Chapter 6
Advances in PhET Interactive Simulations: Interoperable and Accessible

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Abstract Over more than a decade, the PhET Interactive Simulations project has created a suite of interactive simulations (sims) that support learning of science and mathematics content through exploration and discovery. Here we describe the state of the art in interactive science simulations, historical innovations that enabled this state, and current initiatives to advance the field.

Recently, the PhET project has engaged in two initiatives, PhET-iO and accessible PhET sims. PhET-iO increases the interoperability of sims and supports increased customization such as selection of available controls and starting conditions of the sim. PhET-iO also supports expanded integration of sims into interactive e-textbooks and virtual lab notebooks. Access to backend data streams from PhET-iO allows for the development of rich performance tasks suitable for innovative assessments that measure the learning of science practices and allow for adaptive feedback. These capabilities create new ways to positively influence science pedagogy and create targeted and adaptive learning environments for students.

Accessible PhET sims are addressing the need to ensure that all students, including students with disabilities, are allowed equitable access to high-quality learning experiences. Creating accessible interactive learning tools requires the development of new infrastructure to support communication between the simulations and assistive devices. PhET's efforts in accessibility include new features that enable sim use by students with mobility or vision impairments or learning disabilities. These features include keyboard navigation, auditory descriptions, and sonification. These features support students with disabilities and provide new opportunities for all students to engage with science content.

Keywords Interactive learning · Engagement · Representation · Science classroom · Configuration · e-Textbook · Assessment · Disabilities · Collaborative learning · Multimodal · HTML5

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6.1 Introduction

Digital interactive learning tools have the capacity to transform the teaching and learning of science in today's classrooms. Through technological advances, new capabilities are emerging for digital interactive learning tools to become increasingly customized, integrated, and accessible. These advances are resulting in new opportunities for technology-enhanced learning to support rich learning experiences for students. In this chapter, we set the stage for introducing the latest advances in PhET simulations by first introducing an example simulation and, as exemplified in this simulation, highlighting the project's design goals for the full suite of PhET simulations. We then look back upon the evolution of the PhET project, noting the prior innovations that provided the foundation on which we are advancing the capabilities of these learning tools. With this historical perspective in mind, we then introduce the latest advances in PhET simulations, PhET-iO, and accessible PhET simulations. We share the challenges that each of these advances addresses and the enhanced capabilities provided and project into the horizon new possibilities and contexts for technology-enhanced learning to support the teaching and learning of science and mathematics. Throughout this chapter, we focus on the conceptual evolution of the project and the capabilities enabled by this evolution rather than the research questions and data that supported – and at times propelled – this evolution. For example, we describe what broad goals the PhET project aims to meet, what philosophical approaches led to the state of the art of the simulations, and through these advances what challenges and opportunities are now within sight.

6.1.1 PhET Interactive Simulations

The PhET Interactive Simulations project includes a suite of over 160 interactive simulations (or "sims") for the teaching and learning of topics in science and mathematics. PhET sims are used around the world and across age groups from primary school to university. Each sim is available at no cost from the PhET website (http://phet.colorado.edu), can be used online or downloaded for offline use, and is openly licensed. For each sim we have developed materials to support teacher use (Moore et al. 2014), including Teacher Tips and PhET-created and teacher-submitted classroom activities. Many sims have an associated video primer to quickly orient teachers to sim features and to provide suggestions for scenarios in the sims that teachers may want to incorporate into their lessons.

As an introduction to the state of the art of PhET sims, we will highlight one particular sim, *Forces and Motion: Basics*, and through exemplar features in this sim, we provide a description of the goals that guide the day-to-day design and development decisions that result in PhET sims.

6.1.2 Introduction to Forces and Motion: Basics

The *Forces and Motion: Basics* sim can be used to support student learning of topics related to forces and motion, including net force, friction, and acceleration. This sim is used in classrooms from middle grades to early university level, with students from age 10 to adult.

6.1.2.1 Net Force Screen

Upon startup, the sim lists all four screens available: Net Force, Motion, Friction, and Acceleration. The Net Force screen (Fig. 6.1, upper panel) opens with a cart filled with candy in the center of the screen. Each side of the cart has a rope attached, allowing the cart to be pulled to the left or right. Below each rope is a set of puller-people: one large puller, one medium puller, and two small pullers. Each puller can be moved up to the rope above and be placed on one of four rope positions (Fig. 6.1, lower panel). By selecting a large "Go!" button located just below the candy cart, the puller-people will begin pulling, and the cart will move either to the left or to the right, or it will stay in place, depending on the net force applied by the pullers.

In addition to the interactive objects in the sim, there are also pedagogically useful representations that appear when objects are interacted with. When pullers are moved onto the ropes, a vector representation appears above the candy cart to indicate the amount of force the pullers can apply to that side. Additional options in the upper right side of the screen allow for viewing of other representations: numerical values for the forces being applied by the pullers and a sum of forces vector that indicates the net force all pullers on the ropes can apply to the candy cart.

6.1.2.2 Motion Screen

The Motion screen (Fig. 6.2, upper panel) opens with a crate on a skateboard, next to a pusher-person. At the bottom of the screen are different objects that can be stacked onto the skateboard, including a second crate, a refrigerator, a girl, a man, a trash can, and a mystery box. The pusher-person can apply a constant or an instantaneous force through direct interaction with the pusher-person or through interaction with buttons or the slider at the bottom of the screen. As the pusher-person applies force to the object(s) on the skateboard (Fig. 6.2, lower panel), a vector representation appears indicating the magnitude and direction of this force. As with the Net Force screen, additional representations can be selected, showing the numerical value of the applied force, the mass of each object, and the speed of the skateboard when in motion.

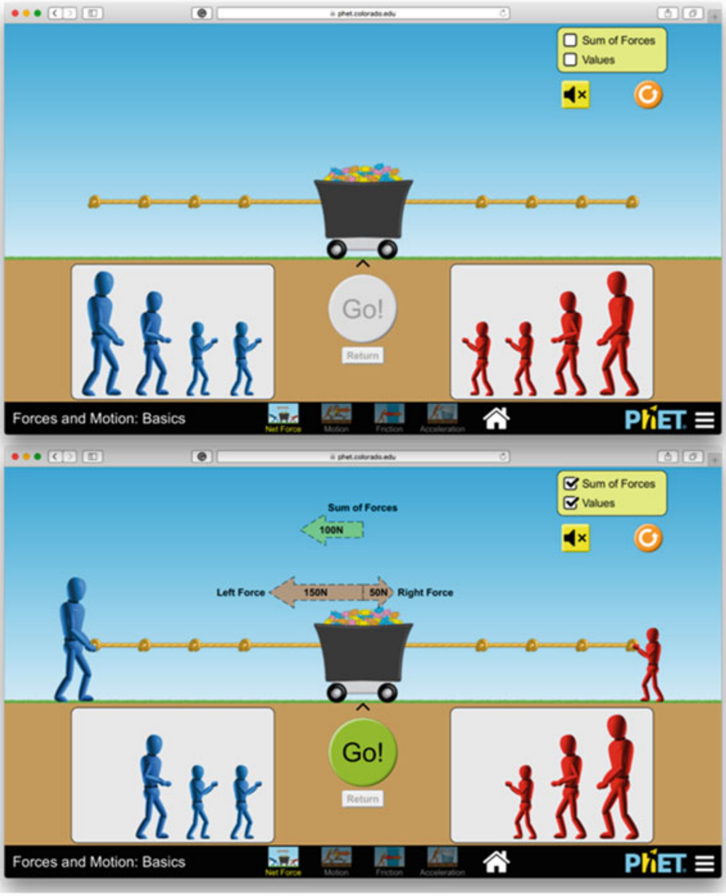

Fig. 6.1 (Upper panel) Screenshot of Net Force screen upon startup. (Lower panel) Screenshot of Net Force screen with puller-people placed on the ropes. The force vectors for each side of the cart and the sum of forces vector are visible

The two other screens available in this sim include the Friction screen and the Acceleration screen. These two screens are similar in layout and interaction to the Motion screen, with a new stackable object (large glass of water), representation (acceleration indicator), and control (friction slider) that support experimentation of friction and acceleration concepts.

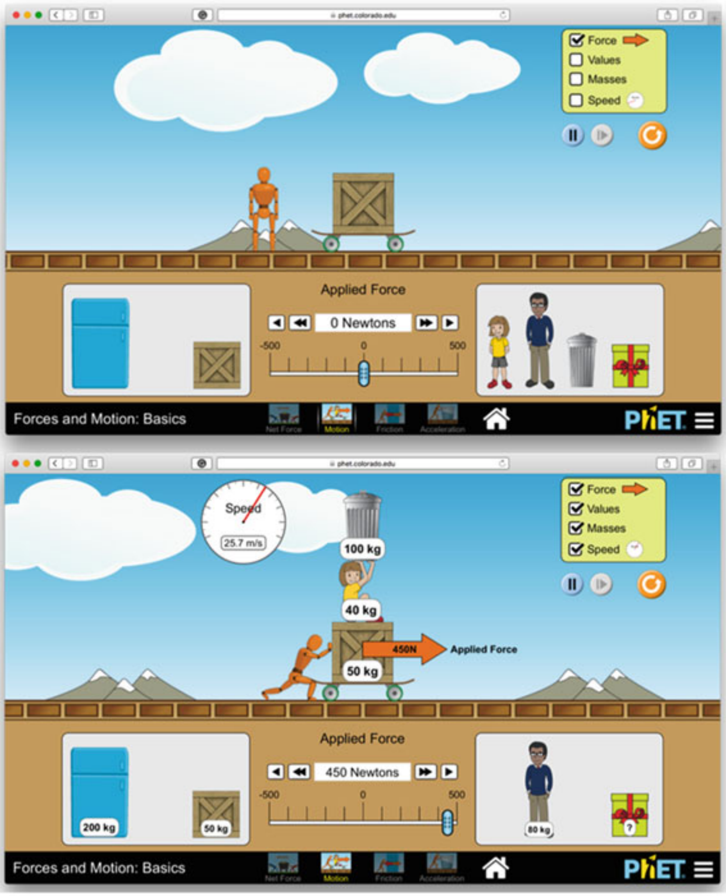

Fig. 6.2 (Upper panel) Screenshot of Motion screen upon startup. (Lower panel) Screenshot of Motion screen with a crate, girl, and trash can on the moving skateboard. The force value, mass values, and speed of the skateboard are visible

6.1.3 Addressing PhET's Goals with Forces and Motion: Basics

6.1.3.1 Engage in Scientific Exploration

Each PhET sim has the goal of engaging students in scientific exploration. In the Net Force screen, the interactive objects were chosen and designed to pique students' curiosity about moving the candy cart. The implicit goal of moving the candy cart encourages student exploration, while the presence of discrete force appliers (the large, medium, and small puller-people) supports students in setting up controlled (and easily repeatable) experiments as they explore. Thus, the resources provided to students through the sim (e.g., discrete force appliers, target locations to place the force appliers) are chosen to interest students and simultaneously enable them to notice relationships necessary to meet the learning goals of the sim.

6.1.3.2 Develop Conceptual Understanding

Beyond exploration, it is also important that students are supported in developing a conceptual understanding of the sim topic. We frequently use representations, such as the vector representations in the Net Force screen, to provide a bridge between the physical system students are exploring and the disciplinary representations used by scientists to understand the topic. In the Net Force screen, students can utilize the on-screen physical system (cart, rope, and puller-people) to make sense of the vector representations overlaid on-screen (e.g., each addition of a puller-person to the right-side rope increases the length of the right-side vector). Conversely, students can also use the vector representations to make sense of the physical system (e.g., when adding pullers to the rope in such a way that the net force is zero, the candy cart will not move).

6.1.3.3 Make Connections to Everyday Life

Where possible, we seek to provide connections between the topic and representations being explored in the sim and the everyday life of students. In the Motion screen of the sim, students are exploring motion with the use of a skateboard, and students can stack everyday objects (e.g., a refrigerator or a trash can) onto the skateboard. By providing opportunities for students to explore everyday objects within the sim, we can support students in recognizing science as a tool for understanding their world.

6.1.3.4 View Science as Accessible and Enjoyable

We aim to support students in viewing science as a discipline that any person can be a part of, and that can be a lot of fun, by providing science resources that support positive experiences. Our goal is that after using the *Forces and Motion: Basics* sim, students have enjoyed their own exploration, furthered their understanding of forces and motion, recognized connections between their investigations of the sim and that of the world around them, and are inspired to continue learning and enjoying science.

6.2 Innovations of PhET Interactive Simulations

The PhET project was started in 2002, during a time of tremendous change and growth in the creation and use of educational technology. Early philosophical perspectives became codified into the three innovations we describe below, each resulting in a set of approaches, practices, and/or resources that set the infrastructure on which the current advances rest.

6.2.1 Design: Flexible and Scaffolded

PhET sims are each designed to support a variety of teaching practices (Wieman et al. 2010; Hensberry et al. 2013; Moore et al. 2013, 2014). The sims can be used as part of lecture demonstrations, labs, in-class individual or group activities, online classes, and homework assignments. This flexibility is made possible by the open-ended design of the sims. There is no single preferred learning pathway through a sim; rather there are multiple learning pathways that can address different learning goals in different sequences. The absence of explicit instructions allows for teachers to embed the sims into their curriculum in many ways and to craft learning experiences with sims that align with their pedagogical goals, context, and practices. For examples of activities teachers have created with the *Forces and Motion: Basics* sim, see teacher-submitted activities under "For Teachers" at https://phet.colorado.edu/en/simulation/forces-and-motion-basics.

Though there are multiple learning pathways through a sim, there are some that more efficiently support the sim's primary learning goals. To highlight these pathways, PhET sims are designed to scaffold student understanding without the use of explicit instructions. We achieve this scaffolding using multiple design strategies collectively referred to as *implicit scaffolding* (Paul et al. 2012; Podolefsky et al. 2013). Implicit scaffolding includes strategies for selecting the scope of each sim and sim screen, supporting students in immediately engaging with each screen through interaction, and enabling continued engagement for sense making and understanding of the sim's learning goals.

When designing the *Forces and Motion: Basics* sim, we selected a set of 3–5 learning goals for each screen. For example, learning goals for the Net Force Screen include: (1) identifying when forces on an object are balanced or unbalanced, (2) predicting how the net force on an object will affect its subsequent motion, and (3) determining the sum of multiple forces on an object and the net force on that object. This set of learning goals is broad enough for a screen design that supports exploration of multiple relationships while being narrow enough for a screen design to implicitly support achievement of all the learning goals.

Each sim screen, upon startup, is designed to implicitly highlight a pedagogically useful starting interaction, for example, moving the candy cart in the Net Force screen of *Forces and Motion: Basics*. In this example, the presence of the large colorful cart in a central location with ropes attached for pulling is intended to cue students that getting the cart to move is a useful task. Providing this visual cue for a starting interaction can also serve to indicate to students that using the sim involves self-directed interaction, rather than passive observation (Moore et al. 2013). We design this initial cued interaction to result in the encounter of pedagogically useful relationships and representations, supporting sim use that leads into a process of experimenting and sense making. It is important to note that each screen is designed to only cue students to make certain useful interactions and it does not require them to start with these interactions. Implicit scaffolding highlights pathways that can be followed or not. As students continue interacting, the available objects (such as the differently sized people-pullers) and representations (such as the net force vector) are designed to support students in experimentation and sense making.

The approach to design the sims without embedded explicit instructions was a departure from the norm in the development of digital educational resources. Rather than creating simulations as a component of a particular curriculum, with a narrowly defined set of contexts for use, the PhET project created highly flexible sims that can be used across a wide range of student age groups, classroom contexts, and teaching practices while also supporting students to engage productively with the sims without explicit instructions (Perkins et al. 2014).

6.2.2 Dissemination: Open Licensing and Broad Compatibility

The PhET project adopted a dissemination strategy that involves an open licensing policy, with no-cost access, broad device compatibility, and online and offline use. Open licensing supports hassle-free no-cost use by teachers and students, which aligns with our belief that high-quality educational resources should be available as free public resources. In addition, PhET's licensing allows use and modification (with attribution) by third-party vendors such as textbook publishers. PhET sims are developed for broad device compatibility and can be run on desktops, laptops, tablets, and mobile devices using multiple operating systems and Internet browsers. The sims can be accessed and run online (no download required) or downloaded for offline use and distribution. The combination of these dissemination approaches has resulted in broad uptake of the sims by schools, teachers, students, and third-party vendors around the world. Additionally, these dissemination approaches influence the infrastructure decisions made by the project, and all design and development decisions are made while keeping in mind the opportunities and constraints inherent when working within a project with a focus on broad dissemination.

6.2.3 Diversity: Translation

As international use of the PhET sims increased, we began to seek out ways to further support learners from diverse backgrounds. The PhET project developed a translation tool (Adams et al. 2012) which allows volunteers around the world to translate the PhET sims and the PhET website into their local language or dialect. Translated versions of sims are available from the PhET website. Because of the translation tool and the efforts of many volunteer translators, the PhET sims are available in 87 languages and the full website is now available in 40 languages. While in many countries students are encouraged or required to learn the English language, we did not want English language skills to serve as a barrier to sim use. Developing this translation capability supported worldwide use of the sims.

Through the development and implementation of these innovations in design, dissemination, and diversity, the PhET project has become a leader in interactive simulation design, and PhET sims have become ubiquitous in science classrooms around the world.

6.3 New Advances in PhET Interactive Simulations

In 2013, the PhET project transitioned from developing sims in Java and Flash to developing sims in HTML5 – the new development standard in online educational resources. This transition provided a unique opportunity to build into the PhET sim infrastructure capabilities that were not possible in Java or Flash, build upon the expertise the project team had gained over the previous decade, and advance new opportunities for innovations with PhET sims. Through two initiatives, PhET-iO and accessible PhET sims, we are focused on increasing interoperability and accessibility of the sims.

6.3.1 PhET-iO: Interoperable PhET Simulations

Education is experiencing vast changes, including the rise of online delivery of educational resources (Beetham and Sharpe 2013), the emergence of adaptive and personalized learning environments, the demand for more engaging and interactive learning environments, and an emphasis on measuring learning progress. The learning goals themselves are shifting in science (e.g., in the United States, the Next Generation Science Standards (NGSS Lead States 2013) and in school more broadly (Trilling and Fadel 2009)), with a focus on deeper learning of content through engagement in science practices, critical thinking, and problem-solving. While interactive sims provide rich opportunities to engage students in science practices and to develop deep conceptual understanding in an online environment, the original Java and Flash PhET sims lacked certain capabilities, limiting their ability to address emerging needs in the changing education landscape. For example, the original Java and Flash sims offered no customization or configurability, no access to information about student interactions with the sim, and no communication between sims and the digital environment in which they are used.

With PhET-iO sims, we empower instructional designers with a new set of interoperable capabilities, eliminating these limitations and enabling many new pedagogical opportunities. The new capabilities include customization and configuration, integration, and real-time data.

6.3.1.1 Customization and Configuration

With PhET-iO sims, the configuration and the starting conditions of sims can be customized. For example, instructional designers can hide or show controls, hide or show any visual element, change labels, fix slider values, pre-configure a scenario, disable actions, or limit which sim screens are available. These options give the instructional designer significant ability to alter the implicit scaffolding within the sims, supporting greater alignment between the sim configuration and specific learning or assessment activities – whether embedded in an e-textbook, used as a virtual lab, or designed as a homework problem.

6.3.1.2 Integration

With PhET-iO sims, you can create an integrated learning environment where a customized sim is surrounded (or wrapped) by other instructional design elements – e.g., prompts, tables, graphs, and buttons – and can communicate with these elements. Each PhET-iO sim uses a versatile application protocol interface (API) that specifies how the software code of the instructional "wrapper" interacts with the sim to enable a range of functionality. For instance, you can load or save the sim state, record data into a table, take a screenshot of the sim, and monitor achievement of a goal. These capabilities can also be combined to create innovative interactive learning or assessment activities.

6.3.1.3 Real-Time Data

PhET-iO sims include multiple data streams that fully capture student usage and can be used in diverse ways – from real-time monitoring of student performance, to driving adaptive learning environments, to providing summaries of student use for teachers. The three data streams are (1) the event stream which logs every user interaction (button press, object dragging, slider setting, etc.) and any resulting change in the sim, (2) the state stream which logs the entire state of the sim every time the state changes, and (3) the input stream which logs the mouse or touch history (locations, clicks, holds, drags, etc.). The instructional designer decides which data streams to enable, monitor, or save to a server and how to employ that data in their learning or assessment environment.

6.3.1.4 Pedagogical Scenarios Enabled by PhET-iO

With the ability to mix and match any of these features, there is significant new advancement in the flexibility and opportunity to improve existing educational products and to create innovative new learning and assessment environments. Below, we look at how these features can be leveraged within three different learning environments: an e-textbook enhanced with an interactive learning experience, an online activity engaging students in science practices, and a homework or assessment task.

6.3.1.4.1 Enhancing the e-Textbook

While substantial research highlights the improved learning that accompanies active learning environments, passive content delivery is still pervasive. By embedding a customized PhET-iO sim, e-textbook authors can provide a targeted interactive experience that is specifically aligned to a concept the moment it is discussed. For instance, consider a passage where an e-textbook explains “When an object at rest is experiencing an applied force, the force of friction will exactly counter the applied force until the moment the object starts moving.” The author could use the customization features of the *Forces and Motion: Basics* sim to create a highly constrained version of the sim to focus student interactions on experimenting with this one idea. The sim shown in Fig. 6.3 has been customized to include only the Friction screen with friction set to its default (moderate) value, speed and force values displayed, one object (the crate) to interact with, control panel hidden, and the background clouds and mountains removed. Student interaction is constrained to applying a force, and when applying an increasing force, they see the opposing force of friction exactly cancels until the crate starts to move. An example of this highly customized sim version can be found from https://phet-io.colorado.edu/examples/etextbook_friction. The addition of customized PhET-iO sims can be a powerful tool to help students interpret a complex idea in an e-textbook.

6.3.1.4.2 Engaging Students in Science Practices

In the United States, the Next Generation Science Standards (NGSS Lead States 2013) have elevated the goal to authentically engage students in science practices, such as planning and carrying out investigations, analyzing and interpreting data, and constructing explanations. Currently, sim-based lessons often include a printed activity sheet and a facilitating teacher, both providing thoughtful prompts and

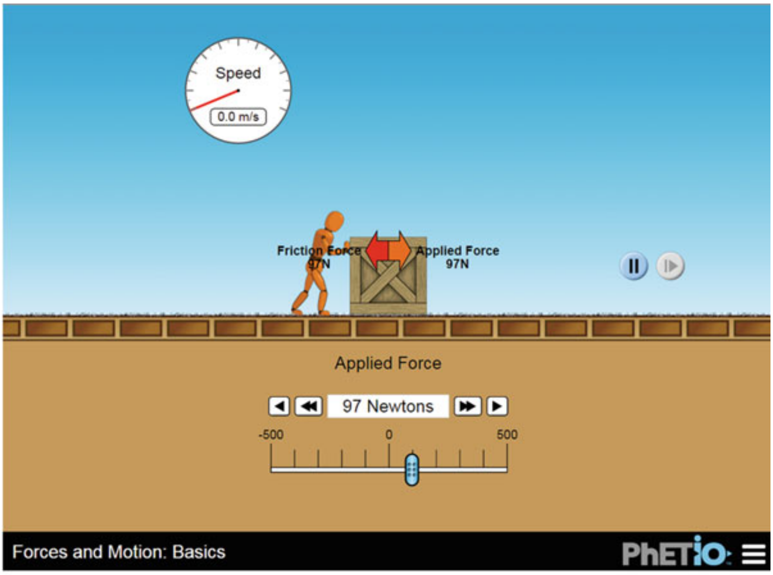

Fig. 6.3 Screenshot of Friction screen customized using PhET-iO capabilities. The pusher-person and crate are on a surface with moderate friction, the force slider is available for interaction, and the speedometer readout is visible. Example sim available at https://phet-io.colorado.edu/examples/etextbook_friction

structures designed to engage students in science practices while the sim serves as their exploratory environment (Moore et al. 2014). PhET-iO sims enable new opportunities to achieve similar goals in integrated and fully online learning environments.

The PhET-iO sims can be used with a variety of instructional approaches with varying features and degrees of scaffolding – from specific models such as the 5E instructional model (Bybee et al. 2006) to instructional designs that share general features of inquiry-based learning (Pedaste et al. 2015). This flexibility is enabled by the use of the implicit scaffolding in PhET sims together with the capabilities of PhET-iO, which supports a wide range of scaffolding and pedagogical approaches.

In this example (Fig. 6.4), students use the Net Force screen of the *Forces and Motion: Basics* sim as an introductory activity toward achieving the Next Generation Science Standard (NGSS Lead States 2013) "Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object." The instruction moves the student through five stages – predict, explore, experiment, reflect, and apply. The activity is available from https://phet-io.colorado.edu/examples/student_investigation_netforce.

Making significant use of the PhET-iO customization and communication capabilities, the sim configuration can be aligned directly with the tasks students are asked to engage in. For instance, when on the Predict tab of the activity, the sim

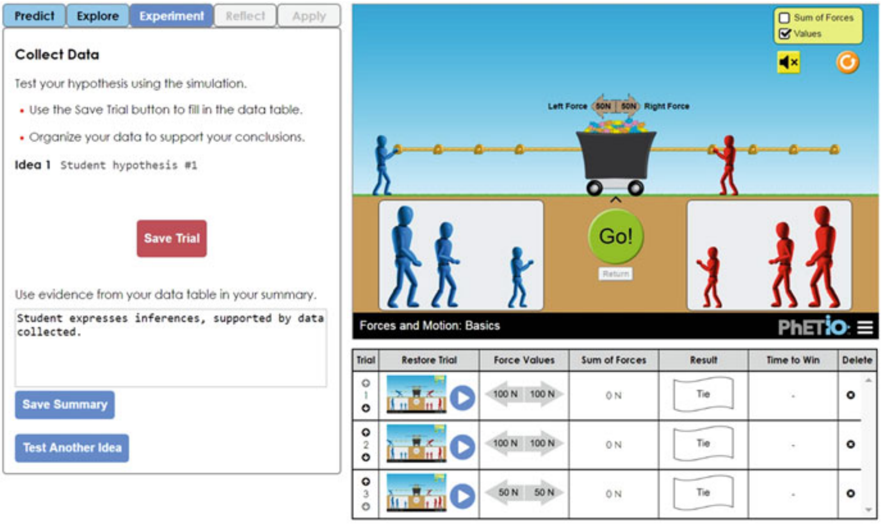

Fig. 6.4 Instructional wrapper for the *Force and Motion: Basics* sim. The "Experiment" tab prompts students to develop a hypothesis and organize their data. The "Save Trial" button collects data from the embedded sim into the table below. Example simulation available at https://phet-io.colorado.edu/examples/student_investigation_netforce

includes only preset scenarios for students to evaluate, with interactions disabled. On the Explore tab, students are invited to "play with the simulation." They are given access to all of the sim controls and readouts and are asked to describe what they notice about how force affects the cart motion. When on the Experiment tab, students are asked to articulate specific ideas they want to test and then test each idea with the sim. Using the capabilities of the PhET-iO API, the wrapper in the Experiment tab enables students to collect data into a table and organize that data with the simple push of a button. The Reflect tab asks students to generalize, writing a set of rules to predict which team wins. They continue to have access to the sim to collect more data into a table, as needed. The Apply tab presents students with four scenarios and asks them to use their rules to predict the outcome and support their reasoning. This tab uses PhET-iO to configure each scenario and to disable sim interaction until the student completes their predictions. With PhET-iO sims, *all* interactions with the sim can be logged, capturing the details of the students' sim explorations and providing the opportunity to analyze their informal exploration practices.

These same PhET-iO capabilities can be leveraged within many existing instructional environments. For instance, this same sim can be integrated within the Go-Lab project's inquiry learning spaces which scaffold students through an inquiry cycle (de Jong et al. 2014), and, indeed, the Go-Lab team has successfully used the PhET-iO API to integrate PhET sims into their environment. Importantly, for any sim-based integrated activity, the student experience and learning outcomes will depend on the details of the instructional tasks, sequencing, and interface design.

6.3.1.4.3 Rethinking Homework or Assessment Tasks

In science, most homework and assessment questions engage students in solving quantitative or conceptual problems, with little engagement in science practices such as planning and carrying out experiments. With the customizability of the PhET-iO sims, instructional designers can create authentic tasks requiring experimentation. In Fig. 6.5, the Motion screen has been altered to provide only four objects and remove the option to show mass, creating a scenario in which students can be challenged to experiment to determine the relative mass of the objects from lightest to heaviest and to justify their reasoning with evidence from the sim. This activity can be extended further, asking the students to collect data using the sim and a timekeeping device to determine the mass of the gift box.

The sim's data streams provide the opportunity to monitor a student's interaction with the sim and examine student problem-solving abilities. For instance, the data streams capture a student's investigative strategies over the course of their sim use and can be analyzed for a student's use of (or lack of) a control-of-variables

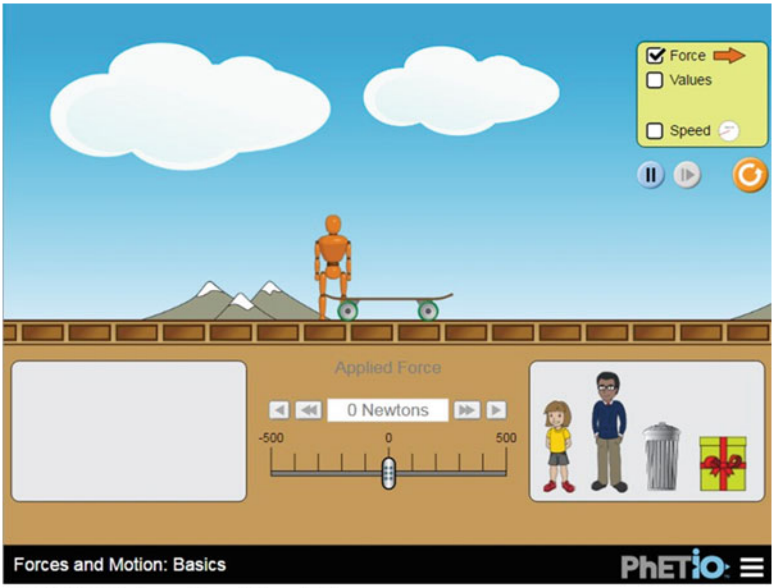

Fig. 6.5 Screenshot of Motion screen customized for the challenge "Experiment to determine the four objects relative mass from lightest to heaviest" using PhET-iO capabilities. Four objects are provided, with the option to view mass removed

strategy. Does the student repeat a similar series of events with each object, allowing comparison? Does the student simplify the scenario or do they create complex scenarios of multiple objects and varying forces? Does the student use the measurement tools available, showing the speedometer and its values? Indeed, in examining this type of interaction data from a different simulation, Käser et al. (2017) found that exploration strategies can be distinguished and can be a significant predictor of learning outcomes. PhET-iO sims present emerging opportunities for personalized learning environments using learning analytics to leverage these data streams for real-time monitoring, providing analysis to inform teachers' classroom facilitation or to provide feedback to students in the form of new prompts or questions.

6.3.1.5 The Future of PhET-iO

PhET-iO began with a working group of educators, researchers, instructional designers, and company representatives gathering to define the new capabilities needed to enable next-generation, simulation-based learning and assessment environments. While many of these capabilities are now realized with PhET-iO, and simulations can be integrated in a wide variety of educational resources, significant work remains. Advances in techniques are needed for analyzing, visualizing, and making use of the fine process data that captures student interaction with the simulations. With these new capabilities, advances in research and methodologies are needed – in both classroom-based and online learning environments – to inform effective instructional wrapper and task design as well as effective facilitation structures. We will continue to explore this frontier together with our research partners, with the immediate next steps of outfitting more simulations with PhET-iO capabilities, advancing our understanding of sim-based science assessment, and supporting the use of these simulations and capabilities in the broader educational market. We invite others to join this endeavor. Additional information is available at https://phet-io.colorado.edu.

6.3.2 Accessible PhET Sims

Students with disabilities are currently not able to participate in science to the same extent as their nondisabled peers, with a low percentage of students with disabilities found in the sciences at the primary, secondary, and career levels (Moon et al. 2012; National Center for Education Statistics 2011; Stevens et al. 2015). For example, in the United States, 13% of the general population have disabilities, while only 4% of graduate students have disabilities (National Center for Science and Engineering Statistics 2015). A contributing factor to the absence of students with disabilities in science is the lack of high-quality accessible science learning resources.

The current paradigm in interactive simulations involves the design, development, and implementation of browser-based HTML5 applications with highly visual dynamic interfaces and the use of mouse, trackpad, and touchscreen for student input. This recent movement toward implementation in HTML5 and design for touchscreen tablet devices has significantly increased the cross-platform compatibility of these science resources but is insufficient to support access for many students with disabilities. Truly accessible interactive simulations require the expansion of interactions to include more input and output modalities, to match the true span of human diversity in perception and correspondence.

The accessible PhET sims initiative has focused on the addition of three new modalities for sim input and output – keyboard navigation, auditory descriptions, and sonification. You can experience the latest accessible sim prototypes and access video demonstrations of accessibility features at http://phet.colorado.edu/en/accessibility.

6.3.2.1 Keyboard Navigation

Keyboard navigation allows users to interact with the sims using only the keyboard (Schreep and Jani 2005). For example, in the Net Force screen of *Forces and Motion: Basics*, a student can press the Tab Key to navigate to different groupings of interactive features (e.g., the left group of puller-people). By pressing the Enter Key, the student enters the grouping and can then go on to select an individual puller and place them at a knot of their choice on the left-side rope. Once the student has added their chosen puller-people to their chosen rope knots, pressing the Tab Key will access the "Go" button. Once on the "Go" button, pressing the Enter Key selects "Go" and will initiate puller-people applying force to the rope.

Keyboard navigation benefits students with mobility impairments who are unable to easily use a mouse, trackpad, or touchscreen device. In addition, the implementation of keyboard navigation supports other alternative input devices, such as *switch devices* (where all keypresses are made through the use of a single physical button) and *sip-and-puff devices* (where all keypresses are made through inhaling and exhaling through a straw-like assistive device).

6.3.2.2 Auditory Descriptions

Auditory descriptions allow users to hear output from the sim through text-based descriptions and read through assistive software called *screen readers* (Massof 2003; "NVDA," n.d.). These descriptions provide nonvisual access to the sims and include real-time description of all interactive features, updates of changes in the sim as the user interacts, and a continuously updated summary of the overall state of the sim. When using the Net Force screen using a screen reader, upon opening the screen the student hears the name of the sim screen. Using keyboard presses, the student can use their screen reader to navigate through a Scene Summary, which provides a brief text description of the different on-screen features (e.g., “A cart with a rope attached to either side,” “Two groups of puller-people,” etc.) and the current state of each object. Students can also navigate to each interactive element (e.g., the puller-people, the “Go” button, the checkbox options for views). At each interactive element, the student can hear a description of the object (e.g., “Large Puller,” “Medium Puller,” “Button: Go! Initiates Pullers”). Upon selecting an object, the student hears any available options (such as how to move a puller-person to the rope) and any on-screen changes to the sim. For example, if a student has added a single large puller-person to the left side of the rope and selected the “Go” button, the screen reader would then read out a description of the motion of the cart to the left.

Auditory descriptions benefit students who use screen readers to access digital information, students who are blind or visually impaired, as well as students with certain learning disabilities.

6.3.2.3 Sonification

Sonification is the use of nonspeech sound to convey information (Kramer et al. 2010). While many PhET sims have sound effects emphasizing particular interactions or outcomes, sonification is the use of sound to convey information about an underlying model or data set. A classic example of sonification of data is a Geiger counter, which is a physical instrument that conveys the level of nearby radiation through a change in the rate of a series of clicking sounds. In the Net Force screen, sonification can be used as a nonvisual way to convey the magnitude and direction of the vector arrows as puller-people are added or removed from the ropes, as well as the speed and direction of the cart when in motion.

This information can also be determined visually, or provided in text description, but a sound mapping of the movement of the cart provides a new modality to access this information that can benefit students who are blind or visually impaired and also benefit students without any visual impairments to utilize a new input channel (audio) to convey subtleties of the acceleration.

While web development standards exist to guide the development of accessible web pages, interactive simulations are not structured like most web pages. To implement the features described above in PhET sims, we have developed an innovative accessible structure called a *Parallel Document Object Model* (PDOM) that couples with each sim. The PDOM updates as the state of the sim changes and provides the necessary communication between the sim and input/output devices (such as keyboards, screen readers, and speakers). The PDOM is an advance in infrastructure that supports the addition of new accessibility features as the accessible PhET sims initiative progresses and can be used as a model for the implementation of accessibility features by other interactive simulation development groups.

6.3.2.4 Pedagogical Scenarios Enabled by Accessible PhET Sims

Accessible PhET sims have the potential to transform the classroom experience for students with disabilities, their teachers, and their nondisabled peers. For example, here are two scenarios highlighting the innovative learning experiences accessible PhET sims could support.

6.3.2.4.1 Collaborative Science Inquiry

Kenzie, Iris, and Anouk are using the PhET sim *Forces and Motion: Basics* to explore net force as part of an in-class activity. Their teacher has asked them to explore the Net Force screen and discuss how the sum of forces vector arrow can help them predict the direction of the cart's motion. The three students share Anouk's computer, which has screen reader software that Anouk can control with her keyboard. Anouk is also wearing bone conduction headphones, which rest behind her ears and allow her to simultaneously hear the screen reader and the people in the room around her.

The students each take turns controlling the computer. Kenzie and Iris use a mouse, and Anouk uses the keyboard. Kenzie places all the left-side pullers on the left-side rope and clicks "Go." Anouk hears a description of all Kenzie's actions as he interacts with the sim, as well as the resulting changes to the sum of forces vector. When Kenzie clicks "Go," Anouk hears a description of the cart's motion. The students discuss the relationships between the size of the puller-people on the rope and the length and direction of the net force vector. Anouk would like to experiment with what happens when you put all the puller-people on the ropes, four pullers on the left and four pullers on the right. Using her keyboard, she navigates to each puller and puts them each on a rope, listening to the description of the change to the sum of forces vector as she goes, and then navigates to the "Go" button. Kenzie and Iris can see the changes in the sim as she does this. Before selecting the "Go" button, each student makes a prediction about the motion of the cart. Anouk selects "Go" and hears a description of the cart's motion from her headphones, and along with Kenzie and Iris, she announces who had the correct prediction – Iris!

Notice how, in this example, the student who is blind is able to seamlessly participate in the learning activity with her sighted peers. She could utilize her screen reader software and bone conduction headphones to follow along with auditory descriptions as her peers experimented, and as she experimented her peers could follow along visually. Rather than resulting in an impediment to her inclusion, the sim provided an opportunity for all of the students in the group to engage in science inquiry together. Also of note, the teacher did not have to provide an alternative activity for the student who was blind. With the appropriate assistive technology and the accessible PhET sim, no alternative activity was needed.

Other groups in this same classroom could include a student with mobility impairments using a keyboard rather than a mouse to interact with the sim and a student with a learning disability that benefits from having verbal description of visual information. In each case, the accessibility features of the sim could be used so that all students in the group could participate fully in collaborative science inquiry.

6.3.2.4.2 Multimodal Science Learning

Marie is sitting at the kitchen table with her mother's laptop, completing a homework activity for her middle school science class. In this homework activity, students are to use the PhET sim *Forces and Motion: Basics*. One of the questions prompts Marie to compare two conditions in the Net Force screen, one in which there is one large puller on one side of the cart and one small puller on the other side of the cart, and a second condition with the same setup but the small puller is replaced with a medium puller. Marie is to write three observations she makes when comparing these two conditions.

First, Marie takes a few minutes to explore the Net Force screen, adding and removing puller-people, determining how to make the cart move to the left and to the right with the puller-people, and turning on the sum of forces vectors and seeing how adding and removing puller-people cause the force vectors to change. Marie then sets up the first condition in the homework activity, one large puller on one side and one small puller on the other side. She observes that the force vector arrow on the large puller side is larger than the force vector arrow on the small puller side. She selects "Go" and observes the cart move in the direction of the large puller. Marie also has sound "on" and hears a tone representing the speed of the cart increase in pitch as the cart speeds up. Marie then sets up the second scenario, by replacing the small puller with a medium puller. She selects "Go" and again observes the cart move in the direction of the large puller and hears the tone representing the speed of the cart increase in pitch more slowly. Marie writes down her three observations: (1) the force vector for the small puller is smaller than the force vector for the medium puller, (2) the sum of forces vector is larger for the condition with large puller versus small puller than in the scenario with large puller versus medium puller, and (3) the cart increases in speed faster in the condition with large puller versus small puller than in the condition with the large puller versus medium puller. Marie then goes on to explore how to get the cart to increase in speed the quickest and to make the tone change in pitch the fastest.

In this scenario, Marie does not have a disability that we are aware of, but still makes use of the sim's sonification feature (the change in tone correlated to the change in speed of the cart). While exploring the sim, she observes the visual representations like the force vector arrows. The addition of sound provided a new modality to cue a potential relationship between the applied force by the pullers and the speed of the cart when in motion. While this relationship was represented visually by the motion of the cart across the screen, the use of sonification provided a cue using a different modality for Marie to consider. This new modality complemented the visual modality and provided a richer, more immersive learning experience than the visual modality provided alone.

6.3.2.5 The Future of Accessible PhET Sims

The accessible PhET sims initiative started with the design and development of three input and output modalities (keyboard navigation, auditory description, and sonification) for a subset of PhET sims (Moore et al. 2016; Smith et al. 2016). We will continue to refine our understanding of effective design and implementation of these features and implement these features in an expanding set of PhET sims. We will continue to share our knowledge of effective design and software infrastructure with the science education community. We will also explore new input and output modalities, with the goal of supporting all students to engage in science inquiry with PhET sims. To find the most up-to-date information about the progress and findings of the accessible PhET sims initiative, see http://phet.colorado.edu/en/accessibility.

6.4 Conclusions and Future

Since 2002, PhET has been innovating in the design and development of educational simulations. In this chapter, we highlighted some of the historical innovations in design, dissemination, and increasing diversity that we believe have contributed to the broad uptake and now ubiquitous use of PhET simulations around the world. Over the course of more than a decade, the PhET project has refined a set of goals that guide the creation of each PhET simulation. These prior innovations and project goals laid the groundwork for continued advances in educational simulations, and the transition from developing Java and Flash sims to developing HTML5 sims created the opportunity to achieve advances through new initiatives. Through the PhET-iO and accessible PhET sims initiatives, the PhET project continues to advance access and opportunity for students to engage in science inquiry with interactive simulations.

Looking forward, as part of the PhET-iO initiative, we will continue to partner with the broader science education, publishing, and assessment communities to provide opportunities for new and highly effective learning materials and assessments. As PhET-iO enables unprecedented customization, integration, and data collection, there are many open questions for the science education community to investigate to determine contexts, supports, and scenarios that are most effective in enabling student learning. As the publishing industry evolves to focus more on the use and distribution of interactive digital resources, there will be an increasing need to understand how to best utilize the sims data collection capabilities to optimize online environments for learners. The combination of highly customizable sims and rich data collection capabilities enables new approaches to assessment, requiring advances in the analysis of student choices during pursuit of a goal – which is quite a different challenge than analysis of student choices when answering more traditional assessment questions.

The work of the accessible PhET sims initiative will continue research and development efforts to explore new input and output modalities and update new sims with accessibility features, including keyboard navigation, auditory descriptions, and sonification, to support increased accessibility for students with disabilities. New input and output modalities currently being explored include the use of speech input (the ability to speak commands to the sim) and haptic feedback output (force feedback, such as vibration). Through all of these modalities, we seek to broaden understanding of effective accessible design for interactive simulations.

Continuing these advances is challenging work, requiring innovations in software development, interface design, and pedagogy as new learning contexts are envisioned and created. Through the new features developed from the PhET-iO and accessible PhET sims initiatives, the PhET project will continue to advance the capabilities of interactive HTML5 simulations, enabling new pedagogical practices for the technology-enhanced classroom and increasing engaging and effective learning opportunities for students.

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