PhET Interactive Simulations

University of Colorado Boulder
Application for The Tech Award, 2011
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Problem Identification

What serious problem or challenge with broad significance does your use of technology address? Explain your context and the existing conditions that you are trying to improve or rectify.

The PhET Interactive Simulations project is addressing a grand challenge that is facing of nations across the world: educating the next generation of scientists, mathematicians and engineers, as well as increasing worldwide science literacy by informing and educating the broader public about science, math, and engineering issues.

THE GLOBAL NEED:
In the US, too many students are failing to learn science. National studies show 46% of 12th graders scoring below the basic level in science with lower results for minority and low socioeconomic-status students (Grigg, Lauko, & Brockway, 2006). In addition, our colleges are neither graduating the number nor producing the quality of science majors needed to fill industries demand or adequately drive innovation. Responding to these data, multiple US reports (e.g. *Rising Above the Gathering Storm*, 2007) have called to increase the number of students pursuing degrees in technical fields and to graduate students who are better prepared to enter the technical workforce and lead the world in technical innovation. They note that improving and investing in math, science, and engineering education is critical to the economic well-being of the US; modern industry needs employees with the problem-solving skills to develop creative solutions to new problems and the flexibility to move effectively into new areas of technological interest. In addition, the Labor Department has shown that of the 20 fastest growing occupations projected for 2014, 15 of them require significant mathematics or science preparation to successfully compete for a job (Bureau of Labor and Statistics, Fastest growing occupations, 2004-14, http://www.bls.gov/emp/emptab21.htm).

These same arguments apply beyond the US to much of the world's population. It is well known that education plays a vital role in the development of nations. But, critical to a nation's sustainable development in our increasingly knowledge-based world is science education. UNESCO believes that science education is key for every person to lead a meaningful life, one that successfully combats poverty and pandemic and emerging diseases. A scientifically literate nation will have sustainable development in cooperation with social and environmental responsibilities. People empowered with science knowledge will be able to get higher-paying skilled jobs. And, people empowered with science knowledge will be able to make better decisions in their own lives concerning their own health and well-being. Indeed, recent studies recognize that students in developing countries themselves see investment in STEM education and interest in science as a pathway to a higher quality of life for citizens (http://roseproject.no./).

The benefits of science education go well beyond this economic perspective, however. The global society is facing increasingly-technical issues, including for example global warming, energy resources and use, environmental pollution, and genetic engineering. The world needs a scientifically-literate public that is capable of evaluating arguments and evidence, and making wise decisions on these critical issues – both at a personal behavior and a policy level.

WHY SCIENCE EDUCATION IS FAILING INSIDE THE CLASSROOM:

Numerous peer-reviewed studies demonstrate that traditional classroom instruction and curricula in the sciences are simultaneously ineffective at 1) motivating and interesting students in science and 2) developing the deep conceptual understanding of science, the scientific process skills, and expert-views of science.

Almost 20 years ago, Professor Eric Mazur of Harvard famously studied his introductory physics students' ability to solve complex algorithmic problems compared to their ability to solve seemingly trivial questions requiring application of basic conceptual reasoning (E. Mazur, Peer Instruction: A User's Manual, 2004). He found that while his students could, for example, proficiently solve for the current and voltage differences in a complex circuit, they could not describe qualitatively whether a bulb would get brighter or dimmer upon closing a switch in a relatively simple circuit – a problem most physics teachers would consider trivial. Despite his highly-praised teaching, his students had failed to achieve a basic conceptual understanding of key physics ideas.

Similar results – students failing to achieve a basic conceptual understanding of key science ideas – have been found across all science disciplines and levels. Professor Richard Hake published a landmark study in physics education where he compiled results from 62 classes with over 6000 students who had taken the Force Concept Inventory exam – an exam that measures students' basic conceptual understanding of force and motion (American Journal of Physics, 1998). The exam includes no calculation questions – instead it probes students' ability to qualitatively apply some key physics ideas to everyday scenarios. For instance, one question shows a ball moving through a circular track that extends around three-quarters of a full circle, and asks what path the ball will take when it leaves the track. A common incorrect idea is that the ball will continue in its circular path, and many students will answer this even after studying physics. Hake et al (1998) found that – in traditionally-taught physics classes – most students taking introductory physics learn **less than 25%** of the material they didn't already know coming into the course.

Student motivation is a necessary precursor to achieving deep conceptual learning. Studies of students' perspectives about science find that most students hold very novice views about physics (or science) (e.g. Redish et al., American Journal of Physics, 1998; Adam et al., Physical Review Special Topics – PER, 2006). They see physics and science as a collection of isolated facts that are handed down by an authority (the teacher) and have little or no connection to everyday life. Their approach to problem-solving often involves pattern matching to memorized recipes. This view is bound to make science boring. Physicists, on the other hand, view physics a powerful and coherent framework of concepts that are grounded in experiment and capable of predicting real world phenomena. To solve problems, physicists use systematic concept-based strategies that are widely applicable. With this expert-like view, science is relevant, useful, and interesting. Unfortunately, while teachers strive to move their introductory physics students toward expert-like perspectives of science, most students in introductory science class shift **toward more novice perspectives** over the duration of a science course! Similar results have been seen in chemistry and biology (research studies at http://class.colorado.edu). And across all of these disciplines, students' interest and motivation suffers as well.

Looking inside the classroom – whether in middle school or college – provides insight as to the sources of these disappointing results. A Horizon Research study, *Looking inside the classroom: A study of K-12 mathematics and science education in the United States*, observed science and math classrooms in 31 middle schools and estimates that only 15% of math and science lessons are high in quality while 59% are low in quality. One of the weakest areas, and most pervasively weak, was the lack of emphasis on sense-making of the mathematics or science content and the comparative emphasis on factual knowledge and procedures (Weiss et al., 2003). High quality lessons – in contrast – would incorporate strategies to encourage students to actively engage with the science content – e.g. they "often invite students into purposeful interaction with the content through experience of phenomena, real-world examples, or other engaging learning contexts." They emphasize the process of science and the dynamic nature of the discipline – that is the ongoing refinement of "understanding through conjecture, investigation, theorizing, and application." They provide "multiple pathways for students to engage with the content and increase their grasp of targeted concepts" including developing "conceptual connections among related phenomena and representations".

As we will demonstrate, the PhET Interactive Simulations project provides key tools for enabling ALL teachers to shift from low-quality to high-quality lessons – simultaneously addressing the need for improved conceptual understanding and improved motivation.

SHORTAGES OF TEACHERS AND RESOURCES:

Compounding the basic, but quite difficult, challenge of increasing students' conceptual understanding of and interest in science are shortages in the number qualified science teachers and limited resources for science labs and classrooms. In 2009, over 50% of all physics teachers have neither a major nor a minor in physics or physics education (American Institutes of Physics Report, November 2010). The National Center for Education Statistics show shortages for all sciences – with these shortages being larger at the middle school level. When learning about physical science, 92% of all middle school students are taught by teachers without a major in a physical science.

With limited budgets, many classrooms throughout the world lack access to the material resources needed to conduct science labs (see examples from email below).

The PhET Interactive Simulations project also helps mitigate the effects of these additional challenges, as discussed below.

Description of Technology Application

Fully describe the technology application. What technology is being used? How is it being used? Who is responsible? Who is benefiting? What processes or systems are in place to deliver this technology application?

OVERVIEW:

The PhET Interactive Simulations project at the University of Colorado has developed over 100 research-based interactive simulations for teaching and learning science (see supplemental documentation for a few examples). All simulations, and supporting materials, are freely available at http://phet.colorado.edu. Through their innovative design, these simulations are providing key tools that enable science teachers to deliver high-quality science lessons – simultaneously improving students learning of core science concepts and scientific skills, as well as increasing their motivation and interest in learning science.

With its emphasis on making these high-quality resources accessible worldwide, teachers and students from around the world are benefitting from PhET's suite of interactive simulations. Over 15 million PhET simulations were run in 2010 and a projected 22 million or more will be run in 2011. In addition, the simulations have been translated into 59 languages and the website into 14 languages.

SIMULATIONS DESIGNED TO ENHANCING STUDENT LEARNING AND MOTIVATION

PhET simulations target specific student learning difficulties and learning goals in science education that can be well-addressed by the capabilities of a simulation. These capabilities include the ability to provide an interactive environment with dynamic feedback, to show the invisible, to link multiple representations, to enable and develop scientist-like exploration skills, and allow the student to easily and intuitively explore and discover cause-effect relationships.

PhET sims such as Circuit Construction Kit, Build-an-Atom, Moving Man, and Energy Skate Park (see supplemental materials) leverage these capabilities. They create animated, interactive, game-like environments in which students learn through scientist-like exploration. They emphasize the connections between real life phenomena and the underlying science, make the invisible visible (e.g. showing electrons, photons, vectors), and include the visual models that scientists use to aid their thinking. As students explore the simulations – often asking "what if" questions – the simulation responds immediately and dynamically, allowing students to test their ideas, to discover and make sense of key cause-and-effect relationships (e.g. increasing a batteries voltage, increases the current flow), and to develop visual, conceptual models of the underlying science processes.

PhET sims are designed to provide implicit guidance that helps students explore productively (Podolefsky et al, 2010). Student thinking is guided and focused by the choice of controls, the visual representations, the animated models, and the immediate feedback provided by visual changes during student explorations. Folder-like “tabs” along the top of the sim support scaffolding the content topics or complexity as students move from tab to tab in their exploration. Connections to the real world are used to anchor students thinking to the familiar and motivate their interest. Purposeful constraints—that is, what students are not allowed to do or see—are used to further guide productive exploration by reducing real-world complexities that can distract from the key ideas.

In these ways, simulations can provide a powerful learning environment that can be more effective for developing a deep conceptual understanding than activities with real-world equipment. In addition, they enable experimentation that is often impossible or difficult in real-world systems (like adding a proton to a nucleus or continuously changing a battery’s voltage), and they provide an environment where students feel safe to experiment without risk of harming themselves or the equipment.

THE PhET TEAM:

The PhET Interactive Simulations project at the University of Colorado was founded in 2002 by Nobel Laureate in Physics Carl Wieman – now serving in science and science education for the Obama Administration as Associate Director in the Office of Science and Technology Policy. Professor Wieman’s passion extended beyond the laboratory; he saw a national educational system failing to educate or interest students in science. Beginning with funding from NSF, the Kavli Foundation, and his own Nobel Prize winnings, Wieman assembled and led a team to develop interactive simulations for teaching key ideas in introductory physics and tying them to everyday life phenomena. Dr. Kathy Perkins and Dr. Wendy Adams took over as co-directors of the project beginning in 2008 with Dr. Kathy Perkins now serving as director since March 2010.

The PhET project’s greatest strength is the composition of its team. The project brings together key individuals with diverse skills including: 1) scientists with expertise in the content areas, 2) science education researchers who have PhDs in the science discipline, but specialize in student learning and teaching in that discipline, 3) simulation design specialists with deep experience in designing simulations and many, many hours of interviewing and observing students use simulations, 4) teachers from college, high school, and middle school with their vast experience teaching these challenging topics and observing student thinking and difficulties, and finally 5) professional software developers.

Currently we are a team of 4 faculty, 1 senior researcher, 2 post-doctoral researchers, 5 software developers, 1 K12 teacher, 2.5 administrative support staff, and many additional K12 and faculty advisors.

THE DESIGN PROCESS:

The PhET team uses a robust design process that grounds the design in research – research on how people learn, on technology design, and on student difficulties in science – and includes iterative feedback and user testing to produce high-quality simulations. Briefly, the simulation design process begins with identifying the core learning goals to be addressed and the common student difficulties around these ideas. The team then collaborates to storyboard a simulation design, specifying the functionality of all features as well as the specifics of the underlying scientific model. Learning goals, models, storyboard drawings, descriptions, and discussions are all documented in a shared google document. Once the team agrees on the simulation design, the software developer leading the coding begins implementation, distributing intermediary versions to solicit general feedback or to resolve questions that arise in implementation. After the simulation is developed to the team's satisfaction, individual interviews are conducted with students to test that the interface is intuitive, that the simulation is engaging for students, and that students achieve the desired learning. Any findings from interviews are addressed through modifications to the simulation design. If possible, we also observe the simulation in classroom use and incorporate those findings into the design. Once completed, the simulation is published to our website with a description, learning goals, keywords, and any PhET-designed activities. The new simulation is then announced via our social-media tools, including our blog, facebook page, and twitter feed.

PhET's software development team practices many parts of agile software development, including rapid delivery of useful software, embracing changing requirements based on feedback from team review and student interviews, pair programming, and consistent improvement of our software foundation and methodologies.

SIMULATION AND WEBSITE SOFTWARE TECHNOLOGY:

The simulations are written in Java, Flash, Actionscript 2, Actionscript 3, Flex, or Scala, and make extensive use of several open source software projects, including Piccolo2D, Away3D, Box2D, JFreeChart, Beanshell, Jade, JMol, and JSci. Simulations range from a few thousand to over 15,000 lines of code, on top of 50000 lines of PhET-developed common code that is used across all of the simulations. The developers use IntelliJ or Eclipse development environments, and perform application profiling using JProfiler and JVisualVM to improve simulation performance. Finally, the PhET team designed our own open-source build process to simplify building, testing and publishing the simulations (~12000 lines of code). This process can build simulations from any of our source programming languages.

The PhET website is written in Java, and uses the Apache Wicket framework, with significant extensions to support interactive translation of all public pages (with previews). The website represents an additional 50,000 lines of code.

The source code for all of our products is publicly available and open source (GPL).

INTERNATIONALIZATION AND DESIGN FEATURES TO ACHIEVE WIDESPREAD USE:

In addition to providing free access, PhET has adopted some key simulation design features and project operational approaches, which together are achieving widespread, worldwide use of these resources. This unique approach – including novel software technologies to enable easy translation of PhET simulations and the PhET website by users worldwide – is described in detail in next section.

WIDE RANGE OF USERS AND USES

The open-style of the interactive simulations means that they are then highly flexible resources - able to be used in multiple environments (in-class activities, lectures, homeworks, virtual courses, etc), at multiple levels (elementary - college), and by multiple stakeholders (teachers, curriculum developers, commercial companies that provide textbooks, online courses, course platforms). Looking at users, you could see: A teacher projecting a simulation at the front of class and asking students to predict what will happen when she makes a change; Two students working together – one student is moving a slider back and forth as she explains and justifies her ideas to her classmate; A teacher inviting a student to the smartboard to use the simulation to demonstrate what he discovered during his exploration; A student doing a circuits lab from home.

Explanation of Leading Edge or Breakthrough Technology

Why do you think that your use of technology is worthy of recognition? Describe if it is a new technology or a new use of an existing technology. How can it be distinguished from existing uses? Explain how it surpasses previous or current solutions.

The PhET project was recognized as a leading technology for advancing science education when it won first place in the 2007 NSF and Science Magazine International Science and Engineering Visualization Challenge in the interactive media category. The project was selected from a field of more than 200 contest entries from 23 countries on six continents. Science magazine quotes Gary Lees from the panel of judges: “Some of the principles of physics have never been as well depicted and elucidated.”

We believe PhET simulations represent a leading-edge technology in 3 key ways. 1) The simulations are of very high quality and grounded in research – far surpassing the norm in interactive technologies being produced by textbook companies. 2) The project has developed novel software that allows the simulations and the website to be easily translated into any language. And 3) we include many features which enable widespread use – including a Creative Commons Attribution license which allows free use by anyone worldwide - including under-served communities, domestically and internationally.

OF HIGHEST-QUALITY AND GROUNDED IN RESEARCH:

As mentioned, the PhET project was started in 2002 by Nobel Laureate in Physics Carl Wieman. His vision was to improve the way science is taught and learned; he wanted to create sims that were aligned with and vetted through educational research. As a result, each sim is developed by a team of scientists, software engineers, science educators, and science education researchers to facilitate learning and address known student difficulties with the content. Every sim is tested through student interviews and observations of use, and the PhET project is actively engaged in research on effective design and classroom use of interactive simulations (Adams et al. 2008). PhET team members have published 30 articles, with the vast majority appearing in peer-reviewed journals.

This emphasis on and grounding in research makes PhET’s simulations of the highest quality and usefulness in the classroom. Other efforts in creating simulations typically: involve less interactivity (often times set parameters then press play to watch); include fewer connections to real-world experiences and fewer design features to address student conceptual difficulties with the content; have more rudimentary graphics; are less intuitive, requiring more explanation prior to student use; and are overall less engaging for and less enjoyed by students.

INTERNATIONALIZATION:

Science is a universal language. By that, I mean that the concepts are the same whether they are presented in the US or in Brazil. In addition, scientists around the world use the same visual representations to help them process and understand these ideas – graphs, vectors, motions, fields, etc. Thus, once a high-quality interactive simulation is developed, it has great potential to benefit science learning around the globe.

A goal of PhET is to bring these tools to science teachers and learners everywhere. High-quality translations are essentially – auto-translation utilities will not suffice for an accurate translation of science topics. PhET approached this challenge by creating a Translation Utility java application that allows any simulation to be easily translated from English into any other language without any technical programming experience and to preview a fully-capable version of their translated simulation prior to submission. By making these tools available from our website, scientists and science teachers from around the world have been translating the PhET simulations – with currently 2,798 translations in 59 languages (see http://phet.colorado.edu/en/simulations/translated).

In November 2010, we took internationalization a large step forward by releasing a fully-translatable version of the PhET website. The website software 1) allows a translator or a collaborative group of translators to create and work on a translation through an online interface, 2) provides real-time page previews of their translated site, and 3) allows them to submit their translation for "live publication" after review by us. Again, scientists and science teachers from around the world have responded through hard-work of their own to bring these tools to their countries students and teachers. In only 6 months, the website has been translated into 15 other languages.

ACHIEVING GLOBAL, WIDE-SPREAD USE:

We want the design and technology of PhET simulations to enable the broadest possible use by teachers and students. The following features help us achieve this goal:

1) Creative Commons Attribution license allows for commercial or non-commercial use of simulations by anyone at no cost.

2) Support of online and offline use. From online, simulations use java web start or flash plug-ins to enable easy 1-click launching of simulations. Downloadable JARs – one for each simulation and language – allow for double-clickable, easily-transferable files. In addition, the *entire website* with all of the simulations can be downloaded in 1 file, redistributed, and installed on any computer running windows, mac OS, or lynx. This capability has been particularly useful for providing remote teachers – for instance in Africa – with the simulations, or teachers with limited internet.

3) Automatic update feature. Simulations run from local files will automatically check if there has been an update – so that users of older versions of the simulations can know if there have been fixes or enhancements. (Users can turn off this feature if desired).
4) The open-style of the interactive simulations creates highly flexible resources - able to be used in multiple environments (in-class activities, lectures, homeworks, virtual courses, etc), at multiple levels (elementary - college), and by multiple stakeholders (teachers, curriculum developers, and commercial companies that provide textbooks, electronic course platforms, or develop courses).
5) Each simulation can be used to address multiple goals. The teacher crafts their activity and use of the simulation to address his/her specific learning goals.
6) Intuitive controls means that no directions are needed, so simulations can be used broadly by students and teachers.
7) Students find them engaging and fun.
8) Providing extensive choice – over 100 simulations and growing.
9) Help for new teachers. We host a teacher's activities database where teachers can find new activities to use with the simulations, or share activities they have created with other teachers. We currently have 582 activities available to help teachers get started using simulations in their classroom – 138 were contributed by PhET, and the rest contributed by teacher users from across the US and around the world.

Evidence of Contribution

How do you know that your application of technology is making a contribution?

I. EVIDENCE FROM WEB STATISTICS

A. LARGE AMOUNT OF USE, AND GROWING:

A large number of teachers and students are using PhET's interactive simulations. In 2010, over 15 million simulations were run or downloaded from the PhET website, and we see significant growth in usage each year (~50% growth). Over 200 countries/territories around the world are accessing PhET's resources, and overall international use accounts for about 34% of total use.

B. SIMULATIONS USED IN SCHOOLS:

Tracking by Google Analytics, shows that the simulations are accessed by over 900 US colleges and universities and by K-12 schools in every state. In addition, we see that this use is largely happening during school hours – indicating that teachers are using these simulations in their classrooms. Web statistics shows the rate of visits is about 4 times higher during school hours – between 8am and 3pm – than afterschool.

II. EVIDENCE FROM SIMULATION TESTING AND RESEARCH STUDIES:

A. EVIDENCE FROM INTERVIEWS

Every PhET simulation is tested with multiple individual student interviews. In these interviews, we select students who have not previously learned the science content. The students are directed to play with everything in the simulation and talk aloud as they go. These interviews test for: 1) usability – to ensure that the interface is well designed and intuitive; 2) student interpretation – to ensure that students easily and accurately interpret the representations, text, and animated feedback in the way the designers intended; 3) student engagement – to make sure that students actively engage with the simulation, that they are drawn in to naturally explore and ask "what if" questions to learn; 4) proper scaffolding – to ensure that the natural path(s) students use to investigate the simulation properly support their learning of the main ideas, allowing them to build their understanding from simpler to more complex ideas; and finally, 5) student learning – to examine whether students are achieving the learning goals through their investigations. Interviews almost always reveal some issues that need to be addressed through modifications – so once a simulation is published to our website it has been shown to achieve these milestones in usability, correct interpretation, engagement, appropriate scaffolding, and learning.

B. EVIDENCE THAT STUDENTS GAIN DEEPER UNDERSTANDING OF SCIENCE CONTENT:

PhET's research studies have investigated the impact simulations have on learning in a variety of environments – including use by the instructor during class, use in labs and in-class activities where students work in small groups with the simulation, or use outside of class where student use simulations with assignments. Some sample studies are discussed below.

In the classroom, we've found that PhET simulations can offer significant benefits over traditional demonstrations. In a study of students visualization of standing waves, the use of the 'Wave on a String' simulation to demonstrate standing waves resulted in significant improvement on questions probing students conceptual understanding of the velocity of different points along the string – 71% correct with the simulation versus only 27% correct with the standard demonstration (Perkins et al., 2006). Another in-class study found that students had more productive student-student discussions – that is, discussions leading to a larger number of students being able to reason out the correct answer – when PhET's 'Circuit Construction Kit' simulation was used to augment the teachers' instruction than when standard demonstrations with batteries and bulbs were used (Keller et al., 2006).

In laboratory environments, research studies show that college students using PhET sims often demonstrate higher learning gains on conceptual understanding than students doing the same activities with traditional lab equipment. In addition, these students also demonstrate better facility building and diagnosing real electric circuits after conducting the lab with a PhET sim compared to conducting the lab using real equipment (Finkelstein et al., 2004). In subjects where real-equipment demonstrations are limited, such as quantum mechanics, the use of PhET's suite of interactive simulations on quantum mechanics significantly improved students conceptual understanding of these difficult physics ideas – concepts of critical importance to high-tech innovations (McKagan et al., 2008a, 2008b, 2009).

In chemistry classes, we recently investigated the use of a simulation to improve students' conceptual understanding and visualization of molecules participating in a chemical reaction. We found that college students who worked through an activity using the simulation in recitation demonstrated significantly greater understanding than students in previously-published studies – scoring 51.4% correct versus 20.5% for students experiencing standard chemistry instruction (Lancaster et al., in preparation). This is the highest-published achievement of learning on this concept – a difficult, but important, core concept to chemistry.

Through detailed interview studies, we have examined and documented how PhET simulations are able to promote and enable scientist-like exploration Specifically, we characterize how affordances, constraints, and analogies designed into sims foster this type of student engagement (Podolefsky et al., 2010).

C. EVIDENCE THAT STUDENTS ENJOY PHET SIMULATIONS AND FIND THEM USEFUL FOR THEIR LEARNING:

In addition to measuring learning outcomes, our studies probe how students view the simulations – that is, whether they enjoy using the simulations and view them as useful for their learning. Overwhelmingly, students find the simulations both enjoyable and useful for their learning.

At the end of the term in a large lecture course for non-science majors on the "Physics of Everyday Life", we asked the students how useful the sims were for their learning. Responding on a 5-point scale on usefulness from "not useful" to "a great deal", 84% found them useful with 62% ranking them as very useful (4 or 5) for their learning and 22% ranking them as a 3 or "somewhat useful". In contrast, the textbook was rated of little use (1-2) by 52% and very useful by only 27% (Perkins et al., 2006). Similarly positive rankings were found among classes for science and engineering majors. In a modern physics class, students were particularly enthusiastic: "The simulations were crucial in the learning process.", "The simulations were the best part of class, they practically answer physics questions all by themselves. I would recommend continuing to develop these and add more. Without these I think I would have been lost in the course.", "I definitely not only enjoyed the simulations, but I'd go as far to say that the simulations taught me the most about the course because I could really visualize the inner workings of the physics processes that were going on." (McKagan et al., 2008).

Finally, third-party researchers are also publishing papers around PhET's effectiveness. For example, Andrzej Sokolowski published a paper titled "Using Physics Simulations to Enhance Learning in Pre-calculus Courses" in the *Proceedings of World Conference on Educational Multimedia, Hypermedia and Telecommunications*, 2010.

III. EVIDENCE FROM USERS:

A. TEACHERS REPORT THAT PHET SIMULATIONS ARE A KEY RESOURCE FOR UNDER-FUNDED SCIENCE CLASSROOMS

We receive regular emails that indicate that teachers in under-funded science classrooms benefit from PhET simulations. Some examples include:

A teacher from Texas writes, speaking about the Circuit Construction Kit simulation: "This is so important to them since we cannot afford to buy the electricity kits that districts in Texas with more money can afford. More than 50% of our students come from very low income homes so it truly brings tears to my eyes---not something done easily--- when I can give them access to something as wonderful as your program. We share one mobile lab of 23 laptops with 800 other students but they will work themselves silly just to get a few minutes with your kit!"
A teacher from South Africa writes: "My name is Bongani Gumede, I am a high school science teacher in Johannesburg, South Africa. I have been using the Phet sims since last year and have done wonders in my class. I teach a school that is under resourced in terms of lab equipment. The Phet simulation have been very helpful. Phet simulation have not only been helpful with regards to resources but I believe that Phet sims has an effect on conceptual change and conceptual understating."

B. INCREASING NUMBER OF COMMERCIAL COMPANIES USING PHET SIMULATIONS

Increasingly, commercial companies – producers of textbooks, online courses, online homework systems, etc. – have contacted PhET to use our simulations in their products. They are looking for high-quality interactive learning resources. Use of PhET by these groups helps us achieve our goal of providing every student and teacher easy access to the simulations.

Examples of 3rd party users:

- Pearson Publishing uses PhET simulations in multiple products, including their Mastering Physics online homework system, their #1 selling undergraduate physics textbook, Hewitt's popular conceptual physics book, and an ITT Technical Institute course that distributes PhET on over 15,000 DVDs/year.
- Other examples of publishers that are using PhET simulations include: McGraw Hill, It's About Time, Via Afrika (in South Africa), Oxford University Press Southern Africa, Han Lin Publishing Company (Taiwan).
- State departments of education, such as Idaho Digital Learning and Oregon Virtual School, as well as private online schools and curriculum providers, such as Cheneliere, VSchoolz, Compass Learning, Learning.com, FYI Online, NIIT School Learning Solutions (India), are incorporating PhET into their online curriculum.

Presentation of Measurable Results

Describe the method(s) you are using to measure your results. How are you reporting your results and to whom? To whom are you accountable?

As illustrated above, we use multiple methods to measure the impact of the simulations and to inform how simulation design impacts learning. These include:
1) Analysis of web reporting statistics
2) Classroom research studies of simulation use. Methodologies used in these studies include:
a. Pre-post measures of learning – these examine student understanding of key science ideas before and after an intervention using a PhET simulation
b. Comparison groups - e.g. using real equipment versus using simulations

c. Field observations and video-taping of classroom environments and student discussions – these allow detailed analysis of how simulations effect student discussions and teacher approaches to facilitating learning

d. Student surveys

3) Video-taped student interviews

4) To a much lesser extent, we look at reporting via email or otherwise by external third-party users

We have published over 30 papers on PhET, appearing in peer-reviewed journals. Including:

Science
Nature Physics
Physics Today
Physics Education
The Physics Teacher (2 articles)
The Science Teacher
Physical Review Special Topics – Physics Education Research (3 articles)
Journal of Online Teaching and Learning
Physics Education Research Conference Proceedings (9 articles)
American Journal of Physics (3 articles)
Journal of Interactive Learning Research (2 articles)
Multimedia in Physics Teaching and Learning Proceedings (2 articles)
Proceedings of SPIE
Using Computers in Chemical Education newsletter (not peer reviewed)
Journal of Science Education and Technology

In addition to publishing in journals, we also submit grant reports on our progress and findings to our primary funders – the National Science Foundation, the William and Flora Hewlett Foundation, and the O'Donnell Foundation.

Sample papers, including those cited above, included:

W.K. Adams, H. Alhadlaq, C. Malley, K.K. Perkins, J.B. Olson, F. Alshaya, S. Alabdulkareem, C.E. Wieman, "Making Science Simulations and Websites Easily Translatable and Available Worldwide: Challenges and Solutions", Journal of Science Education and Technology, (2010).

N.S. Podolefsky, K.K. Perkins, W.K. Adams, "Factors Promoting Engaged Exploration with Computer Simulations", Physical Review Special Topics: Physics Education Research. 6, 020117, (October 2010).

K.K. Perkins, P. Loeblein, & K.L. Dessau, "Sims for Science", The Science Teacher, 77 (7), pp. 46-51, October 2010.

C.E. Wieman, W.K.Adams, T. Loeblein, and K.K. Perkins, "Teaching Physics Using PhET Simulations". The Physics Teacher, 48(4), pp. 225-227, (April 2010).

C.E. Wieman, W.K. Adams, and K.K. Perkins, "PhET: Simulations That Enhance Learning", Science, 322, 682-683, (2008).

S. B. McKagan, W. Handley, K. K. Perkins and C. E. Wieman, "A research-based curriculum for teaching the photoelectric effect", American Journal of Physics 77, 87 (2009).

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Description of Potential Negative or Unintended Consequences

Describe any outcomes that may not be beneficial that you have considered. Who might consider your application problematic and why?

There has been some perception that the PhET team advocates replacement of hands-on equipment with simulations. We do not. We advocate examining your learning goals, and choosing the best tool to address those learning goals. Often a combination of hands-on equipment and simulations is best. However, where hands-on equipment is not available, PhET simulations provide opportunities for virtual learning environments.

In rare instances, we receive comments from science faculty who are complaining about a particular approximation or choice that we've made in the simulation design. For instance, in the Photoelectric Effect simulation, the electrons are all emitted perpendicular to the surface of the metal, while the physical reality would have the electrons emitted in all directions. A couple of faculty have complained about this choice. However, such design choices are made to focus student investigations on the critical physical ideas – that electrons are only emitted when photons of high-enough energy are available and that the electrons are emitted with differing speeds. These ideas are more available – more discoverable by students – when presented without the complicating detail of the angle at which the electrons are emitted. These design choices also enable teachers to facilitate discussions about "models" and examine in what ways these simulations are models. Scientists' use of models is another key learning goal for students.

We recognize that – like any educational tool – the impact of the simulations depends not only on the simulation design (which we hone for effectiveness) but also on HOW the PHET sims are used by teachers. Consistent with research on how people learn, the PhET simulations are designed to support constructivist activities – those in which students develop their understanding through more open-style exploration, using the process of science inquiry either as an individual, group, or classroom and debating and reasoning with their peers. However, teachers can use PhET simulations in less ideal ways. Integrating them into a "cookbook" lab, for instance, will not reap their full potential, but even when used in this way, PhET sims will still provide benefits through the dynamic visualizations, feedback, and real world connections.

If selected as an awardee, the $50,000 prize will be used to significantly enhance our professional development opportunities for teachers – providing key training opportunities and support to enable all teachers to incorporate PhET simulations into their teaching in highly effective ways.

Discussion of Replication Potential

Describe how your work might be a model for others to emulate. Could this application be put to use in other places or contexts?

PhET is already designed for worldwide adaptation and use, through its features that allow easy translation and easy worldwide dissemination via the internet, CD, or third-party use. The project is continually expanding into new languages and new topics, developing approximately 10-15 new simulations per year.

In addition, PhET serves as a model project that can inform similar future projects, in several ways.
1) PhET is a premier example of how investment in high-quality open educational resources (OER) can significantly impact teaching and learning throughout the world.
2) PhET is an excellent example of how a research-based approach produces high-quality tools – that is grounding the design of the educational resources in research on how people learn, on student difficulties in science, and on interactive media design. It's also provides an example of the importance of student testing educational resources and using the findings to modify and hone the designs as well as feeding those findings back into the overall design principles.
3) PhET includes several design principles that enable widespread adoption. Other projects which aim for widespread adoption design (in advance) with that goal in mind. These include a) the open-style design allowing teachers to use the simulations as they see most fit (adaptable use); b) effectively addressing common student difficulties – teachers easily see benefit; c) intuitive interface and ease-of-use; d) easy translation to other languages; and e) online or offline dissemination and use.
4) The technology for translating the simulations provides a framework that similar products can use for developing a team of volunteers to translate their work.
5) The open-style interactive environment pioneered by PhET can be used in many disciplines in which models of the real-world with cause and effect situations can be visualized though

animations or other graphical representations – e.g. all sciences, math, engineering, economics, and even some socio-economic or political causal relationships.

Finally, all of the source code is open-source (GPL license) and can be reused by any developers of science simulations or other software applications.

Short Description of Technology

Describe your technology in 75 words as you would like it to appear on our website.

The PhET Interactive Simulations project at the University of Colorado has developed over 100 free, research-based, interactive simulations for teaching and learning science (http://phet.colorado.edu). These simulations improve science learning by providing animated, interactive, game-like environments in which students learn through scientist-like exploration. Students can see the invisible and investigate the visual models that scientists use to aid their thinking. PhET simulations are used worldwide, with over 15 million runs/year and translations into 59 different languages.

Recognition of Contribution

Specify if this work draws upon the intellectual property or substantive contributions of others who should be acknowledged and appropriately referenced.

Over the years, the PhET Interactive Simulations team has had many team members.
Current members: Dr. Kathy Perkins (Director), Dr. Noah Podolefsky, Dr. Michael Dubson, Dr. Robert Parson, Dr. Noah Finkelstein, Dr. Kathy Dessau, Dr. Emily Moore, Dr. Kelly Lancaster, Trish Loeblein, John Blanco, Jonathan Olson, Chris Malley, Sam Reid, Oliver Nix, Mindy Gratny, Nina Zabolotnaya, and Linda Wellmann.
Past team members include: Carl Wieman (Founder), Wendy Adams (former co-Director), Sarah McKagan, Daniel McKagan, Marjorie Merges, Archie Paulson, John DeGoes, Ron LeMaster, and Linda Hadfield.

The simulation software code uses several languages and open-source libraries in its development that deserve acknowledgement. These include:
Languages: Java, Flash, Actionscript 2, Actionscript 3, Flex, Scala
Open source software libraries: Piccolo2D, Away3D, Box2D, JFreeChart, Beanshell, Jade, JMol, JSci
Development environments: IntelliJ, Eclipse
Application profiling: JProfiler, JVisualVM
The website software is run on a GNU/Linux server with Apache's HTTPD and Tomcat web servers, is written to use the Apache Wicket framework, and uses the following other libraries and applications: Dom4j, EHCache, JBoss Hibernate, Apache Lucene, cron4j, log4j, slf4j, JUnit, Selenium, swfobject, pngfix, JQuery, Wordpress and the modified Yashfa theme. It is mainly Java-based, but also uses JavaScript and ActionScript 3 built with Adobe's Flash CS4.

Finally, we want to acknowledge and thank all of our volunteer translators across the world as well as our teacher-users who have submitted activities to share with other teachers visiting our website. The translators, in particular, have contributed hours and hours of their time to translate the website and/or the simulations in order to bring these resources to their country's students.

Designation of Use of Prize Winnings

The purpose of awarding the $50,000 cash prizes is to contribute to solutions for the urgent challenges that The Tech Awards address. To that end, we ask you to briefly describe below how the cash prize will be used if you are selected to receive it. To promote the values of the Awards program and sustain the high level of credibility of both you and the Awards program, The Tech Museum will require that highly funded Laureates designate another entity as the recipient of the actual cash. If you are selected as a cash prize winner, describe how you will use the funds or if applicable, designate another recipient.

As a prize recipient, PhET will use the $50,000 cash prize to specifically enhance our online teacher professional development and community outreach activities. While much of our work and support is in simulation development and deployment, we see significant potential to enhance our projects' impact through an increase in our teacher professional development activities – that is providing more training opportunities where teachers learn about the pedagogical theory behind the simulations and the most effective ways to incorporate the simulations into their classes. With more and better training and support for K-12 teachers to use PhET simulations effectively in class, we expect more students to be learning with PhET simulations and for that learning to lead to students' deeper understanding of science concepts, their application to real-world situations, and improved science literacy.

Teachers who use PhET typically find and access these resources through web searches or other online pathways. Similarly, we need to provide a suite of teacher professional development opportunities online, including webinars, online tutorials, video examples of effective use, online exemplary lessons and activity templates, social media forums and other community forums. In addition, we will pursue the possibility of providing teachers with the option to earn university credit for participating in these training and extension opportunities.

Historically, we give numerous professional development workshops at conferences, attending over 15 conferences since November 2009. In terms of educating new users in the K-12 system, we've reached out to many hundreds of teachers, curriculum developers, and education technologists interested in using PhET at the International Society for Technology in Education (ISTE) conference and the iNACOL Virtual School Symposium. We also continue to be a featured presenter at the American Association of Physics Teachers conference, and to do workshops at the NSTA National meetings. In March 2011, we helped organize a conference on Cyberlearning Tools for STEM Education which preceded the March 2011 NSTA meeting.

Although highly engaging and productive for these teachers, in-person workshops are expensive and offer access to a limited group of educators. A series of webinars and self-paced, online tutorials will form the cornerstone of our new professional development efforts. The content in these offerings will leave teachers with a strong foundation in the underlying pedagogy and concrete ideas for how to effectively use the simulations in their classrooms. Video-clips of simulation use in real classrooms will be used to spur teacher discussion and reflection, as well as model effective use. Similarly, comparison of different approaches to lessons and written activities will be used as a springboard for productive discussion about how lesson and activity design impacts the learning environment, student discussions, and student understanding of science. For interested teachers, we will provide extended support of teachers – forming teacher cohorts who work closely together and support each other as they integrate simulations into the classroom. This extended support has been found to be highly effective in many teacher professional development programs. With a small pilot effort, we are giving our first webinar on May 10 entitled, "Using PhET Simulations for Science Inquiry: Free, Researched, Web-Based Resources," through a partnership with EdTechTeacher.

In addition, prize money would be used to develop and implement a framework for collaborating with groups of classroom teachers through online communities, forums, blogs and other outreach avenues. Constant contact with teachers will keep us informed as to what support teachers need in order to effectively use PhET sims in the classroom. In November 2010, to foster and grow our community of teacher users, we initiated a social-networking effort. We launched the PhET Blog (http://phet.colorado.edu/blog) where we regularly post updates, along with an RSS feed, and we created a Facebook and Twitter presence where we post the latest news on new sims, improved sims, workshops, webinars, and articles.

Lastly, with the prize money we plan to enhance our online teacher resources with exemplary inquiry-based activity templates along with examples which model how these activity templates are used to create activities. In addition, from our experience working with and observing teachers in the classroom, we know that we need to include model video examples of students and teachers using sims effectively in class— to show teachers what it looks like if students are engaging in using sims effectively.

If PhET were to win the Tech Awards, we would be able to greatly enhance our online professional development offerings, reaching out to K-12 teachers worldwide and significantly advancing our goals of educating the next-generation of scientists and of increasing science literacy worldwide.