Theory of Change Model
for
Teaching and Learning Algebraic Thinking with PhET Interactive Simulations

February 2017

Design

Sim Design Characteristics

Sims...

- Focus on important topics in math
- Focus on concepts (not procedures)
- Are accessible and intuitive
- Display multiple representations
- Provide scaffolding for student thinking
- Incorporate supports for teacher facilitation
- Provide connections to real life (when desirable)
- Employ an interaction/feedback design
- Provide an exploratory and game-like environment

Lesson/Worksheet Design Characteristics

Lessons...

- Are focused on the sim & move toward learning goals
- Provide time for open play
- Provide time for student-student collaboration & facilitated class discussion
- Include questions that address big ideas and are open-ended
- Have some scaffolding but not too much
- Provide a resource for capture
- Are accessible

Design Characteristics of PhET Teacher Resources

The PhET Teacher Resources...

- Are user-friendly, easy to navigate, and make it easy to find relevant resources
- Include resources authored and/or tested by teachers
- Are actionable, explaining what to do and giving concrete strategies for implementation
- Provide exemplars of strong implementation
- Offer a variety of strategies, provide options for teachers, and enable adaptation

Implementation

Design Goals

Sims and Sim-based lessons...

- Are engaging, fun
- Make math relevant for students
- Enable student choice and student agency
- Enable students to engage in discovery, exploration, and sense-making
- Focus student attention on the important aspects of the content
- Help make invisible things (e.g., abstract concepts, math conventions, invisible symbols) visible for students
- Provide opportunities for rich discussion
- Support differentiation for both students and teachers

Design Goals

PhET Teacher Resources...

- Enable teachers to select the right resources for their own needs
- Reflect teacher voice and ideas
- Support teachers to actually implement sims in their classroom
- Describe/demonstrate strategies that support particularly strong learning opportunities and nudge teachers toward those strategies
- Provide flexibility so that teachers can use sims—whatever their current pedagogical style and whatever the learning goals

Teacher Roles

Teachers...

- Use the sim as a central and integral part of the lesson
- Give students opportunities to explore and play
- Give students opportunities to share and discuss
- Listen to student ideas and allow students to drive their learning
- Facilitate discussion and thinking, bringing attention to salient math points
- Conclude the lesson by making ideas explicit

Student Roles

Students...

- Engage with the sim as the primary vehicle in the lesson
- Explore and play
- Share and exchange ideas
- Act as agents of their own learning
- Think about math
- Reflect and revise

Outcomes

Student Outcomes

Students...

- Have a better understanding of math concepts
- Develop a positive affect toward math: enjoyment, interest, motivation, confidence, and ownership of their learning
- Have new and productive perceptions about what math is
- Are proficient with using technology for math learning

Teacher Outcomes

Teachers...

- Believe that sims can transform learning and support conceptual understanding
- Engage in innovative and student-centered instruction
- Have the ability to address multiple learning goals (e.g., content, process, argumentation, enjoyment) within a single lesson
- Improve their knowledge of using technology to teach math

Program Outcomes

The PhET program...

- Operates at scale, with large numbers of teachers and students using sims effectively
- Advances the field of math education

Fertile Ground

Teacher Characteristics

- Confident
- Knowledgeable
- Tech friendly
- Committed to all students' learning
- Oriented toward student-centered instruction

Student Characteristics

- Prerequisite math knowledge

Classroom Norms

- Teamwork
- Cooperation
- Contributions are valued
- Student-centered
- Sense of community and belonging

School-level Supports

- Teachers have the time and flexibility to incorporate sims into instruction
- Teachers and students have adequate technology (e.g., sufficient devices, reliable internet)

PhET Middle-Grades Math Sims
Narrative Description of the Theory of Change Model
February 2017

Introduction

During the later half of 2016, the PhET team, in collaboration with SRI International, created a Theory of Change to describe the PhET middle-grades math sims and how they work to support math learning. This document accompanies the Theory of Change diagram. While the diagram can and does stand on its own, this document provides additional narrative to further describe and explain the model.

The purpose of the Theory of Change model and accompanying narrative is to thoroughly yet succinctly articulate what the middle grades math sims are, what they do, how they work and under what conditions, and what outcomes they aim to achieve. This kind of articulate vision serves many purposes:

- ***Shared vision:*** Having a clearly articulated model helps to ensure that everyone involved with the project is operating under the same assumptions and working toward the same ends. PhET may also choose to share the Theory of Change with external partners or funders, to help communicate their work.
- ***Guide for Development:*** The Theory of Change provides a framework for informing design decisions and checking products. For example, when selecting a topic for the next middle-grades math sim, developers should be sure that the topic is important within middle grades math curricula and connected to big ideas in mathematics. When working on sim development, designers can check back to the list of design characteristics and design goals to make sure their product meets those descriptions.
- ***Guide for Research:*** The Theory of Change tells us what is important to the math sims program and as such can focus and constrain any research on the sims. The model can be used to help identify salient research questions to study, components of implementation to explore more deeply, and outcomes of interest to measure.

The PhET team drew on their extensive experience with science sims and on research on teaching and learning to articulate this Theory of Change for their middle-grades math sims. The design characteristics and design goals aim to produce a powerful learning experience for students, characterized by guided exploration of key math concepts. The program offers teachers substantial autonomy in how to implement the sims and recognizes that the student experience is mediated by diverse contextual factors including the teacher. While keeping the door open for all kinds of teachers and students to use the sims, the PhET team also hopes to encourage and support teachers to use certain pedagogical strategies that they believe can maximize the potential of sims to produce the desired outcomes.

We note that the shift from science sims to math science is not inconsequential. PhET has extensive experience developing, teaching with, and researching science sims and their use in the classroom to support teaching and learning. While many of the same principles for developing and implementing science sims apply to math sims as well, there are some important distinctions. Notably, the shift from science to math represents a shift from concrete to abstract: while sims in both areas strive to make concepts visible for students, doing so within math sims requires an extra step to transform abstract concepts into something concrete that students can see and manipulate. This important distinction between science and math is one that the PhET team attends to closely in the design of their middle grades math sims.

Further, we note that the Theory of Change describes the vision for how the PhET middle grades math sims operate to support student learning. The linkages between design characteristics, design goals, implementation, and outcomes reflect research-based thinking and rationales—but they have not yet been rigorously tested in the context of PhET math sims specifically.

The Theory of Change model is divided into four main sections: Design, Implementation, Outcomes, and Fertile Ground. We "read" the diagram roughly from left to right, starting with design characteristics of each of the components of the PhET offering—and moving into implementation and outcomes. The "Fertile Ground" section anchors the diagram, enumerating contextual factors that provide an environment conducive to the effective use of sims. The diagram also shows Design Goals, which bridge the gap between Design Characteristics and Implementation. We will discuss each of these sections and sub-sections in turn.

Design

The Design section of the Theory of Change diagram describes the intended concrete design characteristics for each of the categories of PhET resources: the sims themselves, the lessons and lesson worksheets for teachers to use in their classrooms with students, and a broader selection of teacher resources designed to support teachers with using PhET sims as part of their instruction. The design characteristics refer to specific, tangible characteristics of each resource: these are traits or qualities that a designer would intentionally build into each resource—and that a user would see or experience directly. These intended design characteristics do not describe goals for what the resources will accomplish.

PhET Sims Design Characteristics

The centerpiece of any PhET sim lesson, of course, is the sim itself. A set of design characteristics drives the development of each sim, with the goal of producing sims that are grounded in a coherent vision for how to support math learning. The table below lists the design characteristics that sim developers hope will be evident in the sims they create, and provides an explanation and rationale for each.

Table 1: PhET Sims Design Characteristics

Sims are designed to…	**Explanation & Rationale**
Focus on important topics in math	The range of possible topics for middle grades mathematics is vast. PhET sims focus on topics that are central to the middle grades standards and curricula, connect with big ideas in mathematics, and provide an important foundation for building future math skills. In contrast, the sims do not focus on obscure concepts, factoids, or math trivia.
Focus on concepts (not procedures)	PhET sims are designed to highlight mathematical concepts. As such, visual set-up of the sims, the activities therein, are all geared toward emphasizing the target concept. Students do not engage in "drill and kill" or repeated procedural solutions to problems.
Be accessible and intuitive	PhET sims are designed so that users can jump right in: the sims do not include written instructions within the sim, or indeed much writing at all. Instead, the layout and images are designed so that users can quickly grasp how the sim works and begin engaging with the sim right away.
Display multiple representations	PhET sims include multiple representations, including numeric, algebraic, and pictographic representations; graphs; charts; diagrams; pictures, etc. The purpose is both to help students learn different mathematical representations individually and, equally important, to help students make conceptual connections between them.
Provide scaffolding for student thinking	PhET sims include supports for students to help them make sense of what they are seeing and doing. For example, the sims layer conceptual ideas up across screens, they can start with some readouts closed, they can use dynamic visual representations to help students make sense of concepts.
Incorporate supports for teacher facilitation	PhET sims include considerable flexibility and allow rapid change, to enable teacher facilitation. For example, many

	representations can be hidden or shown to enable prediction questioning or elicit student reasoning, or the sim can be paused to enable teachers to step through a dynamic process.
Provide connections to real life (when desirable)	PhET sims often use real-world contexts to situate the sim. These scenarios help make the math more concrete. They can also make content more relevant for students, in turn supporting student interest and motivation.
Employ an interaction/feedback design	PhET sims are designed to be interactive: when a user does something within the sim (manipulates something, changes a parameter, moves an object, etc.) the sim responds accordingly. Through this interaction and feedback, users can explore the sim and develop an increasingly deeper understanding of the mathematics at work.
Provide an exploratory and game-like environment	PhET sims include activities that encourage exploration; many have built-in challenges to motivate the user to continue exploring or to complete certain tasks.

Lesson & Worksheet Design Characteristics

Typically in the classroom, teachers use sims as part of a lesson, oftentimes in conjunction with a worksheet that guides students through their experience with the sim. Based on both experience and research, the PhET team has articulated a set of design characteristics for sim lessons/worksheets that support effective implementation of the sim.

We note that PhET encourages broad use of their sims: teachers can use PhET sims in a wide variety of ways, with or without accompanying lesson materials provided by PhET. The lesson/worksheet design characteristics described here refer first to the lessons/worksheets that PhET creates; and provide suggestions for others who are using sims or creating lesson materials.

Table 2: Sim Lesson/Worksheet Design Characteristics

Sim lessons/worksheets are designed to…	**Explanation & Rationale**
Focus on the sim and move toward learning goals	Using the sim as the centerpiece of the lesson, rather than a tangential or add-on experience, maximizes the opportunity for students to develop a deep understanding of the sim and the math that it explores.

Provide time for open play	Time for open-ended exploration with the sim, particularly at the start of the lesson, enables students to figure out how the sim works and begin making conjectures about the mathematics at play.
Provide time for student-student collaboration & facilitated discussion	Teachers should facilitate discussion to elicit student thinking and draw student attention to salient math points.
Include questions that address big ideas and are open-ended	Open-ended questions that address big ideas provide opportunities for students to reason about important math concepts, to build conjectures, make arguments about their thinking, etc.
Have some scaffolding but not too much	Lessons/worksheets should have enough scaffolding to keep students focused on the important aspects of the math, without eliminating their opportunities to think and reason on their own.
Provide a resource for capture	Having a place to record their work helps students think through the math and remember what they have done.
Be accessible	Students should be able to grasp what the worksheet is asking of them easily, so that they can focus their cognitive efforts on the mathematics.

Design Goals of Sims and Sim-based Lessons

While the design characteristics refer to concrete attributes that designers seek to build into the sims and sim-based lessons and worksheets, the design goals refer to the purpose of those characteristics. That is, the design goals answer the question: What kind of experience do the PhET sims and sim-based lessons aim to build for students? The design characteristics do not, for the most part, have a one-to-one relationship with the design goals. Instead, the design characteristics collectively lead into the design goals to support positive and productive experiences for students.

The Design Goals state that sims and sim-based lessons:

- Are engaging, fun
- Make math relevant for students
- Enable student choice and student agency
- Enable students to engage in discovery, exploration, and sense-making
- Focus student attention on the important aspects of the content
- Help make invisible things (e.g., abstract concepts, math conventions, invisible symbols) visible for students
- Provide opportunities for rich discussion

- Support differentiation for both students and teachers

Design Characteristics & Design Goals of PhET Teacher Resources

In addition to providing simulations and accompanying lesson worksheets, PhET also provides resources for teachers to support the use of PhET sims in the classroom. For example, PhET provides information both about strategies for using PhET sims in general and about integrating specific sims into their lessons. The resources include information, instructional videos, exemplar videos, etc. and are available on the PhET website.

The PhET teacher resources also adhere to a set of concrete design characteristics intended to ensure quality and intentionality across the resources. In the case of the teacher resources, the design characteristics (concrete attributes of the resources) and the design goals (the purpose of those attributes as far as supporting the user experience) do map directly one to the other.

Table 3: Mapping PhET Teacher Resources Design Characteristics to Goals

Design Characteristic		Design Goal
Are user-friendly, easy to navigate, and make it easy to find relevant resources		Enable teachers to select the right resources for their own needs
Include resources authored and/or tested by teachers		Reflect teacher voice and ideas
Are actionable, explaining what to do and giving concrete strategies for implementation		Support teachers to actually implement sims in their classroom
Provide exemplars of strong implementation		Describe/demonstrate strategies that support particularly strong learning opportunities and nudge teachers toward those strategies
Offer a variety of strategies, provide options for teachers, and enable adaptation		Provide flexibility so that teachers can use sims—whatever their current pedagogical style and whatever the learning goals

The first two design characteristics and design goals refer primarily to the PhET website. PhET works to optimize the website, for example, by tagging resources by

subject, topic area, and grade-level, so that teachers can quickly find resources that meet their needs.

The last three design characteristics and associated design goals refer primarily to the individual online resources. These resources are intended to support teachers with integrating PhET sims effectively into their practice. PhET is sensitive about providing resources that open doors for as many teachers as possible, to make it easy and appealing for teachers of all types to make use of the sims. At the same time, PhET does have insights about pedagogical styles and practices that can maximize the potential of the sims for student learning. The resources are designed to delicately balance these two positions: they encourage uptake and enable adaptation so that teachers can use them within their own context and to meet their own needs; they also provide guidance and exemplars to share and gently encourage best practices.

Implementation

The PhET sims, sim lessons and worksheets, and the teacher resources are designed to work together to support effective implementation of the PhET sims in middle grades mathematics classrooms. While the sims and accompanying materials & resources can be used in many contexts and with a variety of pedagogical styles, the design of these products nonetheless lends itself to a particular model of implementation. The Theory of Change diagram describes this model of implementation, focusing on what it means for teacher and student roles in the classroom.

Teacher & Student Roles

The teacher and student roles during a PhET sim-based lesson derive from the design characteristics & goals of the materials, relate directly to one another, and drive toward the desired student learning outcomes. As was the case with the design components of the Theory of Change model, the implementation section similarly describes ideal teacher and student roles, as envisioned by the PhET team. Teachers and students in real classrooms may or may not bear out these roles; oftentimes they may fulfill some roles but not others.

Table 4: Teacher and Student Roles

Teacher Roles		Student Roles
Use the sim as a central and integral part of the lesson		Engage with the sim as the primary vehicle in the lesson
Give students opportunities to explore and play		Explore and play

Give students opportunities to share and discuss		Share and exchange ideas
Listen to student ideas and allow students to drive their learning		Act as agents of their own learning
Facilitate discussion and thinking, bringing attention to salient math points		Think about math
Conclude the lesson by making ideas explicit		Reflect and revise

Outcomes

The core purpose of the PhET middle grades math sims is to help students learn math, particularly to help students gain a deeper understanding of math concepts. Beyond this central goal, the PhET sims also aim to achieve other beneficial outcomes for students and teachers alike—and for the PhET program and the field of math education at large.

Student Outcomes

The PhET middle grades math sims aim to support a variety of academic and non-cognitive outcomes for students.

Table 5: Student Outcomes

Through using PhET sims, students…	**Explanation & Rationale**
Have a better understanding of math concepts	The fundamental purpose of PhET sims is to support student learning, particularly conceptual understanding
Develop a positive affect toward math: enjoyment, interest, motivation, confidence, and ownership of their learning	PhET understands that productive dispositions toward learning in general and toward mathematics in particular are valuable for supporting academic success. The PhET vision is that students need not have these dispositions already in order to be successful with the sims. Rather, the sims can help students develop or strengthen a positive affect toward mathematics. The sims do this through many of the qualities described in the design section, including

	their game-like environment, giving students some autonomy, scaffolding their understanding and success, etc.
Have a new and productive perception about what math is	PhET hopes that students will come to understand that math provides a whole new way of thinking about the world, and that engaging with math allows you to think, explore, and develop ideas about how the world works. The hope is that seeing math in these terms, instead of as a series of facts to be memorized, gives math more relevance and interest for students.
Are proficient with using technology for math learning	PhET sims are a technology-based resource for math learning and, as such, working with sims should help students develop skills with using technology to support their learning. These skills are valuable for success both in school and in the wider world.

Teacher Outcomes

PhET expects that teaching with PhET sims will have certain benefits for teachers as well as for students. Teachers can learn both from teacher resources and from the experience of teaching with PhET sims. The teacher resources are designed to provide direct information and guidance for teachers to help them understand how sims work and how to use them in the classroom. The experience of teaching with PhET sims will in turn give teachers new insights about whether and how sims can support student learning. The teacher outcomes articulated in the Theory of Change represent the outcomes that PhET hopes will occur when teachers use their resources and teach with sims in the classroom.

Table 6: Teacher Outcomes

Through using PhET teacher resources and PhET sims, teachers….	**Explanation & Rationale**
Believe that sims can transform learning and support conceptual understanding	PhET believes that their materials, combined with the experience of seeing PhET sims at work in their own classrooms, will show teachers the value of sims for teaching and learning. Seeing is believing.
Engage in innovative and student-centered instruction	As described above, the PhET teacher resources and sims can support varied teaching styles. That said, the resources highlight student-centered pedagogies, and the sims and sim-based lessons are

	conducive to those same approaches. PhET hopes that teachers who use PhET resources and sims will find themselves engaging in innovative student-centered instruction.
Have the ability to address multiple learning goals (e.g., content, process, argumentation, enjoyment) within a single lesson	The PhET sims provide opportunities for teachers to address different kinds of goals within a single lesson. For example, the focus on conceptual understanding and the interaction-feedback design provide inherent opportunities for teachers to question students about what they think is going on and why. Teachers who skillfully capitalize on these learning opportunities can integrate multiple learning goals into a single lesson.
Improve their knowledge of using technology to teach math	Both the guidance from the teacher resources and the experience & practice of teaching with sims will help teachers develop their skills for using technology to teach math.

Program Outcomes

In addition to supporting positive outcomes for students and teachers, PhET cites two key goals for the PhET middle grades math program overall. First, PhET hopes to operate at scale, with large numbers of teachers and students using math sims effectively. PhET math sims are well positioned for large-scale use because the science sims already have a global audience of many thousands of users.

Secondly, PhET hopes to advance the field of math education. Research on PhET math sims can shed light on multiple topics that are broadly important to the field of math education at the present time. For example, research on PhET math sims could provide insights on questions of how best to use technology to support math learning for all students; relationships between pedagogy and learning; the value of open exploration and argumentation for math learning; the role of the teacher in making ideas explicit for students; and how teacher resources can support effective implementation of supplemental instructional resources.

Fertile Ground

The PhET middle grades math sims can be used in a wide variety of settings, with multiple teaching styles and students from any number of academic backgrounds. Nonetheless, certain contextual factors at the school along with certain teacher and student characteristics, can maximize the value and effectiveness of the sims. This section describes those contextual factors and participant characteristics.

Teacher Characteristics

PhET posits that the characteristics of effective teachers who use sims are essentially the same as the characteristics of effective teachers in general.

Table 7: Teacher Characteristics

Teachers should be…	**Explanation & Rationale**
Knowledgeable	Teachers should be knowledgeable about the content they are teaching—and also about how to teach and how students learn.
Confident	Teachers need confidence to be comfortable with their role in the classroom: comfortable managing students and technology, comfortable leading math-focused discussions, comfortable guiding students toward conceptual understanding.
Committed to all students' learning	Teachers should be committed to making sure that all of their students are learning; they cannot focus on some students to the detriment of others. Such a commitment requires aptitude with differentiated instruction, including an understanding of where students are and how to move them forward.
Oriented toward student-centered instruction	As discussed above, PhET strongly believes that teachers with various pedagogical orientations can make effective use of sims—though a student-centered approach can maximize the potential of sims to engage student thinking and develop an understanding of math.
Tech-friendly	Because sims run on technology, teachers must be open to using technology in their classrooms.

Student Characteristics

The PhET team maintains that the only condition for students is that they have a certain minimum level of pre-requisite math knowledge to engage with the particular sim they are using. The sims, like any other supplemental learning resource, do not teach all of mathematics from the ground up. Thus, in order to engage with, for example, a sim on fractions, students must have a foundational understanding of numbers, addition, subtraction, etc. Beyond this pre-requisite math knowledge, however, PhET does not believe any other student attributes are

required for students to be able to successfully learn from sims. While positive affect (including interest, motivation, etc.) can certainly help students learn, PhET believes that students who do not start out with these attributes can not only still benefit from PhET sims, but will likely begin to develop some of those attributes through their engagement with the sims.

Classroom Norms

The classroom environment influences the teaching and learning that takes place therein. The classroom norms listed within the fertile ground section of the model support teachers and students in fulfilling their roles, as described in the implementation section of the model.

These classroom norms are:

- Teamwork
- Cooperation
- Contributions are valued
- Student-centered
- Sense of community and belonging

Again, PhET does not believe that every one of these norms must be solidly in place in order for teachers and students to benefit from the sims. Rather, these norms support the kinds of teaching and learning—and the kinds of interactions amongst teachers and students—that PhET finds most productive for learning and most conducive to optimizing the value of the sims.

School-level Supports

For teachers to be able to teach and teach well, they must have the time and resources they need to plan, prepare, and instruct. As would be the case for any supplemental resource, teachers who want to use sims need to have the time and flexibility to incorporate sims into their instruction. For sims, like any other technology-based instructional resource, teachers and students must also have adequate technology to enable sim-use. Specifically, teachers need to have a sufficient number of working devices (whether that's just a few and students rotate through or a classroom set where students can work in a one-to-one environment) and an internet connection to access and download the sims.

Conclusion

The Theory of Change model for PhET middle grades math sims describes the characteristics of PhET sims and accompanying resources, and how they operate to support teaching and learning within a school and classroom environment. The Theory of Change provides a thorough yet concise articulation of the vision for PhET sims that can be used to communicate both internally and externally. The Theory of Change can also guide product development (including the development of sims, lessons, and teacher resources) and research (including the definition of research questions and outcome metrics).

Two strands of research are indeed imminent. First, PhET is conducting a pilot study that will look at how math teachers use the middle grades math sims in their classrooms and what that experience is like for teachers and students. They also plan to examine measures of student learning. Second, SRI will conduct external evaluation research looking at how teachers find and make use of the PhET teacher resources and whether and how those resources support teachers to effectively incorporate sims into their classroom instruction. These two lines of research will yield insights that test the Theory of Change, about the extent to which the PhET middle grades math sims (and accompanying resources) are designed and operate as envisioned.