HAMLIN: An augmented reality solution to visualize abstract concepts for science education

Robin Andersson
Chalmers Univ. of Technology
Gothenburg, Sweden
anrobin@student.chalmers.se

Malin Anker
Chalmers Univ. of Technology
Gothenburg, Sweden
anker@student.chalmers.se

Adam Dunford
Chalmers Univ. of Technology
Gothenburg, Sweden
dunford@student.chalmers.se

Johannes Lundqvist
Chalmers Univ. of Technology
Gothenburg, Sweden
johlund@student.chalmers.se

Anna Weiss
Chalmers Univ. of Technology
Gothenburg, Sweden
annawei@student.chalmers.se

ABSTRACT
This paper presents Hamlin, an augmented reality (AR) system for science education that detects the invisible physics forces in nature. It collects and interprets raw data information in 3D space and displays spatial visualizations of it. Students use their smartphones with the Hamlin mobile app to view in real-time the principles the instructor is explaining. Because Hamlin is a visualization tool, not just a sensor box, it offers many ways to see physics data. This paper discusses how the prototype was implemented for sound visualizations, and how teachers and students can toggle various wave and frequency visualizations to tie the concepts together and improve student comprehension.

Author Keywords
Augmented reality; education; interaction design; physics; sound visualization

ACM Classification Keywords
H.5.1 Information Interfaces and Presentation (e.g., HCI): Multimedia Information Systems: Artificial, augmented, and virtual realities; H.5.5 HCI: Sound and Music Computing; K.3.1 Computers and Education: Computer Uses in Education

INTRODUCTION
Educational subjects, such as physics, introduce many abstract concepts with limited visual representations. Simplified examples and illustrations are often used to convey natural phenomena, yet inaccurate explanations of how these forces behave in reality can create flawed mental models and false perceptions of fact. In turn, this can cause complications when applying simplified theory to reality.

BACKGROUND
Physics is regarded as one of the "most difficult subjects," [7] yet research around teaching it shows that teacher expectation is much higher than student learning. For these teachers, a major task is helping students to create mental models so they can understand these forces [9]. Researchers have examined whether AR could improve students' understanding of physics phenomena, and have found that AR surpassed other methods for some subjects, including physics. This superiority includes motivation, conceptual understanding, and changing students' preconceptions about how physics phenomena actually operate [8].

Paper presented at SIDeR 2016
Malmö University, Sweden

Despite this research, few successful AR applications for physics education exist, despite guidelines for optimal solutions offering a path. Kerawalla et al. propose that an ideal application should: adapt to individual student's needs, take the same time as traditional teaching methods, offer opportunities for exploration, and follow a user-centered design approach [3].

CONCEPT
With this background, the authors of this paper propose to increase understanding of abstract physics topics that are invisible to the naked eye with Hamlin, an augmented reality tool for science education. As conceived, Hamlin is both a physical device and an ecosystem of visualizations that present the invisible forces of nature.

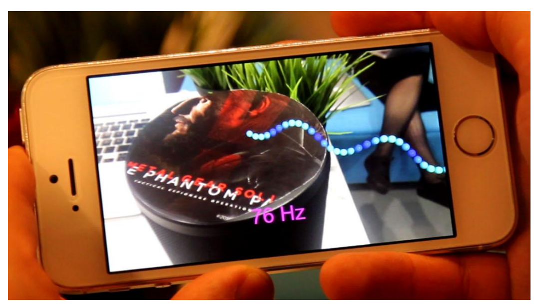

Figure 1. The Hamlin smartphone app displays a visualization on top of the Hamlin device with a fiducial marker.

The Hamlin hardware consists of a compact, wireless instrument containing a variety of sensors to recognize and record various natural forces, such as electromagnetism and thermodynamics (although the final prototype is limited to detecting sound, see Figure 1). A processor analyzes and interprets this data, converts it into visualizations for different teaching scenarios, and transmits this content to recipient devices. The only additional prerequisites are smartphones or touchpads with the Hamlin app downloaded on it, which students use to view the augmented visualizations. With its wireless, small size, the Hamlin device can be integrated easily into a lesson, introduced quickly by the teacher to showcase some concept and then returned just as easily when no longer needed.

More than just supporting students' ability to connect theory to reality, it is also an engaging product that can enhance motivation for students to explore the forces of nature first-hand. Hamlin complements standard auditory and textual learning and supports students who are visual and kinesthetic learners. With this tool, students can examine the problems found in physics class, which can feel more thrilling than just receiving a numerical result after a solved equation.

METHODS & PROCESS

To arrive at this concept, the team began with two initial requirements: the solution must focus on high school education and must incorporate mixed reality. Because of limited domain knowledge, the team's first step was to research both realms and determine what the team could create within the limited time given. Initial explorations included a review of speculative and functional videos [6], supportive hardware such as Google Cardboard and Microsoft Kinect; and implementation platforms such as Unity and EON. Along the way, the team explored projects that introduced technology as a teaching aid. Interestingly, much of what was found focused on younger students [1], not on high school-aged students targeted in this project.

Subsequently, a team brainstorming session following the 5-3-5 method (where the five team members had three minutes to silently jot down five responses for a series of questions) addressed the technology and school from different angles, such as how mixed reality can enable people to create things and what topics students encounter in school. Subsequently, the group engaged in Affinity Clustering, also known as the KJ method, to organize and group related concepts before identifying overarching areas.

Designing the Invisible

A consensus pointed to one idea: *Visualizing the Invisible*. The idea aimed to teach students about the common but unseen forces at work around them by overlaying, or projecting, Mixed Reality in the classroom in order to enhance student's understanding and interest. Most of the concrete examples at that point included topics from the natural sciences, such as showing what happens in chemical reactions on a molecular level or how organisms function.

Extensive research explored technological limitations and possible ways of implementing these ideas. The first question was whether to use Virtual Reality (VR) or AR. While a VR solution (compared to AR) could make the experience more immersive, it would strain the schools' budgets (limiting adoption rate) and could potentially disrupt the teaching flow because of its more advanced and time-consuming setup to begin a visualization. As such, an AR system using smartphones or tablets (from the students or provided by the school) seemed like a better choice.

Bringing together multiple student devices and a sensor device would require some intermediating technology to capture, interpret and display the visualization. Integrating these hardware and software parts together in a functioning way is challenging. To limit complexity, the prototype would deal with only sound. This inserted a further obstacle since the team had limited knowledge about sound physics. Thus, on top of requiring domain understanding of mixed reality (for implementation purposes) and pedagogy (so the solution led to learning), the project required knowledge into the mechanics and principles of sound itself.

Each member then created a moodboard and a sketch to envision how to display sound in a classroom. These artifacts were used to compare and find commonalities. For further insight into the teaching material and the target user group, an expert interview was set up with a physics teacher from Kattegattgymnasiet, a technical high school in Halmstad, Sweden. The teacher explained how he teaches sound, and which pedagogical elements would best support a lecture and classroom discussion with augmented visualizations. He also described which concepts he considered most difficult for students, suggesting that transverse waves were important to visualize because sound is traditionally taught that way. He also pointed out the importance of displaying waves in a two-dimensional plane.

With this, a detailed scenario outlined how a physics lesson using visualization technology could appear. Subsequent prototyping to support the needed technology resulted in possible designs for a physical object (later named Hamlin). This device would act as a spatial anchor for the visualizations, possibly carrying fiducial markers, and at the same time contain a variety of sensors. Making the visualizations physically tied to the sensors would solve the technical challenges of positioning them correctly in three-dimensional space. To communicate the concept to stakeholders, a video prototype (see Figure 1) used a visual effect to show how an example visualization might work. This precursory work also functioned as a brainstorming method to figure out whether to display a schematic waveform or particle level (see Figure 2).

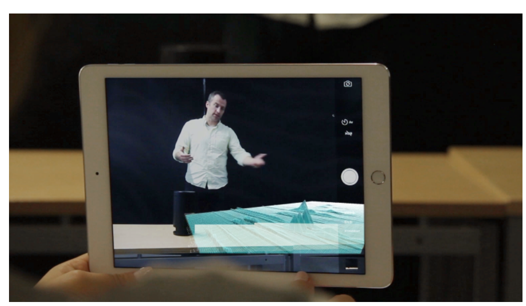

Figure 2. Student use their own devices to display the physics concept the teacher is describing and Hamlin is producing

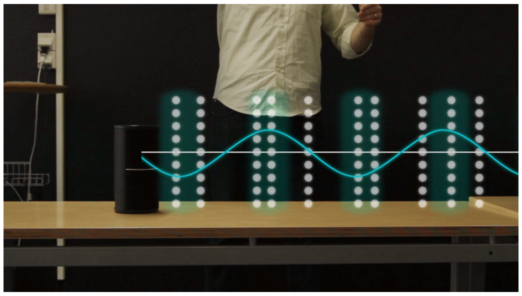

Figure 3. The visualization concept showing layer additions.

Planning the Hamlin Prototype

Next, the team examined the technical domain surrounding AR, identifying several technologies to implement a feasible prototype: first, a game engine to calculate and display visualizations; second, image recognition software to position and overlay visualizations in three-dimensional space; third, an Integrated Development Environment (IDE) to deploy the AR solution onto smartphones and tablets; fourth, a user interface for the teacher to control audio inputs and to change what students' see on their screens; and fifth, a web server to handle inputs and send visualization data to students' mobile AR applications.

Visualizations

The team researched several AR solutions before trying the Qualcomm Vuforia SDK with the Unity 3D game engine, only settling on these tools after resolving fiducial marker issues and deploying a small (but working) prototype as an iOS app. Additional prototypes were developed iteratively, testing different potential features, including line rendering techniques, web connectivity, extended device tracking, and double-sided shaders for viewing the sound waves' interior.

The technical development process continued in parallel with conceptual exploration of the physics, in conjunction with regular discussions about how to best reflect and utilize student's abilities to learn difficult concepts in the Hamlin design. Physics books and online lectures expanded the team's comprehension of the subject and what is actually taught in these grades.

A second expert interview was conducted with another instructor, teaching Modern Physics at Chalmers. From this, the team and teacher reviewed two software simulation tools [2][5] and assessed whether their models of wave reflection and interference would help, as suggested by the previous interview with the high school teacher. While not denying the importance of the presented representation, the Chalmers instructor was more interested in visualizing sound either as transverse waves or in three dimensions.

When designing the final prototype, all ideas from the pre-studies were carefully considered, with the following conclusions: transverse waves are a simplistic yet relevant way of conveying concepts like wavelength, frequency, and amplitude, even if they look nothing like a real sound wave; longitudinal waves in a two-dimensional plane might be a more realistic visualization and would accommodates interference patterns from a second sound source or obstacle; and a three-dimensional sound propagation would contribute to the student's broader understanding of the subject, even if it might not answer a specific teacher need.

Server Implementation

For the server implementation and the teacher's user interface, an initial concept proposed a self-contained tool that would contain the server and offer a tangible user interface on its surface. This all-in-one solution would focus the experience on itself as much as possible and not require the teacher to use a computer for accessing controls. Unfortunately, initial test of Arduinos failed because their processor failed to support the server requirements for either the Hamlin device or the teacher interface. In the end, the team relied on traditional web server technology, particularly JavaScript programming language, including the Node.js and Express.js frameworks for the application server, the Jade templating engine for markup, and the Stylus CSS preprocessor for styling. While pure JavaScript would have minimized dependencies, the only technology suited for the sound generation was the browser-native Web Audio API—a high-level JavaScript API allowing web apps to process and synthesize audio.

RESULTS OF THE WORKING PROTOTYPE

The final prototype included a model of Hamlin—a plastic shell containing a wireless Bluetooth speaker—and a laptop. The laptop accessed a browser interface, which controlled and generated the sounds that were sent to the speaker. The front-end application was in turn supplied by a web server that received sound input, stored it and offered it at a RESTful endpoint for the mobile AR application to poll. For the Unity app on the smartphone to recognize Hamlin, and in order to anchor the visualizations to a fixed position in three-dimensional space, a fiducial marker was placed on the top of the Hamlin artifact. This ensured that the sound source and origin of the visualizations were at the same physical position, connecting this multisensory experience to the right context.

Three different visualizations with increasing complexity levels were implemented in Unity. The first consisted of a traditional transverse waveform, with amplitude displayed perpendicular to the propagation movement. The y-values of the sine function representing the waveform were mapped to the green RGB-channel of the connected material used in Unity, rendering the peak values with a cyan color and intermediate values with a gradient moving towards blue (see Figure 1). This distinguished how changes in frequency correlate to wavelength changes and linked the three visualizations together, since all used the same color mapping. With a screen tap, the visualization changed to a second style, the sound waves emanating from Hamlin in a circle, creating a two-dimensional plane with rings in cyan and blue, typifying longitudinal waves. Here, lower frequencies generated broader bands to represent bigger wavelengths in relation to thin bands at a higher frequency. Another tap visualized how the sound spreads in three dimensions. This illustration attempted to convey that sound travels from its source in all possible directions at the same time, thus creating a spherical expansion. Since sound is often taught using simplified models, the mental model of sound propagation is easily tied to linear representations of transverse and longitudinal waves, and this third visualization introduces another thought pattern.

These different representations can all be thought of as extensions of each other, adding their own unique layer of information to constitute a well-composed learning suite. And as all three visualizations adapt to the frequency from the web interface in real-time, moving to a lower frequency resulted in longer wavelengths in all visualizations on all devices listening to the server, simultaneously.

This prototype was then presented at an exhibition in the Lindholmen Science Park Visual Arena, in Gothenburg, Sweden. The visitors liked how they could see the sound wave change in real time and could imagine it being helpful for learning. Some even suggested it could be taken further, with one visitor asking, "Why does the teacher need to be there? Why can't students use it themselves?"

Figure 4. Demoing Hamlin to exhibition visitors.

DISCUSSION

Designing tools for the future classroom is crucial, as the digital natives 2.0 [4] in schools today already experience the gap between traditional teaching and the ubiquitous technology they are accustomed to in their private life. AR as deployed with Hamlin can mean an effective bridge, bringing advantages such as: increased attention, with its novelty and interactivity; improved comprehension, by combining levels of detail into one joined experience; reduced distraction, as the multisensory experience will engage students on several levels; greater accommodation for varying learning styles and paces; and offering an open system that can be adjusted for new subjects and curricula.

Yet these are primarily educated guesses, because although exhibition visitors reacted positively, Hamlin has not been tested in an actual classroom with an educator teaching and students learning. This kind of user research should be performed to test the effectiveness of Hamlin in promoting effective pedagogy and greater student comprehension of physics principles.

CONCLUSION

As science progresses, skilled professions require more and deeper knowledge of specific areas. Yet invisible natural phenomena are often overlooked in favor of understanding mathematical theories tied to a theme. Hamlin proposes that teaching abstract concepts can change with technology, supporting multisensory learning for students who thrive in a more visual and explorative learning environment.

Hamlin does not replace conventional teaching, it complements it. With Hamlin, teachers explore physics in a flexible, practical way so students can apply their current knowledge to the different modes and abstraction layers and increase their expertise. Thus, as students link their context to theory, interest in physics increases. The concept is intuitive and easy to use for both teachers and students, regardless of technological expertise. The Hamlin prototype proved to convey how sound optimally behaves at different frequencies, but what kinds of visualizations are most suitable for school today should be explored further.

REFERENCES

1. Chris Beyerle. Augmented Reality for Education. List. Retrieved 28 October 2015 from https://edshelf.com/shelf/cbeyerle-augmented-reality-for-education/
2. Paul Falstad. 2015. Ripple Tank on the Mac. Application. Retrieved 28 October 2015 from http://www.falstad.com/apps/RippleTankMac/
3. Lucinda Kerawalla, Rosemary Luckin, Simon Seljeflot, Adrian Woolard. 2006. "'Making it real': exploring the potential of augmented reality for teaching primary school science." *Virtual Reality* 10, 3-4: 163-174.
4. Joaquín Linne. 2014. Two generations of digital natives. *Intercom: Revista Brasileira de Ciências da Comunicação*, 37(2), 203-221. https://dx.doi.org/10.1590/1809-584420149
5. PhET University of Colorado Boulder. 2015. Wave on a String. Website. Retrieved 28 October 2015 from https://phet.colorado.edu/sims/html/wave-on-a-string/latest/wave-on-a-string_en.html
6. Daniel Sjölie. 2015. IxD Project Mixed Reality. Playlist. Retrieved 28 October 2015 from https://www.youtube.com/playlist?list=PL-FiZ7fBs1p4d-OnOGJGO-s9XTrDzCEiD
7. Somsak Techakosit, Prachyanun Nilsook. Using Augmented Reality for Teaching Physics. 2015. *Sixth TCU International e-Learning Conference*. Bangkok, 282-287.
8. Marina Tomara, Dimitris Gouscos. 2015. Using Augmented Reality for Science Education: Issues and Prospects.
9. Kristina Zuza, Jenaro Guisasola. 2013. Closing the gap between experimental data and concepts of electromagnetic induction. *Proceedings of the ESERA 2013 Conference*. Nicosia, Cyprus, 18-25.