions that are independent of particular implementations (such as specific web technologies). Knowledge about the affordances and constraints of a virtual lab type is a requirement for knowledge-based design of virtual lab environments and lab exercises that can address *specific learning difficulties* in e.g. biochemistry, molecular biology and biotechnology. We should remember, however, that the didactic design organization of lab exercises (of all technical types) also requires exercises to be prepared and followed up. In a study of virtual labs in control engineering education it was found that “introducing the virtual lab in the pre-lab preparation session has lead to considerable improvement in the conceptual understanding of the students during the hands-on lab session” [16].

3.2 Specific learning difficulties

In every domain of higher learning there seems to be specific didactic challenges in appropriating scientific content. New generations of students typically encounter similar problems year after year, and it is an important goal of didactic research to identify these problems, to consider why they arise, and to reflect on possible solutions to recurrent problems. Although the didactics of biochemistry have not yet been studied extensively, there are some indications that we should distinguish three types of conceptual difficulties [12, 17]:

- *Computational difficulties* in chemistry and biochemistry inherited from problems associated with basic mathematical skills (e.g. using fractions, logarithmic expressions, exponential functions, graph reading, solving equations, differential equations, linear and non-linear systems etc.).
- *Conceptual difficulties* in biochemistry inherited from *physical chemistry* (e.g. thermodynamics, chemical equilibrium concepts etc.) or *general chemistry*.
- *Conceptual difficulties inherent to biochemistry and molecular biology* such as problems in understanding enzyme-substrate interactions, problems in

visualizing complex protein structures, or problems in understanding the meaning and function of specific instrument-based techniques and procedures e.g. Polymerase Chain Reaction, Electrophoresis, and Mass Spectrometry.

We have to focus here on the latter set of difficulties and we will only look at the case of virtual lab exercises in *enzyme kinetics*. Biochemistry courses will usually include computational exercises in enzyme kinetics as well as hands-on lab exercises with measurement, computation and plotting of e.g. reaction rates of enzymatic reactions. Online virtual labs however provide an opportunity to *interactively explore the dynamics of simulated enzymatic reactions* and to develop *graph as well as model comprehension* (e.g. for reactions that follow or do not follow the Michaelis-Menten equation). As we have seen, this will require the virtual lab to include *model-based simulations* that can be accessed by students (rather than simple animated graphs).

Another opportunity provided by online virtual labs that cannot be supported in hands-on labs is the possibility to *interactively explore the functionality of the instruments used* such as the spectrophotometer in Fig. 2. By using *hypermedia, animations and multimedia* students could virtually “open up” lab instruments on different levels of detail. In the hands-on lab instruments are mainly treated as black-boxes for input of samples and for observing measurements (although students will learn the basic principles).

A third example is the opportunity for students to link the theoretical course content on e.g. enzyme kinetics with the macroscopic events of the exercise, something that does not occur by itself. One possible form of conceptual scaffolding for this could be to provide animations visualizing what goes at a molecular level, e.g. animations of enzyme-substrate mechanisms. As we have seen, it is essential, however, to help students focus sequentially on different aspects of animations (e.g. first the enzyme-substrate binding site, then the products of the reaction).

In the way indicated briefly here the design of virtual labs for biochemistry and molecular biology education should be guided by relevant didactic considerations of the involved media features and their affordances and constrains – as well as the whole didactic situation in which they are to be used. In collaboration with the software company Labster (labster.com) we are presently evaluating a virtual lab exercise in enzyme kinetics within biochemistry courses at the University of Copenhagen and at the Technical University of Denmark.

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