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Teaching Parabolic Motion with Stop-Action Animations*

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Historically, teachers determine the mental models that students have of various concepts by asking them to write. In physics, teachers will use lab reports and class tests, with variable success, to encourage the students to critically examine their mental models and to write about them. With the increasing accessibility of movie making, we have found a new avenue for students to examine and to report their models, and this new avenue is often more intriguing to the student. The goal of a lab report is for the students to tell a story, and through that story, critically examine their understanding of the subject. Having a student report on the outcome of an experiment, however, does not always lead to a change in student understanding. And, in extreme cases, a report can lead to the students changing their memory of the experiment to fit their incorrect mental model. Therefore, many teachers have the students predict first and then compare their predictions with their results. In the movie-making program, we try to take this a step further. We can use the movie environment to encourage students to build a simulation of their experiment and test their model against experimental data. As in engineering, this process relies upon strong fundamental math and science knowledge. In the classroom, generating animations serves as a way to strengthen conceptual understanding. Using the animation design process, we have found students (and teachers) to be far more interested in the outcome of their work. This paper shows some of the results of this technique by looking at how high school students have learned about parabolic motion in a physics class. In particular, we will highlight the work of select students to show what they were able to do through making a movie.

Keywords: animation; engineering design process; physics; mental representation; mental models

INTRODUCTION

IT IS WIDELY AGREED in education and cognitive psychology that students have many different learning styles [1]. Many students learn effectively in more traditional classroom environments (relying on logical-mathematical and analytical activities and content delivery models), but for other students, these environments do not provide them with access to the content or to the methods for demonstrating their knowledge. Effective learning environments center around teachers engaging their students in the content. Engagement is not possible unless the students are connected to the material in some manner, providing them with ownership of their learning. In order to consider engagement as a fundamental component of education, we must recognize specifically how engagement in a topic impacts learning. It has been shown that students who are interested and motivated (manifestations of engagement) think more critically, become more excited in furthering their knowledge, develop greater conceptual mastery of the domain and retain the material better than students who are taught in traditional content-delivery environments [2–4]. To maximize these benefits, learning environments that provide multiple representations of content, multiple forms of expression and multiple means of engagement are essential. Engineering as a pedagogical vehicle in the classroom provides for exactly these traits. The process of design, construction and testing (whatever the content or material) creates an active learning environment where students can construct knowledge. Such engineering-based environments satisfy the need for multiple modes of access to content and at the same time provide students with alternative ways to demonstrate their knowledge. Currently, we are keen on developing a process parallel to engineering design, one where students define a problem and work toward generating animated solutions based upon solid mathematical and physical modeling. The process under consideration is stop-action movie making—an approach that embodies the qualities of an effective learning environment.

Below, we present two case studies of stop-action movie making (or animations) in a New Hampshire high school physics classroom. Animation provides a unique 'blank canvas' scenario for the students. In the software environment we

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discuss (called SAM), students are able to create frame-by-frame animations of imagery captured via a web-camera integrated into the software. This allows complete freedom of conceptual representation for the students, essentially irrespective of the content in question.

The examples presented here are both from the physical science domain but are purely illustrative. Engineering content (especially that of the engineering science) is perfectly acceptable material for the animation design process as well. Through the process of making the animations, students connect their animations to many fundamental physics concepts and to the mathematical relationships that describe them—a frequent task completed in engineering classrooms as well. Applications of mathematics and science, such as the animations presented here, reinforce students' understanding of fundamental concepts. If we can support the understanding of such concepts through a process of creating models, we are supporting engineering; thus, animation warrants consideration by the engineering education community.

Theoretical framework for animation

Mental models may drive the learning process as students use what they think they know to make contextual connections and solutions to physical problems. Movie making forces students to turn their mental model into a physical model—the movie. This movie is easily compared with existing, proven physical models, uncovering the differences between a student's mental model and the reality of the phenomenon. Exposing misconceptions in the mental model in such a manner allows students to be critical of their own model without directly judging themselves. They now have a physical representation (the movie) of their understanding toward which to direct criticism and misunderstanding. Ultimately, critiques of the students' own beliefs are less personal when the critique is centered on an object such as the movie. Where students do not always know the right questions to ask, this medium provides the teacher with a representation of the mental model so that he or she may teach to the preconceptions the students may harbour.

While the trend is shifting in some regions, typical secondary schools use writing as the vehicle for students to communicate their mental model. Some students can accurately express what they know in writing, however, the recognition of varying learning styles leads us to believe that other students would perform better if offered alternative methods for communicating their understanding. First generation attempts to use multimedia in classrooms proved beneficial; however, these initial steps simply added pictures to text and did not involve using multimedia in assessment of student knowledge [5, 6]. With stop-action movie making, students generate animations of science concepts, literary content, or any other domain using a combination of manipulatives, images and text. This multimedia approach differs from writing because it provides students with alternative ways of developing their understanding by building on their strengths. With science and engineering, the hands-on and inquiry-based nature of generating an animation leads students to experience content rather than absorb it. Because making a movie is exciting to children, they end up spending more time working with the content as well. Thus, such an approach builds on the well-established ideas of students building their understanding, or constructivism [7]. With movies, further enrichment of the experience for students comes by building objects for public display and interaction [8]. Lastly, the social nature of making stop-action movies allows students to learn together and help each other construct an understanding of the content.

In a review of educational research on science visualization, we can make the case for animation as a powerful tool for expression and assessment. Evidence suggests that while using multimedia instead of lecture and text is an improvement [9, 10], students still fail to master concepts when delivery consists of teacher-orientated demonstrations [11]. Other researchers suggest a general lack of visuals in science education and the divide this creates between teaching and practice [12]. Scientists, engineers and mathematicians use visuals in practice as perhaps the most powerful tool for presenting information. Based on the role visuals play in formal science, students should be given the option to incorporate visuals into presentations of their knowledge. In physics, students have consistently struggled with concepts such as kinematics and tying physics concepts to graphing [13, 14]. By animating a graph of a physical phenomenon like parabolic trajectory, students are able to see how a graph is built from physical concepts and the governing equations. Mayer and Gallini [6] showed that descriptions of systems where each step of the system's process is shown visually with parts listed as 'on' and 'off' (essentially outlining a static version of the animation) leads to better recall of information than descriptions using static images. So while multimedia is having a positive affect on learning, putting multimedia-driven learning into the hands of the student can maximize the learning potential within a given domain. If visualization in science is emerging from simply adding images in text to step-by-step visual descriptions of processes, then animation falls neatly in line as the next step in further developing this pathway.

From the perspective of engineering, much of the same can be said about putting the power of design in the hands of the students. Design-based learning provides a rich environment, an environment where students solve problems posed to them in their own manner, thinking critically about options, testing options and presenting best possible solutions. We believe the merits of design-

Table 1. Engineering Design Process compared with the Animation Design Process

Engineering Design Process Steps	Animation Design Process Steps	Description of Animation Steps
Define a problem or need	Define the problem	Problem posed by either the teacher or the students.
Brainstorm Solutions	Brainstorm the Conceptual Model	Students build storyboards, discuss concepts with group members, decide how to present their ideas.
Construct a Prototype	Build a Static Model	Create props, scale, sets, etc. for the animation—what will it look like?
	Generate the dynamic model	Shoot the animation—take the individual images en route to building the movie.
Test the Prototype	Review the Animation	Watch the movie and review it for accuracy or content. Here is where many of the real discussions take place.
Redesign	Remake the Animation	Based on the discussions of the first-order animation, students adjust the scale of their static model, make their measurements more accurate, and develop next iteration of their movie.
Communicate Solutions	Share the Animation	Review the animations with class members, teachers—discuss conceptual representations.

based learning are embodied in generating animations, therefore animation warrants consideration by the engineering education community. The Engineering Design Process takes on many forms; however, there appears to be some fundamental agreement on which steps are crucial to the success of the process. Table 1 lists these steps while comparing them to what we call the Animation Design Process. We propose (and will show with case studies below), that generating animations follows a similar process to engineering design. Given that the content of an animation is undefined (thus, engineering topics can be included), we feel animation and engineering share very similar process-driven ideals.

ANIMATION CASE STUDIES

There are significant indications that students learn more effectively when their learning styles are matched to teaching or instruction methods [15–18]. Now we show how, in two specific cases, the students drove the learning process by creating animations of concepts they did not at first understand. The unique reporting medium provided ownership over the project for the students, for them to progress through the learning process in a style they defined. All of this led to three notable advantages we saw from using the stop action movie software, SAM (www.samanimation.com) in a high school classroom in New Hampshire:

1. Animation encourages students to reflect on their understanding while uncovering the misconceptions they carry into an activity.
2. The ownership resulting from creating a movie engages, excites and motivates students.
3. Animation offers alternative assessment and communication methods for teachers to guide students down a pathway toward understanding.

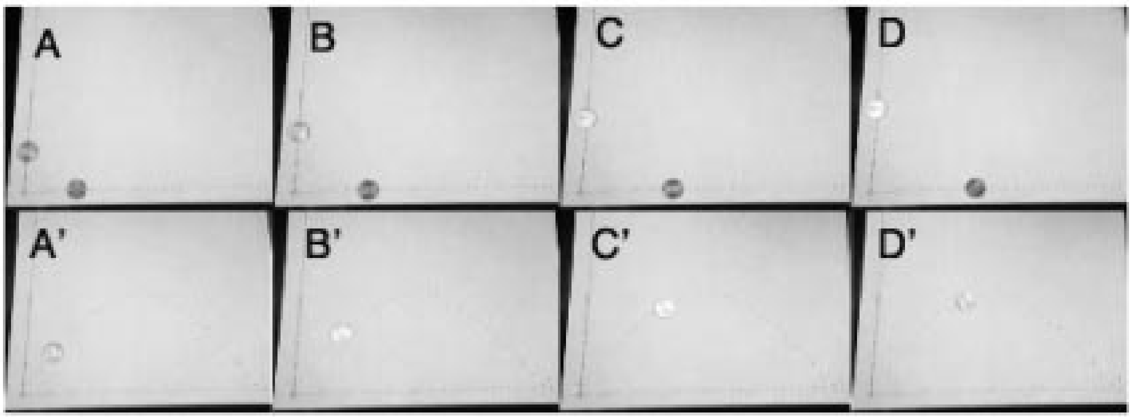
The two case studies are (A) animations showing constant horizontal motion, vertical accelerated motion and parabolic trajectory and (B) applying those concepts to a personalized scenario such as shooting a foul shot in basketball. More samples of successful student experiments (from understanding temperature to animating the definition of force) can be found at www.samanimation.com [19]. Since this was not a controlled study, but rather a complete change in pedagogical style in a single classroom, we will present these studies as two anecdotes.

The penny model: exploring theory through animation

In high school physics courses, one topic of kinematics that students find particularly challenging is parabolic trajectories. Research has shown that students from high school through college struggle with this concept [20, 21]. In parabolic motion, teachers ask students to comprehend two things at once—constant-speed motion and accelerated motion. To overcome this challenge, textbooks usually display an information-rich image called the strobe photo. Such images show three balls: one is dropped, one is shot outward in a parabolic arc and one is rolled across a table. The point of the strobe photo is to display the balls at equal time intervals and show that if you measured coordinates from the horizontal and vertical balls, you would find the ball in the parabolic arc. Animating such a scenario makes the information-rich static imagery dynamic, maximizing the benefit of visualization.

In the freshman (high school) physics classroom under investigation here, an animation assignment was used to introduce two-dimensional motion. Students were asked to create an animation of a penny rolling horizontally across a piece of graph paper at a constant speed. They were then asked to animate the same penny at the same starting point being tossed vertically up the graph paper. Both animations are derived from the equations for motion of both constant velocity and accelerated motion (in this case, accelerated by the force of

(a)



(b)

Fig. 1. (a) Single image from parabolic penny animation. Overlaying the animations of constant horizontal motion, accelerated vertical motion, and the resultant parabolic trajectory allow for the student to investigate, step-wise, two-dimensional motion. The full-length animation is in the Movie Gallery at www.samanimation.com (b) Individual frames from the animation showing how the vertical and horizontal components (A, B, C, D) of motion correlate to the parabolic trajectory (A', B', C', D'), respectively.

gravity). Students then plotted out the Cartesian X,Y coordinates of their horizontal and vertical animation points, generating static images for an animation of the parabolic curve derived from the prior X,Y points.

Pedagogically, the students have not yet been 'taught' (delivered content by the teacher) about parabolic motion. Instead, they are asked to reflect on whether this motion makes sense to them; they must analyse the physical model they created against their mental model, created from previous experiences. In our experience, students typically report that the motion does not makes sense, and they report asking themselves that same question throughout the process of making the animation. Most students have an intuitive sense, or a mental model, of what the three separate cases (constant horizontal velocity, vertical acceleration, and two dimensional parabolic motion) should look like, and they are constantly comparing their final work against their intuition. With two-dimensional parabolic motion, the composite of the horizontal and vertical motions do not match their mental models, and this provides a starting point for a discussion of the components of motion. Additionally, the strong theoretical component of building graphs from ballistics equations inserts mathematics into the discussion, reinforcing understanding from both a physical and a mathematical point of view.

The software used in this classroom is SAM (Stop Action Movie Maker). A feature in SAM allows students to superimpose animation clips on top of one another. In the end, they have a composite of the three individual penny animations. The animations are all set at the same frame rate so that the students can step through their animation and see that indeed the parabolic path is derived from the horizontal and vertical components of motion (Fig. 1). What makes this strategy powerful is that the students authored their own learning tool, providing for ownership and a means for matching learning styles to instruction methods—beneficial components of learning environments cited earlier. The animations become an artifact that both the teacher and the student can reference when discussing the concepts.

In this particular case, the use of animation leads students to critically examine their own mental model. The students brought an understanding of each component of motion into the learning environment. While animations of horizontal and vertical motion generally confirmed the students' beliefs, the composite of horizontal and vertical motion results in parabolic trajectory, which often conflicts with their mental models. This apparent conflict opens the door for discussions with the teacher and with peers regarding the rationale behind this new model. Students have been shown to learn best from demonstrations where discussion with peers precedes explanation from the teachers [22]. In creating the animations, an ongoing dialogue occurs between members of a group concerning the content. Therefore, when the new representation of parabolic motion is discovered, the students appear more comfortable discussing the content with the teacher and with peers. In the animation design process, there appears to be a number of factors contributing to increased understanding of content in the students. However, as stated previously, connecting more closely with students' personal lives can result in deeper investigation and understanding of the concept of two-dimensional parabolic trajectory.

Personalized models: conceptualizing the real world

When students generate animations that are personally relevant (that is, based upon topics of personal interest), there exists a set of individual experiences that provide unique points of access to the conceptual knowledge being developed. Animations concerning an event or interest in the student's life appear to create greater opportunities for motivation and engagement. Children who are motivated, thus, are more willing to challenge themselves and to engage in topics that may not have previously been of interest.

An example of an activity based upon personal relevance occurred with two high school juniors exploring SAM's 'blue-screening' capability. Their task was to create an equation-based animation (i.e. the coordinates of the animated object must be derived from kinematic equations) and overlay their animation on some real scene. The students, Tyler and Steve, produced their equation-based animation using a typical scene from a basketball game—a free-throw. One of them stood at the free-throw line and moved his hands as if he were throwing the ball while being videotaped. They then imported this short video clip into SAM and proceeded to animate a ball leaving his hands and moving along a parabolic arc to the net. Both of these students really enjoyed basketball and had strong background knowledge of the physical dimensions of the sport.

Their prior knowledge served as a foundation from which to undertake the complicated tasks of scaling and finding the right trajectory for the ball. For example, one of the first hurdles faced was calculating an initial speed of the ball at the point of release. To discover this, they used their knowledge of things such as Tyler's height, a realistic maximum height of the ball, the distance from the free throw line to the basketball hoop, the height of the hoop and the equations of motion. As they worked, both students were able to relate difficult material to the reality of the situation. Comments such as, 'That can't be' or 'Ok, that makes sense because the ball should be at about 10 feet or around 3 metres there' were overheard. When they required help from the teacher, their conceptual knowledge and personal experiences led to more articulate questions. In their final work, Tyler stands at the free-throw line and shoots a mathematical model into the hoop. An interesting side note is that the students choose to do this project 'for fun' in the last week of school, spending their free time after school to generate the animation, thus demonstrating, again, the power of the reporting medium in increasing student enthusiasm to learn physics.

DISCUSSION

It is decidedly evident in these two stories (and from other observed occurrences in classrooms and workshops) that students are excited and interested in making movies. The marvel of the technology, the ability to share their ideas in a new way and the autonomy inherent in the process make using stop-action movies beneficial in the classroom. The real benefit to education appears to be that students are engaging in much deeper reflection of the particular content. The animation is a physical representation of the student's mental model, therefore, when it does not make sense to the student, he or she is forced to work through the problem with greater depth than written assessments would produce. This intense examination of one's understanding creates a rich learning environment and affords students an iterative process for investigating their own understandings.

The personal aspect of these animations opens up further areas for educational benefit. Students learn from making predictions and then matching their resultant simulation to reality. Animations provide for these conditions, allowing the student to drive his or her own learning. In the case of the basketball example, the personal connection to the context allows students to pull from previous knowledge while building upon newer conceptual understanding.

By having a personal connection to the material, students are encouraged to 'make sense' of numbers and measurements. There are two layers to this—one is pattern based and one is reference-point based. In the pattern-based layer, students make sense of the numbers they are calculating by referencing the sequence of numbers in their calculation. If a number falls out of that sequence, they recognize it does not make sense and they will check their work. In the personal reference-point-based layer, the students check their calculation against numbers they know from their personal experience with the scene and objects they are animating.

Generating animations in the classroom creates an environment where students can explore new content in constant reference to representations of their mental models. This environment also provides a new avenue for the teacher to assess student understanding. While the student is working through his or her mental model, the model becomes apparent to the teacher in the form of the animation, giving the teacher an opportunity to teach to specific preconceptions. In addition, the animation now becomes something around which students can formulate a question. At the end of each class, teachers often ask, 'Are there any questions?' Yet, if students do not ask questions, one cannot assume they understand everything. Students often lack the vocabulary or understanding of the concept to articulate the questions they may have. Such questions often arise due to conflicts between a mental model and the physical (or real) model. The animation now serves as a focal point for discussion and a starting place for students to explain what they do not understand. When an entire class produces animations, there are many representations of a similar concept and students now have multiple examples to reference. Aside from assessing student knowledge, the stop action movies provide a new discussion point for the classroom with each student personally invested.

Engineering education on the primary and secondary level is gaining momentum across the globe, largely due to some key factors that engineering uses as a pedagogical approach. These factors include student engagement levels, reflection on conceptual issues, personal relevance and meaningful activities, and a variety of media for students to represent their knowledge. The process of generating animations creates an environment with the same factors, so has the potential to impact student learning. As design-based learning becomes a topic of further educational research, the animation design process should also be researched for the potential benefit to student learning.

FUTURE WORK

To move the ideas presented in this paper forward, we are currently active in three initiatives:

1. development of two versions of the SAM software (a feature light version and a feature rich version);
2. an educational research program centered on learning math, science and engineering concepts through generating animations;
3. development of a website to disseminate curricula and research-based best practices as well as serve as the repository of SAM animations from K-12 classrooms nationwide.

The research we conduct will specifically address using animations to predict science/engineering phenomena, using animations to report understanding of a concept, and as alternative assessment techniques. Part of this research will be development of formal metrics for assessing student knowledge represented through animations. Currently, animations have been used in a qualitative sense—as formative assessment tools in the classroom. Formal metrics will allow comparison of animations across populations which will inform the research. Research studies with multiple ages, genders and cultural influences will be conducted to examine social factors in using animation in the classroom as well. It is our belief that this environment creates a situation of distributed cognition—where the artifact (i.e. the animation) facilitates greater cognitive activity amongst those developing it. We will disseminate our work widely in the field of engineering education because, as presented in this paper, we feel that the process of making animations strongly correlates to the engineering design process. It is our goal to show that the animation design process is also highly effective at teaching students fundamental maths, science and engineering concepts and skills. Future research work is motivated by the need for students to have better ways to access the content of science and engineering while also having a variety of ways to communicate what they know.

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