Chapter 10
Model-Based Inquiry in Computer-Supported Learning Environments: The Case of Go-Lab

Tasos Hovardas, Margus Pedaste, Zacharias Zacharia, and Ton de Jong

Abstract This chapter focuses on model-based inquiry in computer-supported environments, especially through the use of the Go-Lab platform (www.golabz.eu). Go-Lab is an online learning platform that offers students the opportunity to engage in inquiry-based science learning, in a structured and supportive manner, by providing environments for learning (i.e., Inquiry Learning Spaces), where virtual or remote laboratories and software scaffolds (e.g., tools for generating hypotheses and designing experiments) that support inquiry learning processes have been integrated. The purpose of this chapter is to unravel how the Go-Lab platform, especially some of its virtual laboratories, can be used for model-based learning. In so doing, we discuss core requirements for model-based inquiry in expressing, testing, and revising models. Further, we present three examples of Go-Lab virtual laboratories, with modeling and simulation affordances, to explain how they could be used by educators as means for enacting model-based inquiry.

Keywords Affordance · Guidance · Model-based inquiry · Inquiry cycle · Modeling tool

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10.1 Introduction

In this chapter we attempt to address a series of instructional and design challenges of enacting model-based inquiry with virtual laboratories of the Go-Lab platform (http://www.golabz.eu/labs). Go-Lab learning materials have been designed and instantiated in an inquiry-based context while using virtual and remote laboratories as means of exploration and experimentation (e.g., see the "learning spaces" at www.golabz.eu). For the purposes of this chapter, we attempt to show that the Go-Lab platform could move beyond the general inquiry-based approach (e.g., Pedaste et al. 2015) and support other inquiry-oriented learning approaches. In particular, we focus on the enactment of model-based inquiry, which has been reported in the literature as a rather challenging approach, but with a lot to offer learning-wise to the students (Windschitl et al. 2008a). Computer-supported learning environments, such as Go-Lab, can provide the means for a model-based inquiry enactment. Besides the virtual laboratories with modeling affordances, they can also offer guidance which can provide support to the students throughout a model-based enactment. To fulfill this purpose, we organized the chapter in the following sections: First, we define model-based inquiry and associate it with recent research of the domain. Next, we introduce our inquiry framework and explain how this framework fits the model-based inquiry approach. Then, we discuss the Go-Lab guidance tools available for supporting students when enacting model-based inquiry. We also report on the experience of the Go-Lab project to outline specific recommendations for fine-tuning guidance offered to students during their inquiry. In the next section, we present three examples which instantiate model-based inquiry in the context of Go-Lab. Finally, we draw some conclusions coming out of the three examples and discuss how these examples could inform practice.

10.2 Model-Based Inquiry in Computer-Supported Learning Environments

Models and model-based inquiry have been a primary teaching and research focus in science education during the last three decades (Clement 2000; Gobert and Buckley 2000; Louca and Zacharia, 2008, 2012, 2015; Hovardas 2016). Models are understood as scientific representations of systems or phenomena, which allow for tracing and monitoring the interrelations and interactions among the structural components that compose the system or the phenomenon at hand (e.g., McComas 2002; Matthews 2005). In science education, the term "model" might refer to mental models (e.g., Clement 2000, pp. 1042–1043; Gobert and Buckley 2000, p. 892) or external/concrete models (e.g., Louca and Zacharia 2012). A mental model reflects the initial ideas of students for a phenomenon under study. Such a mental model might be depicted by students via several means, for instance, as a paper-and-pencil drawing or by a modeling tool. Indeed, science instruction

often engages students in expressing their mental models. The idea is to construct models that align with scientific accounts of the targeted systems or phenomena (i.e., "scientific models" or "expert consensus models"). However, models employed in science education as desired outcomes of instruction might differ from fully fledged scientific models, and they might be simplified to suit learning goals, without losing their epistemological rigor (i.e., "teaching models" or "target models"). The desired transition from initial mental models of students toward target models might involve a series of "intermediate models" (Clement 2000, p. 1042). At the end of an educational intervention, student competence might be readily evaluated by the convergence of the updated mental models of students with scientific models. Student knowledge and skills would be assessed through a direct comparison of the primary aspects of the models constructed by the students with the corresponding aspects of the target models at task.

Testing and revision of models has been a prominent avenue for model-based inquiry (Campbell et al. 2013; Clement 2000; Grünkorn et al. 2014; Halloun 2007; van Joolingen et al. 2005; Windschitl et al. 2008a)[1]. A basic distinction noted in this direction has been between testing and retesting models constructed by students, on the one hand, and using ready-made models, on the other (see also Mellar and Bliss 1994). In both cases, a considerable difficulty has been to bridge models depicting student ideas, on the one hand, with scientific explanations of the systems or phenomena under focus, on the other (Soulios and Psillos 2016). A first challenge for educators has been to align target models in accordance with students' capabilities and knowledge and, at the same time, configure target models so that they retain core aspects and functionalities of scientific models. A further challenge for educators has been to plan an effective learning activity sequence (or "learning progression" for longer or larger teaching units), which would support the transition from initial models to target models. All options that have been proposed, in that direction, have involved a series of intermediate steps in modeling pedagogies (Oh and Oh 2011), in an attempt to foster reflection on alternative or gradually advancing models of the same system or phenomenon and to elaborate on their strengths and weaknesses. This has also included the utilization of empirical data to validate a model (van Joolingen et al. 2005). Overall, a trajectory would be traced from students' initial mental models, through testing and revision of intermediate models, up to the target models, namely, the scientific version of models employed for educational purposes (Campbell et al. 2013).

A recent review has revealed that the most technological support to modeling pedagogies in computer-supported learning environments has been offered for

[1]Broadly approached, terminology on modeling would separate among different modeling pedagogies (van Joolingen et al. 2005; Campbell et al. 2013), i.e., "expressive" modeling has been largely related to elicitation of students' initial ideas, namely, students' initial mental models, "experimental" modeling would necessitate empirical data to validate a model, "evaluative" modeling would involve screening among rival versions of a model, "exploratory" modeling would be operationalized by means of a ready-made model (i.e., a model which was not created by students themselves), and "cyclic" modeling would include model revision.

"expressive" modeling (elicitation of students' mental models) and "exploratory" modeling (operationalized by means of a ready-made model) (Campbell et al. 2015). Once again, the idea here is to bridge the apparent instructional and technological interface between student initial ideas and the target model of instruction that is aligned to core scientific assumptions of the modeled system or phenomenon. The concern for educators and designers to better operationalize and support the transition from student first mental models to sound target models has been echoed in the model-based inquiry perspective proposed by Windschitl et al. (2008b). This latter perspective has been quite critical to school practice that does not give credit to images of the world that precede observations. Student representations of phenomena prior to observations correspond to student mental models that will first need to be expressed and made explicit, in order to guide exploration or experimentation later on. This view is in line with an epistemological position, according to which, the formulation of hypotheses can be taken as interrelation of variables. Since hypotheses link dependent variables to independent ones, multiple hypotheses might be processed to study multiple dimensions of a phenomenon under study, as these dimensions are described by the variables tested. A scientific model of the phenomenon would provide a coherent whole structure by these variables, and it would comprise a solid reference base for variable identification and hypothesis generation. In this regard, hypotheses would incorporate and interrelate structural components (i.e., variables) of a model (e.g., Giere 1991; Nersessian 2002, 2005). Model-based inquiry is compatible to nature-of-science approaches that interpret scientific theories as constellations of models, especially in facilitating the epistemological rigor of theories by elaborating on model attributes (Ariza et al. 2016; Develaki 2007; Lefkaditou et al. 2014). Such an approach would challenge a stand-alone view of exploration or experimentation with ready-made models, and it would direct educators and designers toward embedding the sequence of learning activities needed to plan and execute an exploration or an experiment (i.e., formulation of hypothesis, designing an experiment, executing the experiment) within the broader frame of model building and testing (see, for instance, Windschitl et al. 2008b, p. 311)[2].

Within computer-supported learning environments, certain virtual laboratories (i.e., open-ended virtual labs that allow the preparation/building of an experiment

[2]Close-ended simulations do not offer students the option of expressing their mental models, because the model is already there. In this case, possible relations between variables would have to be assumed/discovered**.** It is an issue whether this variable-by-variable approach would allow the student to grasp a complete picture of the whole phenomenon under study, as if one would have expected based on a modeling procedure, during which the whole phenomenon would be modeled and remodeled. After all, the design rationale behind any modeling tool has been to first give students the opportunity to create a model and then simulate it. It could be that we might isolate a limited number of variables to study a phenomenon. However, nonlinear thinking and system dynamics with feedback mechanisms and delay cannot be easily addressed with matching variables in pairs of two, where we mostly presuppose linear relationships between two variables at a time. Here we come across epistemological issues linking model-based inquiry to systems thinking, where the latter cannot be facilitated without the former.

setup) are resources that could facilitate model-based inquiry. For instance, many virtual laboratories offer affordances that allow for outlining the basic components of a system or a phenomenon, enacting modeling tasks, and using scientific models (i.e., simulations) for exploration or experimentation purposes (de Jong et al. 2013; Zacharia and de Jong 2014). Further, virtual laboratories may enable speeding up or slowing down phenomena running at varying speed. Another important aspect of using virtual laboratories in computer-supported environments is that they carry affordances that make non-visible components of systems or phenomena visible (e.g., de Jong et al. 2013; Olympiou et al. 2013; Zangori and Forbes 2015). For instance, virtual laboratories may allow for zooming in or out in small-scale or large-scale systems, respectively. Identifying and distinguishing between readily observable (i.e., visible) as well as hidden (i.e., non-visible) elements is crucial for being able to use a model as an explanatory device and for following underlying causes and effects that relate to that model (Hmelo-Silver and Azevedo 2006; Jacobson and Wilensky 2006; Olympiou et al. 2013; Zangori et al. 2015). At the same time, however, some types of virtual laboratories might not be suitable for enacting model-based inquiry. For instance, when virtual laboratories do not offer modeling options or when the modeling options they provide are minimal (i.e., close-ended simulations that do not allow the users to build their own experiment setup; see Sect. 10.6 for examples of open-ended virtual labs and close-ended simulations), then model revision cannot be effectively operated, or it may be even heavily impaired. Further, when basic modeling assumptions are not readily traceable for the user of the virtual laboratory and when simulation is the only option, then the user might perform multiple simulation tasks, but he/she would still fail to acknowledge the core underlying principles of the model, on which all simulations depend.

In what follows, we will attempt to address a series of instructional and design challenges of model-based inquiry with virtual laboratories by presenting the work undertaken within the Go-Lab project (http://www.go-lab-project.eu/). As modeling would go along with quite demanding learning tasks, students would need to be substantially supported in their learning trajectories while constructing and revising models. Computer-supported learning environments can offer valuable guidance to students during their learning routes throughout an inquiry procedure based on modeling. Initial mental models would largely overlap with prior knowledge of students. Virtual laboratories that offer modeling affordances would allow for an exploration of the basic structural compartments involved in a model. This would enable students to identify the variables, which would be needed later on for the formulation of research questions or hypotheses. Virtual laboratories would allow students to simulate models and generate data based on these models. Students would then continue their inquiry as long as they would be able to use simulation data to accept or reject their hypotheses. At the latter stages of the inquiry procedure, students will need to reach conclusions, report their work to peers and the teacher, as well as reflect on the whole learning activity sequence. For all these tasks, the Go-Lab platform can offer a series of virtual laboratories and software scaffolds to design and enact model-based inquiry (see Sect. 10.4 and Table 10.1).

Table 10.1 Scaffolds available in the Go-Lab platform for all inquiry phases and their main affordances

Phase (sub-phase) of the inquiry cycle	Software scaffold/application	Main affordances of the software scaffold/application
Orientation	Concept Mapper (https://www.golabz.eu/app/concept-mapper)	Predefined terms provided to students to construct a concept map
Conceptualization; Questioning (sub-phase)	Question Scratchpad (https://www.golabz.eu/app/question-scratchpad)	Predefined variables provided to students to formulate their questions
Conceptualization; Hypothesis generation (sub-phase)	Hypothesis Scratchpad (https://www.golabz.eu/app/hypothesis-scratchpad)	Predefined variables provided to students to formulate their hypotheses
Investigation; Exploration (sub-phase)	Observation Tool (https://www.golabz.eu/app/observation-tool)	Students can record and arrange observations during an experiment
Investigation; Experimentation (sub-phase)	Experiment Design Tool (https://www.golabz.eu/app/experiment-design-tool)	Predefined variables provided to students to design their experiment
Investigation; Data interpretation (sub-phase)	Data Viewer (https://www.golabz.eu/app/data-viewer)	Variables and data sets provided to students to construct graphs
Conclusion	Conclusion Tool (https://www.golabz.eu/app/conclusion-tool)	Learning products of prior activities provided to students to draw their conclusions
Discussion; Reflection (sub-phase)	Reflection Tool (https://www.golabz.eu/app/reflection-tool)	Feedback provided to students about their use of an Inquiry Learning Space
Discussion; Communication (sub-phase)	Report Tool (https://www.golabz.eu/app/report-tool)	Learning products of prior activities provided to students to report on their inquiry

10.3 Inquiry Phases and Learning Trajectories in Model-Based Inquiry with Virtual Laboratories

In their review of inquiry-based learning, Pedaste et al. (2015) identified five phases that define an inquiry cycle (Fig. 10.1). These phases include fundamental tasks of scientific inquiry and streamline learning activities so as to achieve optimal learning gains. The first phase has been called "Orientation," and it involves learning activities aimed at arousing student interest toward the domain. In this phase, the research topic and the driving questions about a system or phenomenon should be also clarified. The next phase is "Conceptualization," which includes tasks related to the identification of variables about the system or the phenomenon at hand and which will be handled by students. "Conceptualization" might take two forms, depending on students' prior knowledge about the domain or experience in inquiry learning. Novice learners, who would have their first encounter with the topic, would

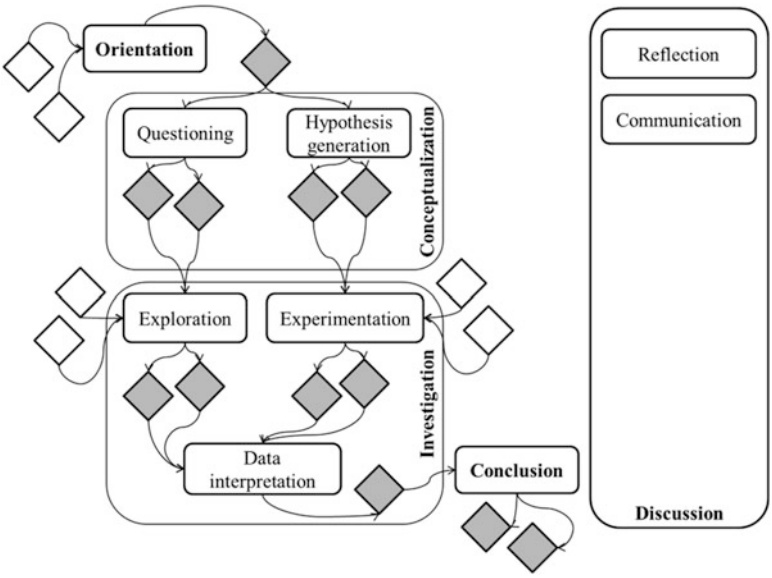

Fig. 10.1 Phases and sub-phases of the inquiry-based learning framework (Adapted from Pedaste et al. 2015). Rectangles depict sub-phases or phases (the latter in bold), dark rhombuses learning products, and white rhombuses any reference material offered to students by the teacher or the learning environment. Arrows show the sequence of phases. The flow presented is only indicative (for a complete report of relations between phases and sub-phases, see Pedaste et al. 2015)

pose questions with main variables outlined ("Questioning" sub-phase), while more experienced learners, who would be familiar with the topic, would be able to formulate hypotheses ("Hypothesis generation" sub-phase). This duality would be continued in the "Investigation" phase, where novice learners would proceed to an exploration of the topic ("Exploration" sub-phase), while experienced learners would execute an experiment ("Experimentation" sub-phase). Expressing, testing, and revising a model would be integrated in the "Investigation" phase in either sub-phase, namely, either as exploration, to detect indications of a relation between variables identified, or experimentation, to verify a hypothesized relation between variables and address a research hypothesis (de Jong 2015)[3]. After modeling and data generation, students would go on to the third sub-phase of "Investigation," where they would have to interpret their data ("Data interpretation" sub-phase). The main challenge in this latter sub-phase would be to arrive at meaningful results out of

[3]With regard to the inquiry cycle, "exploratory" modeling (i.e., students working with ready-made models) might not always equate to the exploration trajectory in the inquiry cycle as defined by Pedaste et al. (2015). For instance, the exploration trajectory is distinguished from the experimentation trajectory in the inquiry cycle in that the first incorporates research questions, while the latter presupposes hypotheses. However, "exploratory modeling" might accommodate both questions and hypotheses.

the data students had collected and analyzed. "Conclusion" is the phase that follows, with students drawing main conclusions out of their exploration or experimentation. In this phase, students also need to align their conclusions with research questions or hypotheses formulated earlier in their inquiry. The fifth phase of the inquiry cycle is termed "Discussion" and includes the sub-phases of "Communication" and "Reflection." In "Communication," students interact with peers or teachers to share outcomes and experiences and to receive or offer feedback on their inquiry. In "Reflection," each student reflects on his or her learning tasks and the learning route taken. These sub-phases might be activated within or between other phases, as well as at the end of an entire inquiry cycle.

The inquiry cycle could be completed via two alternative pathways, which are split in the "Conceptualization" and "Investigation" phases (Fig. 10.1; "Questioning" and "Exploration" sub-phases, for novice learners, "Hypothesis generation" and "Experimentation" sub-phases, for more experienced learners). These two alternative trajectories would involve the construction of different learning products[4] by students, as they would undertake learning activities. For instance, in the "Questioning" sub-phase, students will produce questions, and these questions will be used later on as part of the input students will dispose of in the "Exploration" sub-phase to construct or revise a model. This model will be another example of a learning product. Alternatively, students would need to formulate a hypothesis (i.e., learning product in "Hypothesis generation" sub-phase), before proceeding to an experimentation with a model in a virtual laboratory ("Experimentation" sub-phase), where data generated and organized in tables or figures would be the next learning products of students. All input necessary for processing learning activities has been given in Fig. 10.1 either as dark rhombuses, which denote learning products, or as white rhombuses, which denote any other reference material offered by the teacher or the learning environment.

With regard to model-based inquiry, virtual laboratories with modeling and simulation functionalities might be used by educators and designers for structuring the whole inquiry cycle. The heuristic value of models has been frequently underlined, especially in terms of generating predictions, hypotheses, and explanations (Coll and Lajium 2011; Forbes et al. 2015; Justi and Gilbert 2003; Hovardas and Korfiatis 2011; Lefkaditou et al. 2014; Petridou et al. 2013; Schwarz and White 2005; Schwarz et al. 2009; Verhoeff et al. 2008; Windschitl et al. 2008a). The model of a phenomenon under study can provide an insightful reference base for examining various dimensions of the phenomenon, as they can be operationalized by the variables included in the model. In this direction, the multifarious compatibilities

[4]Learning products that are created by students themselves as they go through a learning activity sequence have been characterized as "emerging learning objects (ELOs)" in the frame of the Science Created by You (SCY) project (see de Jong et al. 2010, 2012). These can include concept maps, models, questions, hypotheses, experimental designs, tables or figures with simulation data, and any other artifact that is the product of student work and can be stored and recalled upon demand for educational purposes. Learning products provide a core alignment of computer-supported learning environments with the theoretical and operational framework of constructivism.

of modeling and inquiry-based learning have been frequently highlighted to single out testing, revising, and retesting models (e.g., Lehrer and Schauble 2006). Models constructed by students themselves as learning products would constitute expressed models at the initial steps of their inquiry. If these models can be simulated to generate data, then student inquiry would build on elaboration of research questions and hypotheses via model simulation. In that direction, model construction and revision might be seen as a strategy of configuring the whole inquiry cycle in model-based inquiry, where models and modeling would comprise an indispensable device for promoting student knowledge and skills as well as their epistemological understanding[5]. This design would ultimately lead to a possible way of resolving the challenge in facilitating intermediate steps in model-based inquiry and supporting the transition from initial models of students to target models. A first task for educators, where they might need considerable assistance, is to select or configure target models suited for model-based inquiry (Windschitl et al. 2008b). Then, students might take the trajectory delimited for novice learners and explore the system or phenomenon under study in their first modeling tasks ("Exploration" sub-phase). To begin with, students would need an adequate backing in the "Orientation phase," so that they would be guided to mark out one or two core variables, with which they will also encounter when using the virtual laboratory. Such an assistance would foster an acknowledgment of variables that would be shared between initial models of students and target models. Moreover, this option would provide the necessary bridge between the initiation of model-based inquiry and the desired learning outcome.

If the first trajectory in our design was exploration of a system or phenomenon, the next trajectory involves experimentation, which might need the articulation of a new inquiry cycle. Learners in that cycle would have had a familiarization encounter with model, modeling, and the virtual laboratory. Such an experience might allow them to formulate hypotheses. In turn, generating simulation data would prove crucial for any model revision, namely, for being able to validate the model constructed by students on the basis of the data it can generate. A manifest assumption in that approach of ours is that educators would need to schedule at least two subsequent inquiry cycles (i.e., one cycle involving exploration and another one involving experimentation), which largely overlap with the two alternative learning trajectories depicted in Fig. 10.1. This option might reflect the well-documented fact that experimentation has been for long a primary focus of science education and it has therefore attracted the attention of educators and designers (van Joolingen and Zacharia 2009). However, if we conceive of hypotheses as statements that interrelate variables identified in models (see, for instance, Windschitl et al. 2008a), then the ability to formulate a hypothesis content-wise would depend on the ability to employ a basic model of the system or phenomenon under study. Offering the option of simulation (i.e., trajectory involving experimentation) without

[5]In that regard, our approach presents a marked resemblance with learning by design; see Kolodner et al. (2003), de Jong and van Joolingen (2007), and Weinberger et al. (2009).

delineating a basic model of the phenomenon under study first (i.e., trajectory involving exploration) might eventuate in trial-and-error attempts of students that would hardly be informed by a comprehensive ability to reflect on models and modeling and on testing and retesting their models, accordingly. Furthermore, the precedence of exploring before experimenting would provide the opportunity to students to familiarize themselves with the virtual laboratory they would use, the main modeling skills, and the main variables to begin with.

10.4 Laboratories and Applications in the Go-Lab Platform

For either learning trajectory, the production, storage, retrieval, and reprocessing of learning products are supported by the Go-Lab platform with tools (software scaffolds/applications), which can be embedded in all phases and sub-phases of the inquiry cycle, in order to provide necessary guidance and scaffolding to students (see Table 10.1 for an indicative list of software scaffolds across phases and sub-phases of the inquiry cycle[6]). For instance, students can use the Question Scratchpad to formulate research questions and the Hypothesis Scratchpad to formulate hypotheses (Figs. 10.2 and 10.3, respectively). The entire arrangement with a selected laboratory[7], support in the form of software scaffolds, and all other instructional guidance in the form of reference material offered to students, comprises an Inquiry Learning Space (ILS; http://www.golabz.eu/spaces). An ILS is a learning environment structured along the phases and sub-phases of the inquiry cycle and serviced with the support needed so that students will be able to choose a learning activity sequence and have an optimal inquiry route[8].

The integration of virtual laboratories in Inquiry Learning Spaces might allow for much more flexibility in student inquiry than when using virtual laboratories in a stand-alone fashion[9]. Implementation studies in the frame of the Go-Lab project have revealed that there seems to be a minimum amount of time that should be spent on a task, while working with a virtual laboratory or software scaffolds, so that students would effectively execute a series of learning activities (Hovardas et al. 2017). When less time than this threshold is spent, then students might have quite

[6]All software scaffolds available at the Go-Lab platform can be found at http://www.golabz.eu/apps. For a comprehensive review of guidance provided to students in computer-supported learning environments with virtual and remote laboratories, see Zacharia et al. (2015).

[7]The Go-Lab platform offers online an entire array of laboratories for supporting inquiry-based learning, including virtual laboratories and remotely operated educational laboratories (http://www.golabz.eu/labs). In this contribution, we have focused on virtual laboratories.

[8]Inquiry Learning Spaces available in the Go-Lab platform can be found at http://www.golabz.eu/spaces

[9]Educators can use the Go-Lab authoring tool to select virtual laboratories and software scaffolds/applications and embed them in phases and sub-phases of the inquiry cycle in order to create an Inquiry Learning Space (de Jong et al. 2014).

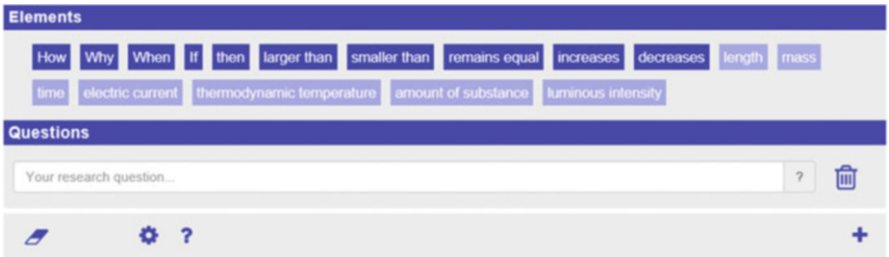

Fig. 10.2 The Question Scratchpad (https://www.golabz.eu/app/question-scratchpad)

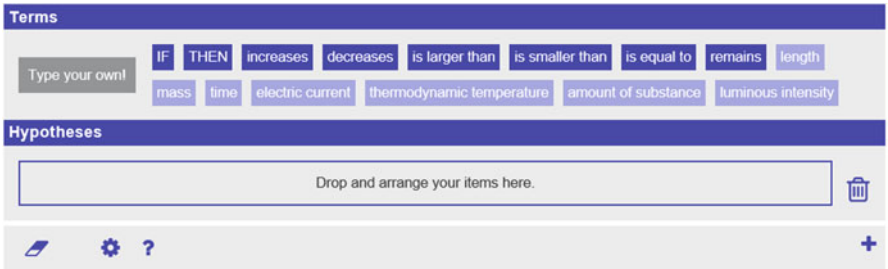

Fig. 10.3 The Hypothesis Scratchpad (https://www.golabz.eu/app/hypothesis-scratchpad)

low contextual or task and process awareness that leads to insufficient learning gains (Pedaste and Sarapuu 2006a, b). In this case, students should revisit former steps in their trajectories and rework their learning products to account for the remainder. For instance, if students had not identified all variables needed to undertake an exploration or an experimentation, then they would need to move backward in the activity sequence and devote additional time to working with the virtual laboratory and software scaffolds. This retrospective action might compensate for the time required to complete basic assignments. There can be multiple designs, which might foster such retrospective action and which might build on synergies between virtual laboratories and software scaffolds. For instance, when students would be ready to construct a graph in the Data Viewer (https://www.golabz.eu/app/data-viewer) (Fig. 10.4), the tool could offer students only one variable (e.g., the dependent variable) to construct their graph, and in this case students would need to identify the independent variable to plot. This option could be operationalized by linking the Data Viewer to a virtual laboratory (e.g., the Electrical Circuit Lab; http://www.golabz.eu/lab/electrical-circuit-lab) (Fig. 10.5; see Sect. 10.6.1 and Table 10.2 for a detailed account of model-based inquiry for electrical circuits) with a data set container. In an alternative linkage, students might be offered more than two variables to construct their graph, and in this case they would need to screen among variables and select the dependent and independent variable to accomplish the

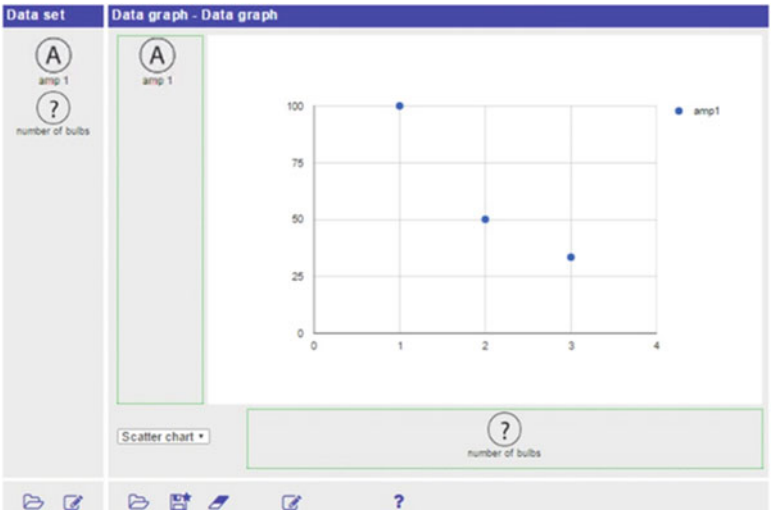

Fig. 10.4 The Data Viewer (https://www.golabz.eu/app/data-viewer)

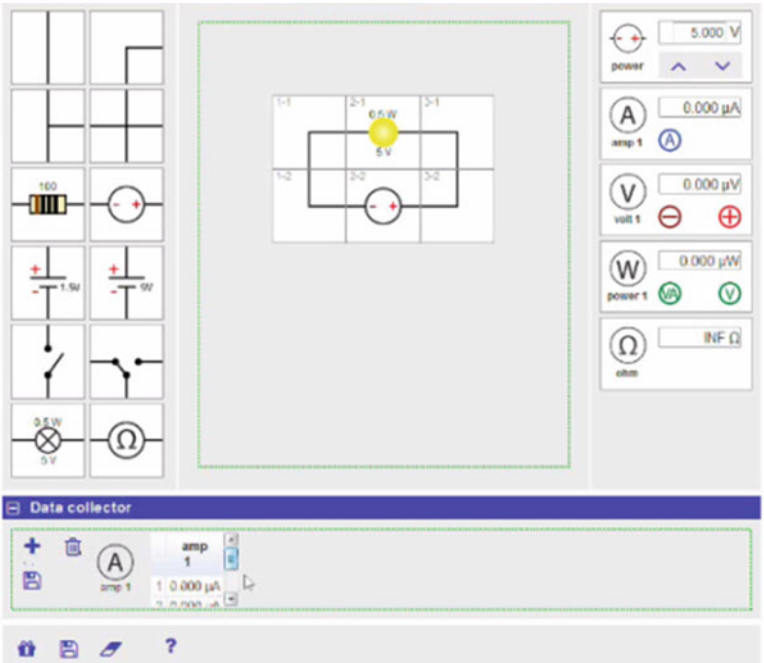

Fig. 10.5 Electrical Circuit Lab (http://www.golabz.eu/lab/electrical-circuit-lab)

Table 10.2 Subsequent cycles of model-based inquiry for electrical circuits

Inquiry cycle	Main modeling rationale	Operationalization of the Investigation phase of the inquiry cycle	Main exploration/experimentation rationale
First	Model a simple electrical circuit	Hands-on exploration	Interrelate basic structural components (e.g., power source, wire, bulb) and monitor the simplest function of a simple electrical circuit (e.g., the bulb lights up)
Second	Model a simple electrical circuit	Exploration with online lab (e.g., Electrical Circuit Lab; http://www.golabz.eu/lab/electrical-circuit-lab)	Interrelate basic structural components (e.g., power source, wire, bulb) and monitor the simplest function of a simple electrical circuit (e.g., the bulb lights up)
Third	Model electrical circuits in series and in parallel	Experimentation with online lab (e.g., Electrical Circuit Lab; https://www.golabz.eu/lab/simple-pendulum-1)	Interrelate basic structural components (e.g., power source, wire, multiple bulbs) and monitor the brightness of bulbs in the two types of circuits (e.g., in the circuit in series, brightness decreases when number of bulbs increases; in the circuit in parallel, brightness remains constant when number of bulbs increases)
Fourth	Model electrical circuits in series and in parallel	Experimentation with online lab (e.g., Electrical Circuit Lab; http://www.golabz.eu/lab/electrical-circuit-lab)	Monitor number of bulbs and total electric current in the two types of circuits (e.g., in the circuit in series, total electric current decreases when number of bulbs increases; in the circuit in parallel, total electric current increases when number of bulbs increases)
Fifth	Model electrical circuits in series and in parallel	Experimentation with online lab (e.g., Electrical Circuit Lab; http://www.golabz.eu/lab/electrical-circuit-lab)	Monitor voltage and electric current in the two types of circuits (e.g., in both types of circuits, electric current increases with voltage)

The sequence of inquiry cycles presented is only indicative; multiple other sequences might be possible, depending on main modeling and exploration/experimentation rationales

graphing task. This option might be operationalized through a linkage of the Data Viewer with the Experiment Design Tool (https://www.golabz.eu/app/experiment-design-tool) (Fig. 10.6). Both designs would trigger retrospective action, which is easier to enact in computer-supported learning environments and might open novel avenues in inquiry-based learning.

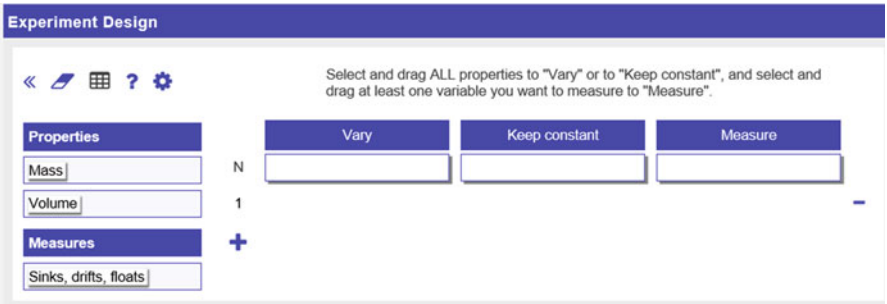

Fig. 10.6 The Experiment Design Tool (https://www.golabz.eu/app/experiment-design-tool)

10.5 Support Offered to Students in Model-Based Inquiry with Virtual Laboratories

Within the frame of the Go-Lab project, we have arrived at specific recommendations for fine-tuning guidance across the phases of the inquiry cycle, which will be presented in this section. The overall aim behind these recommendations is to achieve an optimum effect on student performance through the use of all the resources offered via the Go-Lab platform (Tasiopoulou and de Jong 2016). Guidance is provided through a number of tools and throughout the whole inquiry process (see Table 10.1). Specifically, guidance tools have been developed to support students in each inquiry phase (for details see Zacharia et al. 2015). On top of these guidance tools, we have noticed through previous studies (Tasiopoulou and de Jong 2016) that special support should be provided for any inquiry-oriented enactment, including model-based inquiry, and enhance peer and teacher feedback. Moreover, we have noticed that alternative configurations of certain guidance tools could further optimize the support provided. Below we discuss all these aspects in detail.

In terms of providing teacher feedback and enacting on-the-fly formative assessment, teachers might focus on one or two crucial learning products along the learning activity sequence. For instance, hypotheses formulated by students or their experimental designs would give an overview of their progression. This can involve the variables which students would have identified, how they would have categorized these variables (e.g., dependent variables, variables remaining constant, independent variables), and how many experimental trials they would have planned. The learning products, which would be depicted by the teacher for such a procedure, would reveal student performance, and they would denote student progression up to a certain point in the learning activity sequence. These learning products would also play a crucial role in the forthcoming activities. For instance, if a student had not identified the variables involved in an experimentation, then tasks undertaken

while building or simulating a model in a virtual laboratory would carry along that weakness. The teacher would diagnose student progression by concentrating on these learning products, and he/she would be ready to provide timely feedback, when this would be required. Although a substantial number of formative assessment formats have been using a wide array of instruments to diagnose student performance, such as multiple-choice items, data collection by means of these instruments would necessitate allocation of additional time for data analysis, and this would endanger the proper timing of teacher feedback. Using learning products for the purpose of enacting formative assessment would shorten considerably the time frame from diagnosis of student performance to provision of teacher feedback (for more details, in this direction, see Hovardas 2016). Future research might shed more light on how much and what kind of feedback provision might be undertaken by computer-supported learning environments without the direct involvement of the teacher. Additionally, there is a need to examine options for configuring upcoming cycles of model-based inquiry based on student performance in former cycles, so that support would be as much as learner-tailored as possible. Across all these options, target models would prove crucial for outlining the optimal form of all learning products expected along learning trajectories.

Subsequent rounds of model-based inquiry would necessitate adequate and effective configuration of guidance tools, such as scaffolds. There might be different versions of the same tool, which would correspond to varying degrees of guidance. A challenge for designing computer-supported learning environments has always been to find a balance between structuring student work (De Boer et al. 2014; Zacharia et al. 2015), for instance, partitioning tasks and letting them be processed serially (Clarke et al. 2005; Kalyuga 2007; Pollock et al. 2002; van Joolingen et al. 2011) and problematizing student inquiry, namely, directing student attention to aspects (e.g., mistakes made by the students during their inquiry enactment) that would remain unaccounted for if students would not have been alerted (Reiser 2004; Sweller et al. 1998). For students with less prior knowledge, scaffolds need to be configured so as to provide increased support and guidance. For instance, in a tool such as the Question Scratchpad, all words need to be provided for students with relatively less prior knowledge so that they can formulate their research questions. As student knowledge advances, this support might be gradually removed (see Pea 2004; McNeill et al. 2006 for a detailed account on "fading" scaffolds). Accordingly, lesser words in the Hypothesis Scratchpad would be enough for more experienced students to formulate their hypotheses. If students succeeded in formulating their hypotheses with lesser words, then this would be an indication that they had progressed in the corresponding inquiry skills. All scaffolds, together with their introduction and fading, need to refer to target models and to fuel the desired transition from initial models of students to target models.

10.6 Working Examples of Subsequent Cycles of Model-Based Inquiry with Virtual Laboratories

In this section we will provide three working examples of subsequent cycles of model-based inquiry, which center on working with virtual laboratories. We will need to underline, first, that our level of analysis will not be an inquiry cycle itself but it will refer to a higher grain size, namely, the movement from one cycle to the next so as to foster an analogous transition from initial models built by students, through intermediate model versions, to target models. Second, we should highlight that we will take advantage of the two learning trajectories we have already identified when presenting phases and sub-phases of the inquiry cycle, that is, the path through questioning and exploration, on the one hand, and the alternative path leading through hypothesis generation and experimentation, on the other. It can be that some virtual laboratories might support student inquiry along both creating a model and simulating it. Other virtual laboratories, however, might allow only for executing simulations. A laboratory might be informed by a ready-made model, where students might not be able to intervene and change model compartments or their interrelations. These types of laboratories let students only change parameters of variables and monitor model behavior through these alterations, but they do not offer a remodeling option. To enable model building and exploration, educators would need to plan a preceding inquiry cycle with another laboratory which would enable model building. Laboratories that enable model building as well as model simulation and data generation would be eligible for both inquiry cycles, namely, the first cycle, where the model has to be constructed, and the second one, where the model will be simulated. Another note that we need to make here is that there would be multiple options of planning subsequent cycles of model-based inquiry, where model building and exploration or experimentation with a virtual laboratory would alternate with hands-on activities or outdoor activities to facilitate optimal learning gains. The working examples, which will follow, will illustrate this perspective, too. One among our main points will be to exemplify model-based inquiry aiming at unraveling hidden assumptions in virtual laboratories.

10.6.1 Electrical Circuits

The Electrical Circuit Lab (Fig. 10.5; http://www.golabz.eu/lab/electrical-circuit-lab) can be used by students to build and simulate simple or more complex electrical circuits. Building a simple electrical circuit is already a modeling task, while more complex electrical circuits in series or in parallel might increase the complexity of the modeling exercise. In the same vein, when a student adds structural compartments available in the Electrical Circuit Lab to advance a circuit, which had been constructed previously, then this might be considered as model revision. The Electrical Circuit Lab provides simulation and data generation capabilities,

which would guide model testing, revision, and retesting. Students might begin their inquiry in electrical circuits with a hands-on (physical lab) exploration followed by a subsequent exploration in the virtual laboratory. In either case, the main exploration rationale would be to interrelate basic structural components of an electrical circuit (e.g., power source, wire, bulb) and monitor the simplest function of a simple electrical circuit (e.g., the bulb lights up). The transition from hands-on exploration to an upcoming exploration of a simple electrical circuit within a virtual laboratory could serve as a task for aligning basic structural components of models between the two modeling contexts. It can also include a discussion of basic assumptions behind the functionalities offered by the virtual laboratory. Such a contradistinction would be scheduled so as to unravel assumptions in the virtual laboratory which might remain hidden and unaccounted for. More inquiry cycles can be enacted with the Electrical Circuit Lab by having the students experimenting with in series and parallel circuits, while examining the differences between these two types of more complex circuits along a series of variables (e.g., number of bulbs, brightness of bulbs, total electric current, and voltage). Overall, the sequence of cycles of model-based inquiry presented in Table 10.2 has been planned to present an increasing complexity in modeling tasks and inquiry skills. After that sequence, student inquiry might go on by adding further inquiry cycles, which might again alternate between the virtual laboratory, hands-on exploration and experimentation, or exploration and experimentation outside the classroom (e.g., school experiment or home experiment).

10.6.2 Bicycle Gearing

The GearSketch is another virtual laboratory included in the Go-Lab platform (Fig. 10.7; http://www.golabz.eu/lab/gearsketch). It can be used to model the motion of the gearing mechanism of a bicycle (Table 10.3). Namely, students can insert the basic structural components of the gearing mechanism (e.g., front and back gear, chain, back wheel) and monitor its simplest function. The basic exploration rationale here is to follow how pedaling effort is setting the front gear in motion and how that motion is transmitted through the chain to the back gear and then to the back

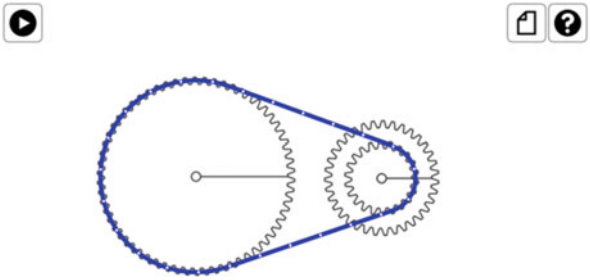

Fig. 10.7 GearSketch (http://www.golabz.eu/lab/gearsketch)

Table 10.3 Subsequent cycles of model-based inquiry for bicycle gearing

Inquiry cycle	Main modeling rationale	Operationalization of the Investigation phase of the inquiry cycle	Main exploration/experimentation rationale
First	Model the motion of the gearing mechanism of a bicycle	Exploration with online lab (e.g., GearSketch; http://go-lab.gw.utwente.nl/production/gearsketch/gearsketch.html)	Interrelate basic structural components (e.g., front and back gear, chain, back wheel) and monitor the simplest function of the gearing mechanism of a bicycle (e.g., motion from the front gear is transmitted through the chain to the back gear)
Second	Model bicycle gearing for a bicycle with a single gear	Outdoor exploration (turn bicycle upside-down and perform hand-powered pedaling; friction between ground and bicycle wheels removed)	Interrelate basic structural components (e.g., front and back gear, chain, back wheel) and monitor the transmission of motion from the gearing mechanism of the bicycle to the back wheel
Third	Model bicycle gearing for a bicycle with multiple gears	Outdoor experimentation (turn bicycle upside-down and perform hand-powered pedaling; friction between ground and bicycle wheels removed)	Interrelate basic structural components (e.g., one front and multiple back gears, chain) and monitor the speed of the back wheel of the bicycle for higher vs. lower gears (e.g., the higher the gear, the higher the speed of the back wheel for the same pedaling force)
Fourth	Model bicycle gearing for a bicycle with multiple gears	Outdoor experimentation (use bicycle and perform foot-powered pedaling; friction between ground and bicycle wheels added to the system)	Monitor rider effort for higher vs. lower gears (e.g., the higher the gear, the higher the pedaling force needed due to static friction)
Fifth	Model bicycle gearing for a bicycle with multiple gears	Experimentation with online lab (e.g., GearSketch; http://go-lab.gw.utwente.nl/production/gearsketch/gearsketch.html)	Interrelate basic structural components (e.g., one front and multiple back gears, chain) and monitor routes of chains for gears of varying radiuses (e.g., the higher the gear, the longer the route)

The sequence of inquiry cycles presented is only indicative; multiple other sequences might be possible, depending on main modeling and exploration/experimentation rationales

wheel of the bicycle. A first point to note is that the GearSketch provides modeling functionalities that are much closer to the initial representations of learners, in contrast to the Electrical Circuit Lab, which enables the construction of more abstract models. This is why it can be readily used as a virtual laboratory before any other inquiry cycle preceding it. Of course, that would not exclude outdoor exploration or experimentation, which can follow. Indeed, students might employ a real bicycle and turn it upside-down to perform hand-powered pedaling (Fig. 10.8). In that configuration of the bicycle, friction between ground and bicycle wheels

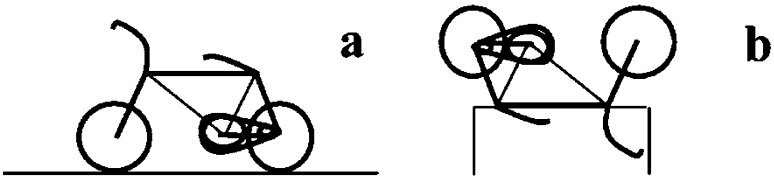

Fig. 10.8 Bicycle standing in the upright position (**a**) and bicycle turned upside-down (**b**)

would have been removed. Students can identify the basic structural components of the gearing mechanism in the real bicycle (e.g., front and back gear, chain, back wheel) and monitor the transmission of motion from the gearing mechanism of the bicycle to the back wheel. In an upcoming experimentation, students will be able to continue using the real bicycle turned upside-down and monitor the speed of the back wheel of the bicycle for higher vs. lower gears. It is expected that the higher the gear, the higher the speed of the back wheel for the same pedaling force. In a next inquiry cycle, students might use the bicycle and perform foot-powered pedaling. In this case, the friction between ground and bicycle wheels would have been added to the system. The students would be able to monitor rider effort for higher vs. lower gears. It is expected that the higher the gear, the higher the pedaling force needed due to static friction. A last inquiry cycle would return the students back to the GearSketch to model bicycle gearing for a bicycle with multiple gears. Students would need to interrelate basic structural components of the new system (e.g., one front and multiple back gears, chain) and monitor the routes of chains for gears of varying radiuses. It is expected that the higher the gear, the longer the route. Student inquiry can go on further by modeling a tandem bicycle for two riders.

10.6.3 Simple and Inverted Pendulums

Our third example concerns simple and inverted pendulums (Table 10.4). Students can first use modeling software like Algodoo to interrelate basic structural compartments of the simple pendulum (e.g., pivot and weight) and prepare a first draft of their model (Fig. 10.9). Students will be able to monitor the simplest function of a simple pendulum, where the weight performs oscillations of standard width after displacement. The next inquiry cycle might involve an experimentation with the Simple Pendulum (Fig. 10.10; https://www.golabz.eu/lab/simple-pendulum-1). This is a virtual laboratory, where students can study the motion of a simple pendulum motion with damping and follow the motion of the weight back to rest position after displacement (e.g., after the weight has performed oscillations of decreasing width after displacement). Further inquiry into pendulums might involve an outdoor exploration with a child swing (Fig. 10.11a). If a person swings, then he or she might not move his/her legs, and in this case there is a damping effect. If the person moves his or her legs, however, then this resupplies the system with energy

Table 10.4 Subsequent cycles of model-based inquiry for simple and inverted pendulums

Inquiry cycle	Main modeling rationale	Operationalization of the Investigation phase of the inquiry cycle	Main explo-ration/experimentation rationale
First	Model the motion of a simple pendulum	Exploration with modeling and simulation software (e.g., Algodoo; http://www.algodoo.com/)	Interrelate basic structural components (e.g., pivot and weight) and monitor the simplest function of a simple pendulum (e.g., weight performs oscillations of standard width after displacement)
Second	Model the motion of a simple pendulum motion with damping	Experimentation with online lab (e.g., Simple Pendulum; https://www.golabz.eu/lab/simple-pendulum-1)	Interrelate basic structural components (e.g., pivot and weight) and monitor the motion of weight back to rest position after displacement (e.g., weight performs oscillations of decreasing width after displacement)
Third	Model the motion of a child swing	Outdoor exploration (person swings first without moving his/her feet and then with his/her feet moving)	Interrelate basic structural components (e.g., pivot and weight) and monitor energy transformations in a pendulum (e.g., movement of the child's legs resupplies the system with energy lost due to damping)
Fourth	Model the motion of a Segway (inverted pendulum)	Exploration with online lab (e.g., Segway Control Simulation; http://www.golabz.eu/lab/segway-control-simulation)	Interrelate basic structural components (e.g., center of mass above the pivot point) and monitor the simplest function of an inverted pendulum (e.g., vehicle starts when driver shifts body slightly forward or backward; upright position retained through calibration provided by a digital control system including gyroscopic sensors and accelerometer-based leveling sensors, which drive the wheels of the Segway forward or backward, respectively)
Fifth	Model the motion of the human body when walking (inverted pendulum)	Outdoor exploration (lean forward up to the point that one's foot needs to move also forward in order not to fall)	Interrelate basic structural components (e.g., upper part of the human body behaves as an inverted pendulum with weight center of the body as its pivot) and monitor the simplest simulation of an inverted pendulum (upright position retained through calibration provided by semicircular canals in the inner ear)

The sequence of inquiry cycles presented is only indicative; multiple other sequences might be possible, depending on main modeling and exploration/experimentation rationales

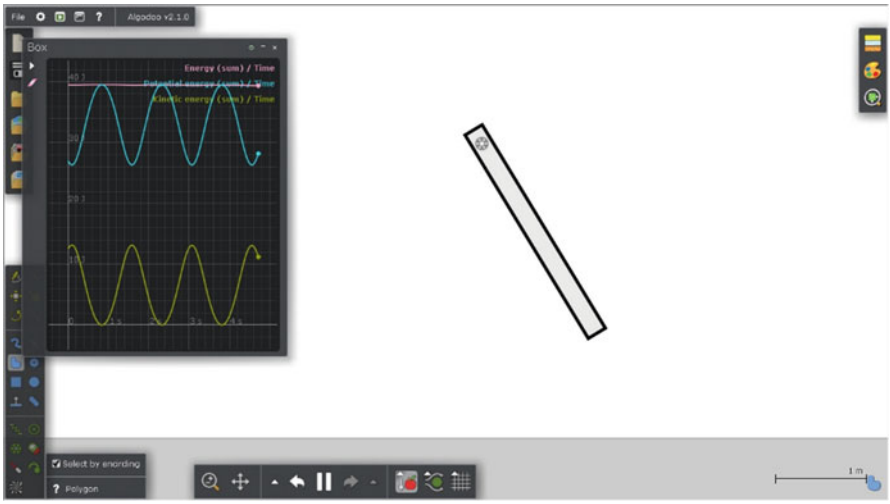

Fig. 10.9 Simple pendulum modeled in Algodoo

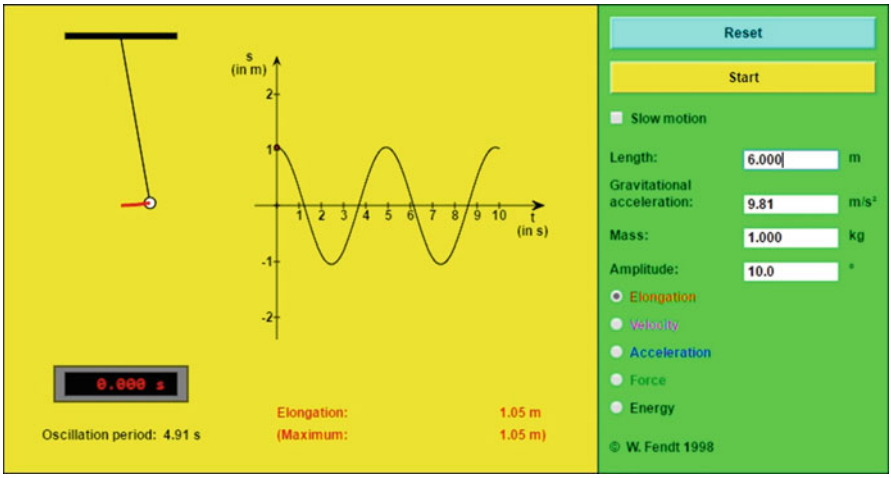

Fig. 10.10 Simple Pendulum (https://www.golabz.eu/lab/simple-pendulum-1). Lab owner: Walter Fendt; http://www.walter-fendt.de/html5/phen/pendulum_en.htm

lost due to damping effects. In a next inquiry cycle, the Segway Control Simulation (Fig. 10.12; http://www.golabz.eu/lab/segway-control-simulation) can be used to interrelate basic structural components of the inverted pendulum (e.g., center of mass above the pivot point) and monitor the simplest function of an inverted pendulum. The vehicle starts moving, when the driver shifts his or her body slightly forward (Fig. 10.11b). Upright position is retained through calibration provided by a digital control system that drives the wheels of the Segway forward. In contrast

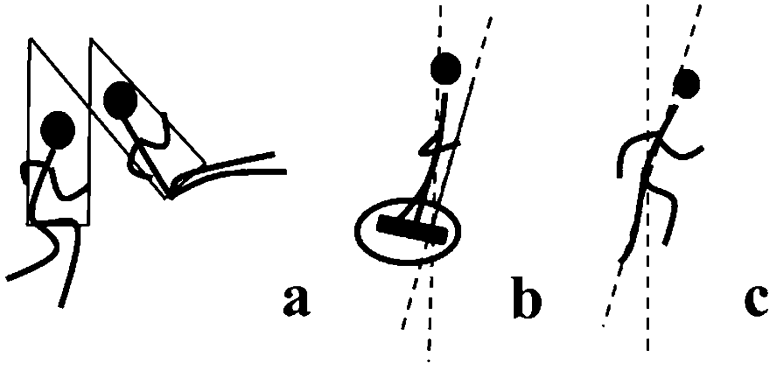

Fig. 10.11 Simple and inverted pendulums: swing (**a**), Segway (**b**), walking (**c**)

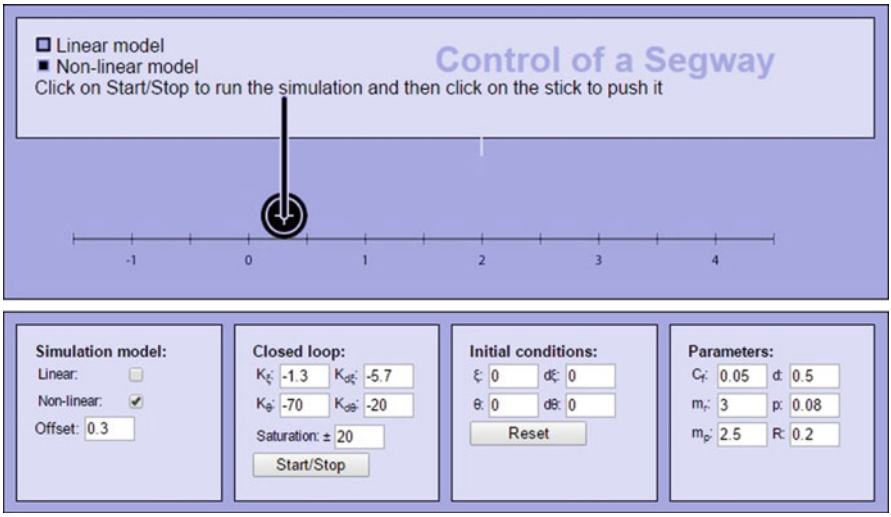

Fig. 10.12 Segway Control Simulation (http://www.golabz.eu/lab/segway-control-simulation). Lab owner: Benjamin Fankhauser

to simple pendulums, inverted pendulums involve a mechanism of correcting for any divergence from the upright position. These mechanisms are responsible for initiating movement, on the one hand, but also for returning the weight to the upright position, when needed. The case of the human body, when walking, is another exemplification of the inverted pendulum. An outdoor exploration can let students lean forward up to the point that one of their feet needs to move also forward in order not to fall (Fig. 10.11c). The upper part of the human body behaves as an inverted pendulum with weight center of the body as its pivot. Upright position is retained through calibration provided by semicircular canals in the inner ear.

10.7 Conclusion and Implications for Practice

In the three examples presented above, we tried to showcase how Go-Lab virtual laboratories could be used for enacting model-based inquiry. We have attempted to highlight "virtues" of virtual laboratories in terms of their modeling affordances and how instructional arrangements could instantiate them. In so doing, teachers need to employ at least two inquiry cycles in their instruction in order to address both model building as well as using models for exploration and experimentation of the system or phenomenon under study.

Some laboratories offer the option of constructing a structure (e.g., an electrical circuit in the Electrical Circuit Lab; a gear mechanism in the GearSketch) and, then, simulate that structure to derive a simulation outcome. Indeed, the simulation would not be possible unless the first step would be completed. This would align with the most basic modeling requirement of any modeling tool, namely, a two-step process of first constructing a model and, then, simulating that model. In that direction, the Electrical Circuit Lab and GearSketch could be seen as laboratories that enable model-based inquiry, meaning that models of electrical circuits or gear mechanisms could be constructed, tested, and revised to progress gradually to more complex models. Other laboratories (e.g., Simple Pendulum; Segway) do not allow for this two-step process. Students can only change parameters and observe the simulation outcome, but they are not able to construct a model and simulate their model or revise it. Students cannot even add new variables and thus test these new variables. For this second category of labs (i.e., close-ended simulations), in order to incorporate them in any model-based inquiry paradigm, we would need to accompany them with software that would allow modeling the phenomenon included in the close-ended simulation. This relates to the third example we have included in the paper, i.e., the case of the simple pendulum, where we used the Algodoo software to allow students to model the simple pendulum before using our close-ended, ready-made simulation.

All sequences took into account the modular nature of model-based inquiry (i.e., building an initial model and, then, testing and revising this model to arrive at the target model of instruction), which might be quite adaptable to curricula and school practice. However, teachers would need substantial support to screen among resources available, arrange them along phases and sub-phases of inquiry, and plan their instruction accordingly. The Go-Lab platform offers user manuals and online courses, tutorials, and a community forum for teachers to interact (http://www.golabz.eu/support). To further build on teacher input, design-based research might provide valuable insight for model-based inquiry in computer-supported learning environments through evidence-based learning progressions (e.g., Cobb et al. 2003; Duschl et al. 2011; Shea and Duncan 2013; Lehrer and Schauble 2015). The iterative nature of design-based research might be perfectly compatible with successive inquiry cycles in model-based inquiry, and it might give considerable opportunities for refining learning trajectories. Designing virtual laboratories and embedding them in adequately configured learning environments must incorporate evolving student and teacher needs and desires so that student performance might be optimized.

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