Using computational essays to demonstrate physics concepts

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We create two example computational essays using a combination of text, input code, and computer output to describe different physics concepts from University Physics 2. These computational essays can also be used as demonstrations due to their interactive nature. To demonstrate simple harmonic motion, we use a horizontal mass and spring system on a frictionless surface. We create and animate a visual representation of the system, then plot the position, velocity, and acceleration as functions of time. We also use a computational essay approach to determine the optical path of light rays through two and three media to determine the apparent position of a fish in a pond and that of a fish in a tank. Computational essays allow us to test the limits of the problems and solve problems too difficult or time consuming to solve by hand.

I. INTRODUCTION

Computational essays can be used to express just about any idea, making them a useful tool especially for students. A computational essay uses a combination of text, input code, and output to express ideas [1]. The text explains how the code is written and what the author is trying to accomplish with the code to make the ideas hidden in the code easier to follow. The input code allows for the user to see exactly how the problem is approached and solved, which makes the solution easier to replicate or adjust to different parameters. The output gives the solution generated by the code or displays the graphic to demonstrate what the text was discussing and code was performing.

The ideas used in learning to write computational essays extend to future projects, as the ideas can be applied to many different types of problems. Computational thinking involves approaching problems in a way that leads to writing the code to generate a solution rather than trying to calculate the solution by hand. Problems that are difficult to solve by hand can be quickly solved by the computer given the right input, and the output can take many forms. Plots for functions can be created and combined, difficult equations can be solved, and diagrams can be animated to express ideas. These can aid understanding by having easily manipulable output to see the effect of changing each variable. The diagrams and animations simulate the situation to visualize the concept.

Through the interaction with computational essays, problems can be understood at a deeper level. Manipulating certain variables allows us to see where the problem fails, so we can place the proper conditions on the problem to make it physically possible.

We use the notebooks built into the Mathematica software to write our computational essays. The notebooks provide an easy way to format a single document to contain code that can be ran while also including normal text cells to describe the process, ideas, and code used and headings to separate the big ideas. When ran, the output of the code is displayed in the same group of cells as the input. This makes it easy to distinguish what output is produced with each line of code. We use this format for both our example computational essays.

II. DESCRIPTION OF EXAMPLE COMPUTATIONAL ESSAYS

We use computational essays to explore concepts in physics. Our focus was on creating two example computational essays, one exploring simple harmonic motion and the other investigating the optical path of light through multiple media. We demonstrate simple harmonic motion using a horizontal mass and spring system with no friction. In order to visualize the optical path of light, we create interactive graphics for the light ray through both 2 and 3 media and show the apparent position of an object given the actual path of the light ray.

A. Horizontal Spring and Mass System with No Friction

In [2], we create a horizontal spring-mass system on a frictionless surface to understand simple harmonic motion. We begin by creating a figure to show the spring-mass system. We create a figure of a block attached to a spring that moves with time. We label the displacement of the block from the equilibrium position and the force on the block in order to understand their relationship and how they change throughout the oscillation. The oscillation is described by the position equation. We use the position equation to determine the position of the block in the oscillation when we animate the system. The animation of the system moves with the velocity and acceleration described by simple harmonic motion. We then plot the position, velocity, and acceleration graphs of the spring-mass system to gain a better understanding of their patterns. As a single figure shown in FIG. 1, we animate the spring-mass system, position, velocity, and acceleration graphs to see the relationship between what is visually happening in the figure, and how the position, velocity, and acceleration relate to each other in this system.

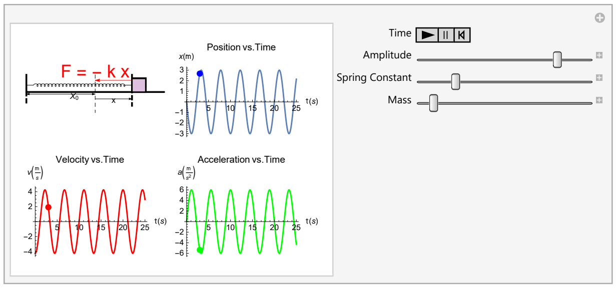

Figure 11: Final figure. We can see in this figure how the system of the block relates to its position, velocity, and acceleration graphs. The point on the position, velocity, and acceleration graphs represents the location of the block in the figure. We can see that at the equilibrium position, the velocity is maximized and acceleration is 0. We can also see that at the point where the block is furthest from the equilibrium point, the velocity is 0 and acceleration is maximized.

FIG. 1. Picture of the final graphic from the Horizontal Mass Spring System with No Friction computational essay showing the system and plots describing the position, velocity, and acceleration over time. When running the file in Mathematica, the block moves with time and the points on the graph correspond with the block's movement. The caption above accompanied the graphic in the computational essay.[2]

Imagining a simple harmonic motion demonstration and trying to connect that to the graphs that represent the motion can be difficult, especially when considering the ways in which the different parameters affect that motion. The computational essay allows us to combine our visual representation of the system and the position vs. time, velocity vs. time, and acceleration vs. time graphs into the same final figure to manipulate as one. Having parameters in a computational essay that we can manipulate, we can demonstrate the way the parameters in that system affect the system and the graphs.

B. Determining the Path of a Light Ray Through Different Media to Find the Apparent Position of an Object

In [3], we discuss light traveling from one point in one medium to another point in another medium. We show first, how to find the potential light ray paths, then how to determine the allowed path by calculating the Euclidean optical path and finding the extremum with a single surface of interface. We verify the path follows Snell's Law. We then create a final figure that shows the light path as the index of refraction of both media 1 and 2, the x and y coordinates of both the observer and object position, and the location of the surface of interface are manipulated.

We include an application of this process as an observer viewing a fish in a pool of water from above. Following the same process, we add a second ray of light. We allow for manipulable input for the observer's eye aperture in addition to the manipulable position. From this and the fixed actual position of the fish, we determine the fish's apparent position. This situation is analyzed using single-surface refraction techniques since light from the fish passes through two media - water and air.

We then expand our methods to investigate refraction with two surfaces. We follow a similar approach as with single-surface refraction where we first show how to find the potential light ray paths. We modify our solution method for the allowed Euclidean optical path and verify the solution by checking that Snell's Law holds for all medium changes. Again, we display a manipulable final figure where we can adjust the indices of refraction for each media, the thickness of the second medium, and the x and y coordinates of the object's position.

We include a second application of refraction with a fish. In this application, the fish is in a glass tank of water. We use the same refraction techniques described when looking at refraction with two surfaces and in the fish with a single surface of interface to find the path of the light ray and show the apparent position of the fish in the tank. The final diagram showing the apparent and actual position of the fish and the path of the light rays from the computational essay is shown in FIG. 2. The first figure number and caption beneath the graphic is the caption from the computational essay itself whereas the second caption relates the figure to this context.

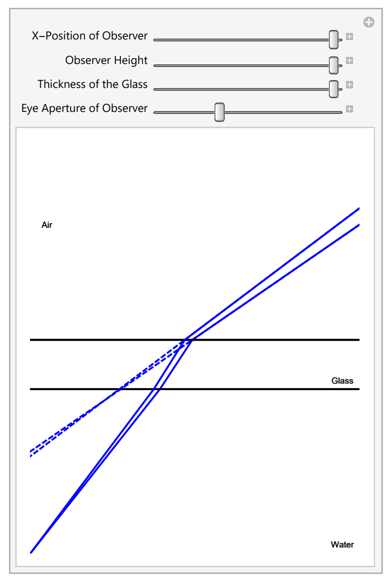

Figure 12: Pinpointing the apparent positon of the fish. The actual path of the light rays are shown with solid blue lines. The dashed lines represent the apparent position since light appears to travel in a straight path. The point of intersection of the two dashed blue lines is the apparent position of the fish. The eye aperture and observer positon can be adjusted to show how the apparent position of the fish changes with these variables, even though the actual position of the fish remains fixed.

FIG. 2. Picture of the graphic from the computational essay on determining the path of a light ray through different media to find the apparent position of an object. This graphic is used to demonstrate the optical path through three media and show the apparent position of the fish. This graphic is interactive in the code to show how the input values affect the path of the light rays and the apparent position. The caption on the figure is the caption included in the computational essay. [3]

Using a computational essay to explore the apparent position of a fish introduces a level of precision that would be difficult to obtain if solving by hand, especially when drawing the graphic. Drawing a graphic by hand can convey a general idea but the angles and distances are extremely difficult to make precise. Using software like Mathematica, we can generate a figure that uses much more precise angles and lengths to see a more accurate representation of the problem. Furthermore, when doing calculations by hand, only one solution is generated at a time using a single set of conditions. The computational essay can be interactive, where equations can be written in terms of the parameters and these values can be manipulated in the output to see how the value of each parameter affects the solution. This interaction can deepen the understanding of the problem and solution.

We can use the output of the figure showing the light ray paths to see constraints on the values different variables can take.

III. OUTLOOK AND CONCLUSIONS

Computational thinking is a relatively new way to approach problems, but can lead to a deeper understanding of the topic at hand and allow for more complex problems to be addressed. The computational essay helps to express the solution in a more understandable form that can be easily adjusted for other applications due to the inclusion of the computer input and text explaining the computer input used throughout the process of solving the problem. The computational aspect introduces a level of precision that is difficult to obtain when solving a problem by hand.

These two example computational essays can be used as demonstrations for Physics 2 students to better understand the topics being covered in the course. They can also serve as examples for students to write their own computational essays on similar topics or any other topic to better understand those concepts and practice computational thinking.

We can expand on these ideas, turning the horizontal spring system into a vertical spring system where we take gravity into consideration. We could also add air resistance and consider the effect damping would have on the system and how it would change the simple harmonic motion. The optical path essay could be expanded upon, adding in conditions for when total internal reflection occurs to ensure the critical angles are not exceeded to where there would not be an image formed for the observer.

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[1] S. Wolfram, What is a computational essay?, Stephen Wolfram Writings (2017).
[2] A. Houck, Horizontal mass spring system with no friction (2020).
[3] A. Houck, Determining the path of a light ray through different media to find the apparent position of an object (2020).