Abstract

Constructionist paradigms provide an opportunity to help learners find personal relevance and interest in originally unappealing or foreign subjects. Using constructionism as the driving force behind our design decisions, we have developed String Theory: a musical simulation app designed to generate interest driven learning across two subjects: physics and music. Through the manipulation of a string’s length, tension, and weight, students are able to explore the ways in which string instruments make a variety of notes as well as explore how physics and music are related. They can then use this knowledge to design virtual string instruments, record music, and share their work. This paper describes our design process as well as presents the future directions of String Theory.

Keywords Science Education, Music Education, Educational Software, Constructionism

1. What is String Theory?

A challenge that many teachers face is motivating students to learn about topics that do not interest them [1]. Constructionism offers a way for students to create personally meaningful artifacts, helping students find personal interests in a variety of classes [2-3]. We used this approach to combine two subjects that appeal to a variety of learners: physics and music. Our goal is to motivate students to learn about these two topics by using them simultaneously through an app that promotes exploration, construction, and sharing. Called String Theory, our app provides an opportunity for students with little background in physics or music to become engaged in meaningful explorations of both subjects through simulations. In this paper, we outline the design and development of the app and relevant learning goals through multiple design iterations. String Theory allows students to explore how a string’s length, weight, and tension interact to change the note a string will produce when plucked. Students can try to create harmonies and frequencies by uncovering the mathematical relationships behind them. Designed with a low threshold [4], String Theory has the potential to be used as a tool by teachers in K-12 physics, music, and math classes.

2. Physics and Music and Simulations

We started this project after a discussion with instructors (including author Berland) about a “physics and the arts” course taught at a local university. A goal of the course is to introduce students with little background in physics to multiple physics ideas through the arts. During this discussion we started thinking about the relationship between physics and music. It became clear that students would likely be well served by building their own musical instruments, but this presents drawbacks: time, difficulty of making a precise instrument, and the lack of opportunities to
receive rapid feedback and create reiterations. *String Theory* was designed as an attempt to address these issues.

Simulations are often created as a means for students to do, rather than study, science [5]. In our case, instead of reading about wavelengths, frequencies, and oscillations, students can use them to create music. Through interacting with *String Theory*, students can change different relevant parameters and observe the outcomes of their changes [6]. This was important to us for two reasons. First, a simulation provides rapid feedback and allows for multiple iterations giving the students an opportunity to check their understanding as they construct their knowledge. This has shown to be valuable by a variety of work, such as [4]. Second, users can further manage complexity by accessing multiple representations, each of which can draw attention to a specific aspect of a given phenomenon to serve as building blocks for deeper understanding, as per [7]. By allowing students to both manipulate and create models, *String Theory* gives students more control over the aspects of the relevant phenomena to uncover misperceptions of the relationships between, say, harmonies and frequencies.

An advantage of many simulated environments is that they can replace complex building projects with one that has both a low threshold of required knowledge and a high ceiling for building potential [4]. Offloading the more time-consuming aspects of construction to a virtual environment allows students to get many of the benefits of design work with a smaller time investment. The rapid feedback from simulations speeds up cycles of iteration. This can allow students to gain a more intuitive understanding of a process through tinkering and immediately observing the results [8]. Students can also work with systems that would be inaccessible in real life due to financial or time constraints [4]. This ability to make inaccessible phenomena both tangible and adjustable within the classroom has led to the uptake of simulations across many disciplines.

Within the physics education community, there has been much excitement over the use of interactive simulations for teaching abstract concepts [9]. Simulations allow students to interact with the variables in an equation, and gain a more intuitive understanding of the equation’s meaning. When students lack physical experience with a subject (such as the motion of atoms [10] or traveling at terminal velocity [11]), a simulation can help them to build this intuition. Though simulations can provide many benefits for physics learners, do they inherently increase student motivation?

While simulations provide a means for interacting with physics, music may provide a reason for doing so by creating an atmosphere in which students will want to learn through creating [12]. Having the opportunity to learn about a subject that one finds intrinsically interesting improves learning and motivation [1, 13]. Music has been used as a way to promote personally meaningful learning in both math and physics. *SoundLab* [2] affords students the ability to participate meaningfully in physics lab. Through using the program to remix their favorite songs, students learned about frequency, amplitude, and other physics and math concepts, topics they had previously been unable to understand [2, 14, 15].

In addition to having a positive impact on physics learning, students will generate a better understanding of music and music theory [16-18]. The musical composition software *Impromptu* has seen much success in helping students build an understanding of many musical concepts, including rhythm, pitch and structure [19]. Through the use of *Impromptu* to create original music and remix the works of others, students have refined their intuitive knowledge of music as well as become aware of the differences in music across cultures [16]. Additionally, encouraging students
to experiment with sounds, pitches, and their durations helped them to build better intuitions about music and sound that was unfamiliar to them [20]. *Impromptu* provided a means for rapid feedback and iteration to explore music and composition. Through reflecting on their composition process, and having the time to try new things, students were able to learn about music in a more personal way. *String Theory* has a similar goal, aiming to make both physics and music theory personally relevant through their combination in a simulated environment.

### 3. The Evolution of *String Theory*

#### 3.1 Overview of *String Theory*

*String Theory* is a web-based application that allows students to experiment with resonance on strings. The current version allows students to adjust the properties of virtual strings to vary their frequency. Users can proceed through seven game-based challenges levels where they must change the properties of a pair of strings to make harmonies or unisons. At any time, the user can shift to construction mode where they can assemble and save a set of strings to create their own virtual string instrument. They can then record music with this instrument and share both their instrument and music with other users. The construction, recording, and sharing features are currently under development.

Our learning goals for the simulation span physics and music theory. We want students to discover the relationships between length, tension, and mass per unit length of strings and the resonant frequencies produced. Students will learn the ratios that produce harmonies such as octaves and major thirds and then use these harmonies to produce their own music. Additionally, students will learn about how to adjust and combine strings in order to make their own instruments.

When constructing this simulation, we chose to limit any extraneous factors that might distract students from our core learning goals. One such factor that was omitted is the effect of an instrument’s resonant cavity on the sounds produced. In our simulation, the string oscillates at its fundamental frequency only. When a real guitar string is plucked, the fundamental frequency and its overtones (integer multiples of that frequency) are excited. The shape of the resonant cavity of the guitar determines which overtones are amplified, and thus affects the timbre, or sound quality, of the note. In order to focus student attention on the properties of the strings themselves, rather than on those of the rest of the instrument, we did not include these effects in the simulation. The construction of different types of resonant cavities, and their preferential amplification of different overtones, fell outside of our learning goals for this simulation. Excluding these effects reduced the complexity of the simulation, allowing users to build instruments more quickly and focus only on the properties of the strings themselves.

Due to our low-threshold, high-ceiling approach, this simulation could be used with students from middle school through high school depending on its implementation [4]. Teaching the physics alongside the simulation deeply enriches the user experience, but users without a physics background or music background are able to experiment with and learn from the simulation. Focus could be shifted to the physics (resonance on strings), the math (ratios), or the music (designing instruments and composing music). Learning goals for the simulation include gaining familiarity with the relationships between the controlled variables and the frequency and an understanding of the mathematical basis of different harmonies.
To facilitate connections between the sounds produced and the underlying math and physics, students encounter a range of representations of resonance on strings. The physical parameters controlled by the student are represented numerically, labeled with the appropriate units, and visually, through the image of the string. As they change the length and weight of the string, its dimensions change on screen. Additionally, changes in tension are represented by a change in string color, ranging from blue for low tension to red for high tension. When the string is plucked, the user can observe the vibration of the string, hear the tone produced, and see the numerical value for the frequency in Hertz. This multiplicity of representations bridges the familiar experience of listening to music with its less familiar mathematical representations. Mapping between different representations can help students to construct their own knowledge [7]. By displaying multiple strings simultaneously, students can compare the tones produced and the physical features of the strings that lead to these differences.

Throughout the development process, we carried out playtests with our peers in education and game design. These informal playtests have focused on the user experience, and have included the challenge and free play rounds. After users played the game, we conducted brief interviews asking for their opinions on usability, where they focused their attention, and suggestions for future development. These playtests have significantly informed the development of the game, as we will discuss throughout this section.

3.2 Challenge Rounds

The challenge rounds, shown in Figure 1, provide scaffolding for users to learn about each variable individually before adjusting all variables simultaneously. Through these rounds, users can discover the mathematical relationships between each of the three control variables and the frequency of the string. In the first few challenge rounds, users must adjust the properties of a string to match a random frequency. In an early playtest, when all three variables were available for manipulation, users would focus on only one variable, length, and ignore the other two while trying to match the frequency. As a result, users had difficulty matching the frequency and would only learn about the relationship between length and frequency. This led us to introduce one new variable each level. Students will now be able to learn about each of the variables one at a time and improve their understandings of all three. Our play-testers were also better able to match a given frequency.

We provided a set of constrained tasks for learners to complete as per Quintana et al’s guidelines for scaffolding process management [21]. This decision was made because simulations without significant scaffolding can lead to confusing and unproductive experimentation, as novice learners often have insufficient knowledge to plan and carry out productive lines of inquiry [22]. By introducing length, tension and weight individually before students move on to free play, students are encouraged to explore the relationships between each of these variables and the resulting frequency of the string.
Initially, the challenge levels consisted solely of matching a series of frequencies. However, during playtests, users suggested that it would be more enjoyable to make harmonies with the strings instead of just matching the notes. In the added Harmony Levels, shown in Figure 1, users are prompted to alter one variable of a string so that its frequency fulfills a specified mathematical ratio compared to a reference string. This adds tools to explore relationships between music theory and mathematical content, and exposes users to harmonies that will be useful in the free play stage. One playtester suggested capitalizing on this potential for math learning by including more harmony levels that require an understanding of ratios.

During the playtests, we found that users focused on the numerical values of the frequency during the challenge rounds while ignoring the changes in the image of the string. After completing just these rounds, some users had difficulty recalling the relationships between the different parameters and the string frequency. In order to focus attention on these relationships, we plan on hiding the numerical values of the frequency for the first few challenge rounds. Users will only be able to view the numerical values after they have matched the frequency or after they have failed 5 times. Later, during the harmony levels, the numerical values will be displayed to focus attention on the quantitative effects of these changes. For levels where the numerical feedback is hidden, we will add additional feedback. Playtesters suggested adding distortion effects when the strings are out of tune, displaying messages that tell the user whether the pitch is too high or too low, and adding alerts when the user is close to the correct value. We will test whether these changes help users to develop greater understanding of the relationships of the string parameters and frequency during future playtests.

3.3 Free Play

Outside of the challenge rounds, students engage with String Theory through free play. In this option, students adjust all three variables. There is no “goal” to free play, but students are
encouraged to experiment with the sounds they can make and what sounds they do and do not like [20]. Students are able to tinker with the strings and receive immediate results [8]. Instead of calibrating strings, students can experiment with more strings and sounds to develop a sense of their interrelationship. In this stage, students can explore the possibilities afforded within the simulation for composition, and consider the string combinations they might want to include in their digital instrument.

In our second round of playtests, we built a level where users could manipulate one string freely. There was no time limit and the only stated objective was to “Play around.” Surprisingly, our users all reported that gained a better understanding of the relationship between length, weight, and tension and the resulting frequency from this unstructured level than from the challenge rounds that preceded it. This is likely a result of attending to “winning” over “exploration” - during the challenge rounds, users focused on matching the frequency as quickly as possible without attending to the effects their actions had on the string itself. Users also noted that having free play levels interspersed between the first few challenge levels, where the objective is to match a given frequency, would give future players a better sense of the relationship between individual attributes and resulting frequency. This would give players the opportunity to construct their knowledge of the variables and apply them instead of focusing on “winning.”

In the Player’s Workshop, shown in Figure 2, students will create their own instruments. These instruments let students create personally meaningful artifacts and provide another way to explore sounds. Single strings can be adjusted to vibrate at a desired frequency. The user can save a set of these adjusted strings as a digital instrument. This instrument can then be used to record music, and both the music and the instrument can be shared with other users. Users will be able to play these instruments and record their own original work or reproduce the works of their favorite artists. As a student combines a series of strings into an instrument, they will notice the ways in which the notes create harmonious or dissonant sounds. While some students may seek out the most harmonious instrument, others may try to create the most discordant combination of notes. They have the freedom to explore the parts of music and physics that interest them the most.

![Player’s Workshop](image)

**FIGURE 2: Concept for “Workshop” page**

3.4 Community
In Discover mode, shown in Figure 3, students can share their work with one another in an affinity space [23]. It was important to us to create a space for their creations to exist outside of the classroom. In this space, students will be able to share their experiences and interests with other students. Students can upload their instruments and songs for others to see, creating meaningful artifacts that will reach out beyond the classroom. Other users will have the opportunity to see their friends’ or strangers’ instruments and listen to their songs. The player can get inspiration, play instruments, and remix songs made by others. They will also be able to comment and give feedback to other users, helping the community create better instruments and songs. Through working with others on common interests, students have the opportunity to expand their understanding of music and physics concepts, and students are able to deeply engage with the topics they care about and construct meaningful understandings [2].

![Discover Interface](image)

**FIGURE 3: Concept for “Discover” page**

### 3.5 User Interface

During our most recent playtest, users frequently commented on the lack of physical fidelity of the user interface. Currently, length, tension, and weight are all adjusted via sliders. Users suggested providing different mechanisms to control these properties that map more closely to their physical counterparts. For example, length could be controlled by directly dragging the mouse along the frets to indicate finger placement. Tension could be changed by turning a dial to tighten or loosen the string, and weight could be adjusted by choosing from a set of strings of different weights. Some of these adjustments, like the dial control for tension, are more suited for a touch screen game and may be more difficult to implement. In addition to adding physical fidelity, this change may help the users differentiate between the variables. Users also noticed that the strings did not sound like a real guitar. When plucked, the virtual strings sound a pure tone of a single frequency with a constant amplitude. A guitar has a much more complicated sound, consisting of many frequencies with a unique attack and decay. We are currently exploring ways to more closely replicate the sound of a real guitar while remaining relevant to our learning goals. We have struggled between physical fidelity and abstraction throughout the design of this application and intend to further explore this tension in future playtests.
4. Conclusions and Future Work

As String Theory is in its prototyping phase, much work still needs to be done to learn about and demonstrate its potential as a learning tool. As we have suggested, one of String Theory’s strengths is its ability to provide rapid feedback through simulations. At the same time, however, one can see the benefits and potential interest and motivation gains from providing students with the opportunity to make their own physical instruments. It may be possible to combine the two models and design a curriculum in which students are able to both explore music and physics through virtual simulations and then produce a physical instrument. Balancing the benefits and drawbacks of these two design models will require further research.

After making the changes outlined in this paper, we will perform playtests with middle school students to study both their game play experience and their learning outcomes. We will perform pre- and post-tests that assess their knowledge of the relationships between the string’s properties and its frequency. Additionally, we will test whether they have learned about the mathematical basis of harmonies. During this playtest, we will conduct informal interviews with the students, and focus on answering the following questions:

1. How long do students spend on the free play levels compared to the challenge levels?
2. In the challenge levels, do students experiment or focus on getting the right answers?
3. What goals do students make for themselves during the free play levels?
4. Which feedback mechanisms (visual, numeric, or audio) do students focus on?
5. What do students learn about the relationship between the different parameters and output frequency?
6. What do students learn about harmonies and their mathematical basis?
7. Do students enjoy playing String Theory?

Through this investigation, we hope to gain more insights into the strengths and weaknesses of this application, and to continue to iteratively improve this application.

String Theory capitalizes on a constructionist framework to promote interest driven learning among students of various backgrounds. Throughout the design process, we have streamlined the app in order to focus student attention on the relationship between the different variables and their effect on string frequency. After initial playtesting, we are redesigning the game to provide more opportunities for free play in order to allow students to set their own goals and explore. This shift in focus encouraged students to perform investigations that are of personal interest while learning about physics, math, and music. Our hope is that String Theory provides a space in which students can explore their interests as they build their knowledge of both physics and music.

References


