HANNAH BARTOLOMEA

TeachXR

TeachXR
by
Hannah Bartolomea

A thesis submitted in partial satisfaction
of the requirements for the degree of

Master of Design
at the
University of California, Berkeley

Fall, 2022

Faculty Director Signature and Date

Associate Director Signature and Date

*How might we enable high school
teachers to use XR tools to enhance
classroom storytelling?*

Empowering Educators

This a graduate thesis project for UC Berkeley
Master of Design program. I am working with
Lucila Duloup to explore how we enable teachers
to implement, customize, and share XR storytelling
experiences in their classrooms.

Written by: Hannah Bartolomea
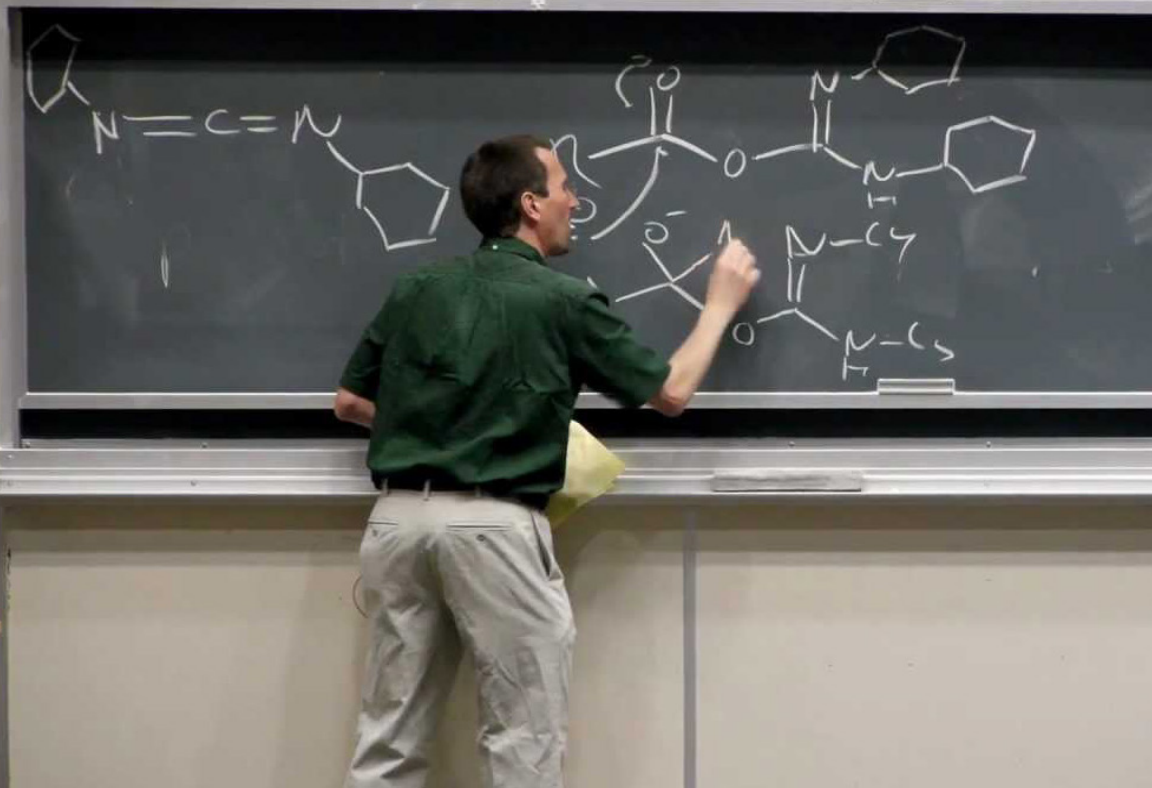In Collaboration with: Lucila Duloup

Table of Contents

nts

One

e

Chapter 1: Introduction

08

It is difficult to teach microscopic chemistry topics.

Chemistry is made up of chemical processes that exist at the microscopic level and cannot be observed by the human eye (Gabel, 1999; Johnstone, 1993). Traditionally, teachers use presentations and paper visualizations to illustrate these complex and abstract visualizations through two-dimensional representations (Oke & Alam, 2010). Many studies (e.g., Ben-Zvi et al., n.d., Griffiths & Preston, 1992) show that it is incredibly difficult for most students to understand microscopic notions of chemistry—and other abstract educational topics—when they are taught using traditional 2D methods of instruction.
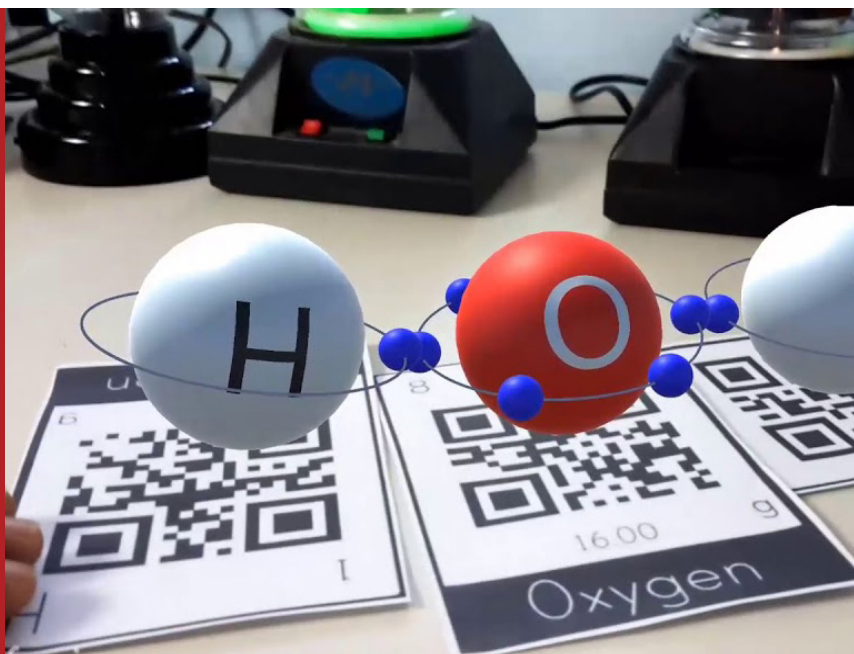
(Ciências Express, 2019)

XR improves learning of 3D science topics.

(Larmand, A., 2022)

Virtual and augmented reality technologies have been shown to improve student learning of 3D science topics by allowing students to learn about these concepts in 3D space (Johnston et al., 2018; Lamb et al., 2018). Yet, the integration of digital technologies does not automatically support learning (Kalantzis & Cope, 2015).

1.3 PROBLEM

Emerging XR technology is providing new ways to improve student learning, but that means nothing if teachers are not able to implement those learning methods in their classrooms.

Many teachers struggle because they do not have time to become sufficiently familiar with new technologies (Walan, 2020) and receive few guidelines on how the technology should be coupled with the subject matter (Walan, 2020).

Teachers are not supported in implementing XR.

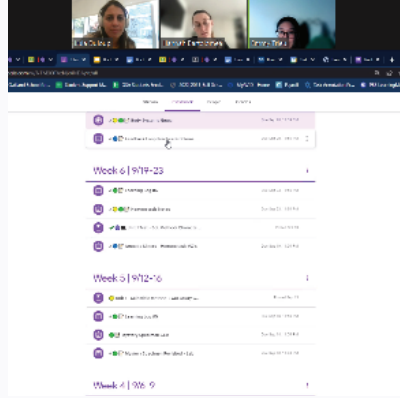# How might we support teachers to use XR?

15

([Woman in VR headset], 2020)

Thie project speculates that if a teachers were supported
with implementing XR technologies in their classrooms,
then they could use XR tools to explain microscopic science
concepts in a way that is easy for students to understand.

Observation of Aaron Glimme lecturing

Zoom call with Emmy Trieu

User Interview with Aaron Glimme

Me preparing an MVP to be tested with Aaron

Case Study

1.5 METHODS

That hypothesis will be tested through a case study of Aaron Glimme, a chemistry teacher at Berkeley High School. This case study builds the foundation for future work to understand how a a tool that provides guidelines for implementing and customizing XR experiences can enable teachers to enhance storytelling of complex chemistry topics by using XR technology in their classrooms. The case study will include interviews with Aaron, observations of his classroom, and designing iterative storyboards, wireframes, mock-ups, and prototypes, all led by observations and direct feedback from Aaron.

Due to the restricted timeline of this project, intensive and repetitive research is limited to Aaron, which narrows the reliability of design solutions. To minimize this limitation, brief interviews are conducted with other science teachers throughout the study to confirm that design decisions are representative of the greater population of high school science teachers. This research is not meant to propose a solution to be immediately implemented at a large scale. The purpose of this work is to identify an essential and overlooked audience in today's educational technology—teachers. TeachXR lays the foundation for future work to bridge the gap between teachers and XR technologies so they can provide students with information in a more digestible way.

1.6 RESULTS

Results include:

1. The TeachXR desktop tool that guides high school teachers to create and share XR activities for their classrooms (interactive desktop Figma prototype)

2. An AR activity designed with Aaron to enhance his stortytelling of enthalpy, as an example of a possible outcome of TeachXR (depoyed on Android Samsung S9).

1. TeachXR

TeachXR Desktop App
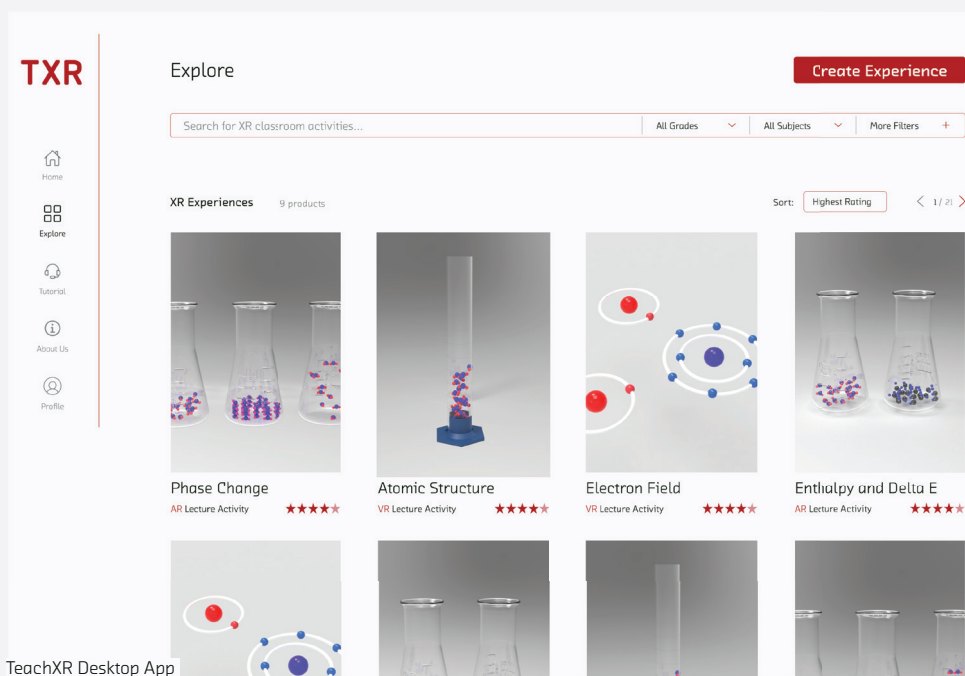
2. Aaron's AR

Aaron holding a conical flask in AR

(Nouvelage, E., n.d.)

20

Impact

Class activities are only limited to imagination

TeachXR creates a future where XR technologies are accessible and exciting for teachers. In this future, students' academic experiences are only limited to the imagination—no experience is too dangerous, expensive, invisible, or even impossible for a teacher to cultivate.

Two

Chapter 2: History

24

Science instruction has improved over the last millenium.

25

Chemistry is made up of chemical processes that exist at the microscopic level and cannot be observed by the human eye (Gabel, 1999; Johnstone, 1993). The US K-12 science curriculum has undergone significant growth over the last millennium to improve the instruction of complex microscopic topics. Still, students struggle to to understand microscopic notions of chemistry using modern 2D methods of instruction (e.g., Ben-Zvi et al., n.d.; Griffiths & Preston, 1992) because these phenomena exist as 3D structures (Barak & Hussein-Farraj, 2009; Wu et al., 2001). The K-12 science instruction needs to continue improving to enable students to access this information in 3D so that students can learn complex and abstract science topics in a way that they can visualize and understand.

(Wickes, L., W. , 1909)

(Oakwood Friends School, 2018)

([Students in chemistry lab], n.d.)

2.1 HISTORY OF INSTRUCTION METHODS

Era of Standardization

In the first half of the 1900s, much of the education system focused on scientific management, which resulted in significant standardization of curriculum (Spring, 2014). Science and other disciplines became a set of facts to be memorized rather than experiences to be understood. John Dewey, widely known for his influential and progressive ideas about education, pushed for the teaching of the scientific process to encourage experimentation and deeper understanding of the material (Belcher, 2018a). Those seeking standardization took Dewey's idea of the scientific process and twisted it into the rigid structure of the scientific method. High school science courses were delivered by textbooks full of vocabulary and assertive statements, with no laboratory experiments or description of experiments to justify any claims.

Establishment of the National Science Foundation

In response to WWII and the Cold War, the federal government started funding K-12 education, which led to the establishment of the National Science Foundation (NSF) (Mazuzan, 1994). Established in 1950, the NSF's mission was to initiate, support, and promote basic scientific research and education (Mazuzan, 1994). Jerrold Zacharias, a physicist at MIT and member of the United States Office of Defense Mobilization's Science Advisory Committee, led the improvement of the K-12 science curriculum and instruction improvement (Belcher, 2018a).. Zacharias started the Physical Science Study Committee in 1956 to change science education to be taught as a living discipline rather than a body of unchanging facts that students must memorize.

Modeling Instruction

Modeling Instruction began in the early 1980s by Malcom Wells, a high school physics and chemistry teacher, and David Hestenes, a physics education researcher at Arizona State University (Belcher, 2018a). This was a laboratory-based method of instruction that emphasized the importance of models to describe and explain physical phenomena and aimed to teach modeling skills as the essential foundation of scientific inquiry (Belcher, 2018a; Wells et al., 1998). It has been shown that if well implemented through K-12 education, students develop a deep understanding of scientifically-accepted conceptual models. Hestenes and Wells created summer workshops to teach Modeling Instruction to other science teachers in the hope to make it common practice in schools today. Still, though, many teachers use presentations and paper visualizations rather than experimentation to illustrate complex and abstract scientific topics (Oke & Alam, 2010).

2.2 UNMET NEEDS IN CHEMISTRY INSTRUCTION

Chemistry is made up of chemical processes that exist at the microscopic level and cannot be observed by the human eye. Complex phenomena are explained by the arrangement and motion of molecules, atoms, or subatomic particles which are not naturally visible (Doymus, 2008; Gabel, 1999; Johnstone, 1993).

Traditionally, teachers use presentations and paper visualizations to illustrate these complex and abstract visualizations through two-dimensional representations (Oke & Alam, 2010). Many studies (e.g., Ben-Zvi et al., n.d.; Griffiths & Preston, 1992) show that it is difficult for most students to understand microscopic notions of chemistry when they are taught using traditional 2D methods of instruction. One reason why it is difficult is that microscopic notions of chemistry exist as 3D structures, yet they are only being taught in 2D methods. However, many students have no background in 3D visualization and have great difficulty converting between the 2D drawing used in textbooks and the 3D structures (Barak & Hussein-Farraj, 2009). Additionally, students' thinking relies on sensory information, and these phenomena are invisible and abstract (Wu et al., 2001)—students need to be able to access this information in 3D so that they can form a visual representation of what they are learning.

It is imperative for teachers to match content with learning style so students can learn complex and abstract concepts in a way that they can visualize and understand. It has even been shown through research that science teachers who use digital technologies to illustrate abstract scientific phenomena are able to help students understand scientific concepts by providing them with meaningful contexts (Eberlein et al., 2008).

It is difficult to teach microscopic notions of chemsitry using 2D methods of instruction.

30

Teaching tech has improved, but that doesn't automatically support learning.

Educational technologies have improved throughout history, allowing students to visualize content in ways that were never previously possible. Today, students can see videos and pictures that explain physical phenomena, and they can hear teachers explain those concepts, but there is no way for students to connect those oral explanations and visualizations with what is happening in the real world. XR technology provides an opportunity for teachers to illustrate complex 3D concepts as they are directly connected to oral explanations. However, integration of digital technologies does not automatically support learning (Cope & Kalantzis, 2007). Many teachers struggle because they do not have time to become sufficiently familiar with the new technology (Walan, 2020) and receive few guidelines on how the technology should be coupled with the subject matter (Walan, 2020).

2.3 HISTORY OF EDUCATIONAL TECHNOLOGIES

Pre Modern Era:

One of the earliest methods of teaching was human speech (Bates, 2015). This has stayed consistent over thousands of decades, yet innovative technology has rapidly provided tools to aid instruction of educational topics. In the 15th century, the printing press disrupted education by making written knowledge more easily accessible. As a result, educational material could be recorded and read without the restriction of location or time. Blackboards and chalkboards began being used in schools around the 18th century, after being first built in India in the 12th century. This advancement allowed teachers to delete and re-write information easily during instruction (Bates, 2015). Up until this moment, teaching material was limited to the teacher's ability to explain concepts.

Early Modernization

During WWII the US Army began using overhead projects for training which became common use for lecturing (Bates, 2015). This allowed teachers to show the physical reality of concepts in photos, and draw over transparency to highlight information. Teachers could also go back to previous information, which was not possible with the chalkboard that lost information after it was erased. In 1969 BBC started using television to show things that were difficult to explain orally through documentaries, demonstrations of processes, and case studies(Bates, 1984). The use of television for education provided learners with a dynamic way to see reality with moving photos and videos. Later, in the 1990s the cost of creating and distributing videos significantly decreased due to digital compression and high-speed internet, which allowed students to view and review visual information at any time and place.

Current Practice

In 1987, Powerpoint presentation software was released which allowed teachers to customize teaching material in advance with the implementation of pictures, photos, videos, and text. The next significant advancement in presentation technology was the release of Keynote 2003. This enabled teachers to easily animate slides to relationships between concepts through the motion of information on slides. In 2008 the SMART board was released, combining affordances of presentations and chalkboards. Rather than indireclty teachers' annotations on a projector or a pre-programmed presentation, students could watch teachers draw directly on the screen and interact with information. Additionally, teachers continue to use physical 3D models to illustrate 3D structures, and interactive 2D experience to illustrate cause and effect relationships.
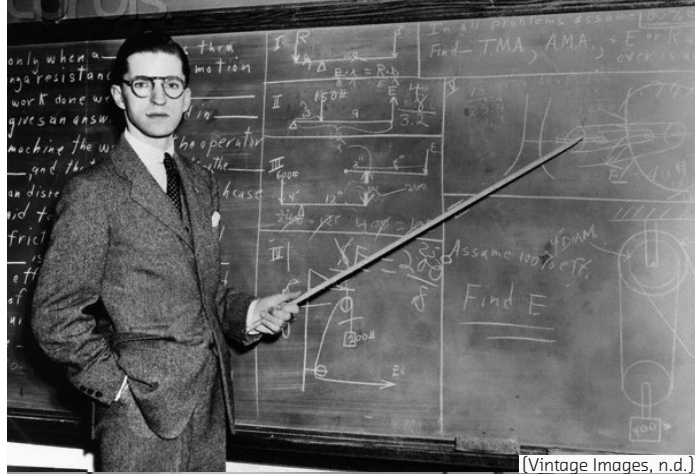
(Vintage Images, n.d.)

(Mdthub, 2018)

(Samsung, n.d.)

No way to connect explanations with the physical world.

Today, students can see videos and pictures that explain physical phenomena, and they can hear teachers explain those concepts, but there is no way for students to connect those oral explanations and visualizations of what is happening in the real world. For example, a teacher can explain molecular bonding and show an animation of bonding, then they can perform a lab experiment that demonstrates bonding in the real world. But teachers cannot directly illustrate where or how that bonding occurs during the lab experiment because the microscopic bonding is invisible to the naked eye.

35

Teachers can use physical 3D models to explain these microscopic concepts while performing a lab, but those models are limited. Aaron Glimme uses a 3D model of an ice molecule structure, but he cannot show how the atoms vibrate and how the intermollecular bonds break when temperature is increased. Additionally teachers can use 2D interactive simulations to show how structure and particle movement changes as temperature is increased, but that is limited to two dimensions.
There needs to be a way for teachers to show how 3D concepts relate to physical phenomena that exist at a microscopic level.

([Students wearing VR headsets], n.d.)

(SpaceTime Enterprises, n.d.)

(Murray, n.d.)

Emerging augmented and virtual reality technologies (extended reality, or XR technologies) provide an opportunity for people to visualize 3D structures in 3D space. Augmented reality is a system that enhances the real world by superimposing computer-generated information on top of it (Furht, 2006). Virtual reality is an advanced form of human-computer interface that provides full immersion and presence to interact with an environment (Trahan et al., 2019). The major advantages of these tools are that they allow users to interact with objects in 3D space, compared to computers and mobile devices that allow users to interact with objects on a 2D screen. As a result, students can see how these abstract concepts exist in the physical world.

2.5 XR IN EDUCATION

(Smithsonian, n.d.)
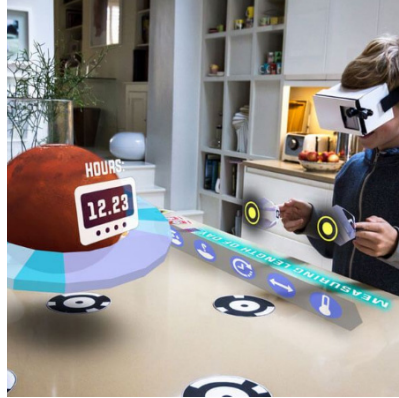
(Zapbox, n.d.)

Related studies have assessed the effects of virtual environments on learning abstract science concepts (Liou & Chang, 2018; Maresky et al., 2019; Rupp et al., 2019). Lamb et al. (2018) used a virtual environment that allowed for the manipulation and movement of DNA, which produced better learning outcomes in content tests than in lectures or a 2D educational game. Johnston et al. (2018) compared test scores of students who learned about cell biology in 2D vs. 3D VR and found that students in the 3D VR condition scored 35% higher than those in the 2D condition. Overall, recent research indicates that complex, abstract material is learned better in 3D VR environments compared to traditional 2D methods of instruction. Teachers' interest in using digital technologies has increased (Grunwalk Associates LLC et al., 2011) as studies have repeatedly reported positive outcomes of using digital technology in the classroom (Balanskat et al., 2013; Dawson, 2008; Ditzler et al., 2016; Ruthven et al., 2005).

(RSplaneta, n.d.)

Abstract material is learned better in XR.

(FatCamera, n.d.)

40

Teachers need support for integrating XR.

41

Integration of digital technologies does not automatically support learning (Cope & Kalantzis, 2007). Many teachers struggle because they do not have time to be sufficiently familiar with the technologies (Hasse, 2017) and they receive few guidelines on how the technology should be coupled with the subject matter (Hasse, 2017). In one notable example, science teachers struggled with the practical use of technology while implementing digital technologies even though they were prepared and enthusiastic. As a result, students lost interest in the lesson and instead of paying attention, they browsed the internet and played games. Emerging XR technology provides new ways to improve students learning, but that means nothing if teachers are not able to implement those learning methods in their classrooms. This project speculates that if there were a tool that supported teachers with implementing XR technologies in their classrooms, then teachers could utilize advantages of XR to explain 3D concepts more effectively.

Thn

42

Chapter 3: Motivation

3.1 RAPID GROWTH OF "THE METAVERSE"

Metaverse is a term that describes the network of 3D virtual worlds including augmented and virtual realities and it is rapidly becoming a common word in modern vocabulary. In 2020 "Metaverse" appeared only five times in the US Securities and Excahnge Commission filings, in 2021 it appeared 260 times, and in 2022 it has appeared more than 2,300 times as of October 2022 (EDGAR Full Text Search, n.d.). This rapid growth is not limited to Western culture. Chinese, South Korean, and European governments have all voiced concerns about the massive impact that the Metaverse will have in the near future (Ball, 2022b). The dramatic response to the Metaverse reflects the growing belief that it will disrupt and transform every industry while reshaping modern society (Ball, 2022b). In a New York Times article, Matthew Ball emphasizes the significance of the Metaverse saying that is "a parallel virtual plane of existence that spans all digital technologies and will even come to control much of the physical world (Ball, 2022a).

VR

Oculus DK1 2012 · Google Cardboard 2014 · HTC Vive 2016 · Oculus Rift 2016 · HTC Vive Focus 2018 · Oculus Quest 1 2019 · Varjo VR-1 2019 · Meta Quest 2 2020/21 · Vive Focus 3 2021 · Playstation VR 2 2022 · Meta Quest 3 2023?

MR + Pass Through

HoloLens 1 2016 · Meta AR 2016 · Magic Leap 1 2019 · HoloLens 2 2019 · Campfire 3D 2020 · Magic Leap 2 2022 · Meta Pro 2022 · Apple Reality 2023?

AR + Smart Glasses

Google Glass 2013 · A-Frame Web 2015 · Snap Spectacles 2016 · Apple ARKit 2017 · Google ARCore 2018 · Focals By North 2019 · Tilt Five 2021 · Lenovo TR A3 2021 · Meta Stories 2021 · Nreal Light 2021 · Nreal Air 2022 · Vuzix Blade 2 2022

XR will not replace the physical world. It will enhance it.

In that same article, the author explains the impact of on education: "Instead of dissecting a frog, we can travel its circulatory systems not unlike the way we drive the Mushroom Kingdom in Mario Kart" (Ball, 2022a). But XR technologies are not meant to replace the physical world, they are meant to enhance it. Traveling through a frog's circulatory system is not a replacement for teacher instruction, it is an additional tool for teachers to explain difficult concepts in a more immersive and visual way. Much like videos have allowed teachers to portray abstract topics that are more easily understood visually, XR will allow teachers to portray complex topics that are more easily understood in 3D space.

([Students looking at molecules in AR], n.d.)

47

Bridging

Advancements in XR technologies have provided a unique opportunity for a drastic improvement in education but these technologies are not currently designed for an essential user in the academic experience—the teacher. The purpose of TeachXR is to bridge the gap between teachers and XR technologies so they can provide students with information in a more digestible way. This project will provide instructional templates to guide teachers in introducing, implementing, explaining, and customizing XR activities. TeachXR creates a future where XR technologies are accessible and exciting for teachers. In a future where students' academic experiences are only limited to the imagination, no experience is too dangerous, expensive, invisible, or even impossible for a teacher to cultivate.

([Woman teaching chemistry with AR], n.d.)

g

(Ground Picture, n.d.)

the gap.

Fou

50

Chapter 4: Methodologies

The Double Diamond Model

Diverge | Converge

DISCOVER | **DEFINE** | **DEVELOP** | **DELIVER**

Diverge | Converge

52
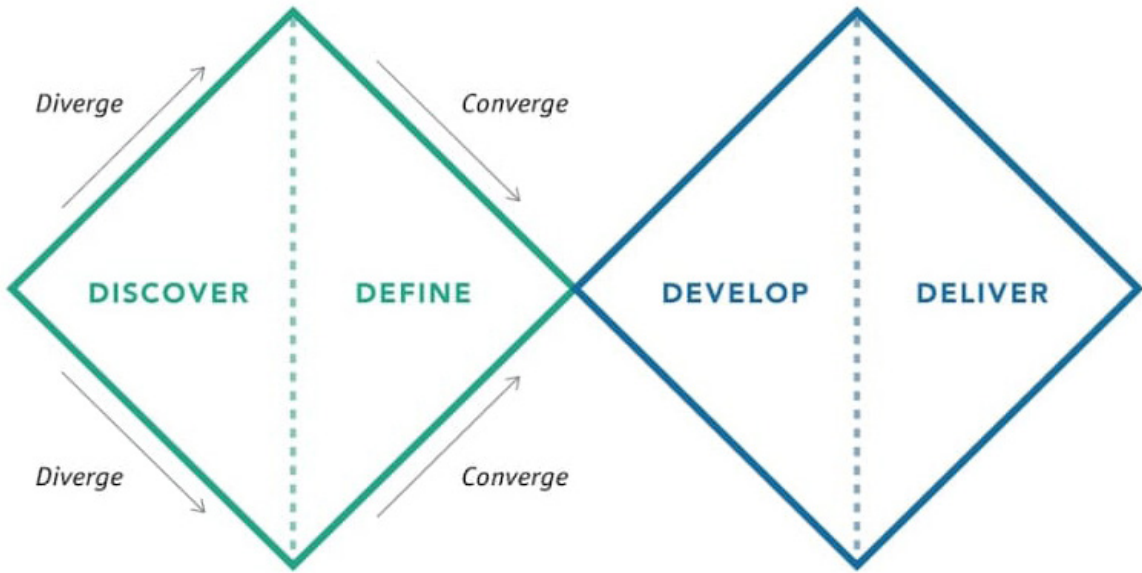
Double Diamond Design Process.

The purpose of this study is to gain insight into how technology can be designed to improve teachers' storytelling. From research and ideation through validation and completion, this study was done in just four months. Research was conducted as a case study of an individual teacher, and the design process was followed by the Double Diamond model (Figure 1). There are two outcomes of this work: 1. The TeachXR desktop tool that provides guidelines to empower high school teachers to create and share XR activities for their classrooms (interactive desktop Figma prototype). 2. An AR activity designed with the focus of the case study to enhance his storytelling and to show a possible outcome of TeachXR (depoyed on Android Samsung s9). The purpose of this is to learn types of interactions a teacher needs when creating an AR experience for storytelling, and to explore which design strategies are most successful in implementing this interaction.

The major limitation of this study is the narrow data collection due to the design of a case study. To minimize this limitation, brief interviews were conducted with other high school teachers and technical advisors to confirm research direction and design decisions.

4.2 DISCOVER

Problem exploration started with a literature review to better understand the problem scope and current technological solutions. After the literature review was completed, meetings with the main teacher of study, Aaron Glimme, began. Aaron is a chemistry teacher at Berkeley High School who has 27 years of teaching experience. Problem exploration research consisted of an initial interview with Aaron to gather demographic information and to understand successes and challenges in Aaron's classroom instruction. This was followed by 2 observations of Aaron's CP and AP classes to learn about his teaching style, how his classroom is structured, how he uses technology in his storytelling, and how students participate in class.

11 units of Aaron's recorded lectures (each containing approximately five 45-minute videos) were thoroughly studied to better understand the concepts taught in Aaron's class and determine which topic would benefit the most from an AR activity.
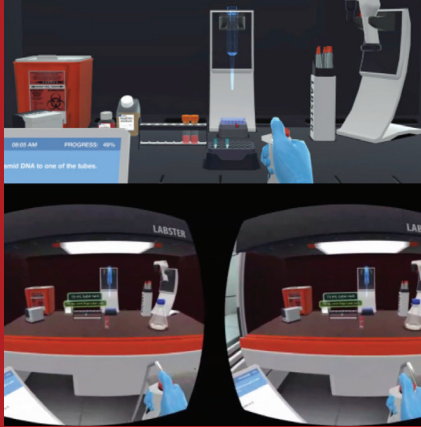
(Maresky, et al., 2019)
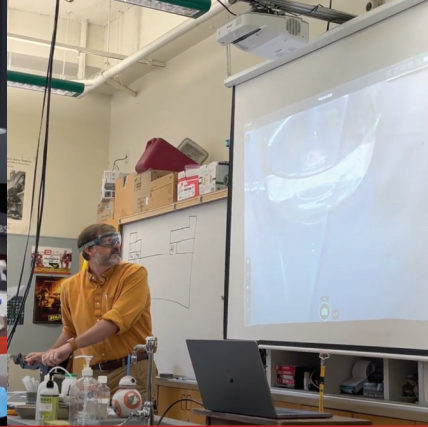
Observation of Aaron conducting a lab

Literature review.
Interviews.
Observations.

56
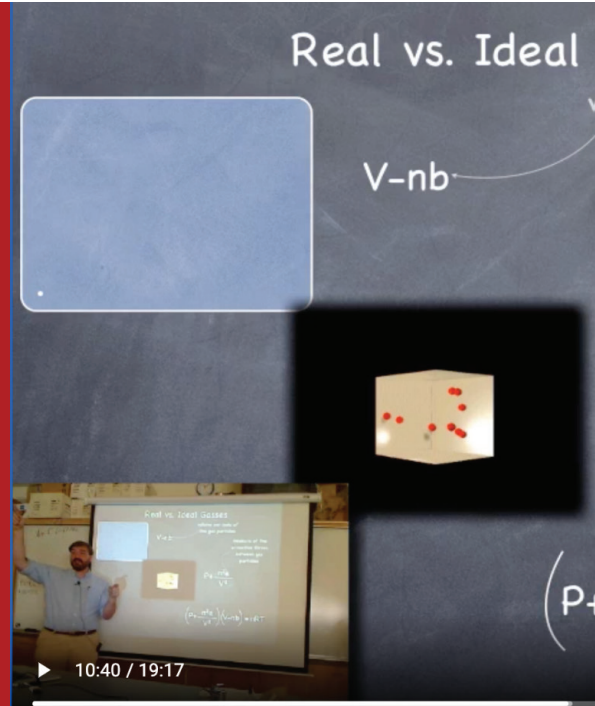
(Glimme, A, 2011)

Narrowing problem scope.
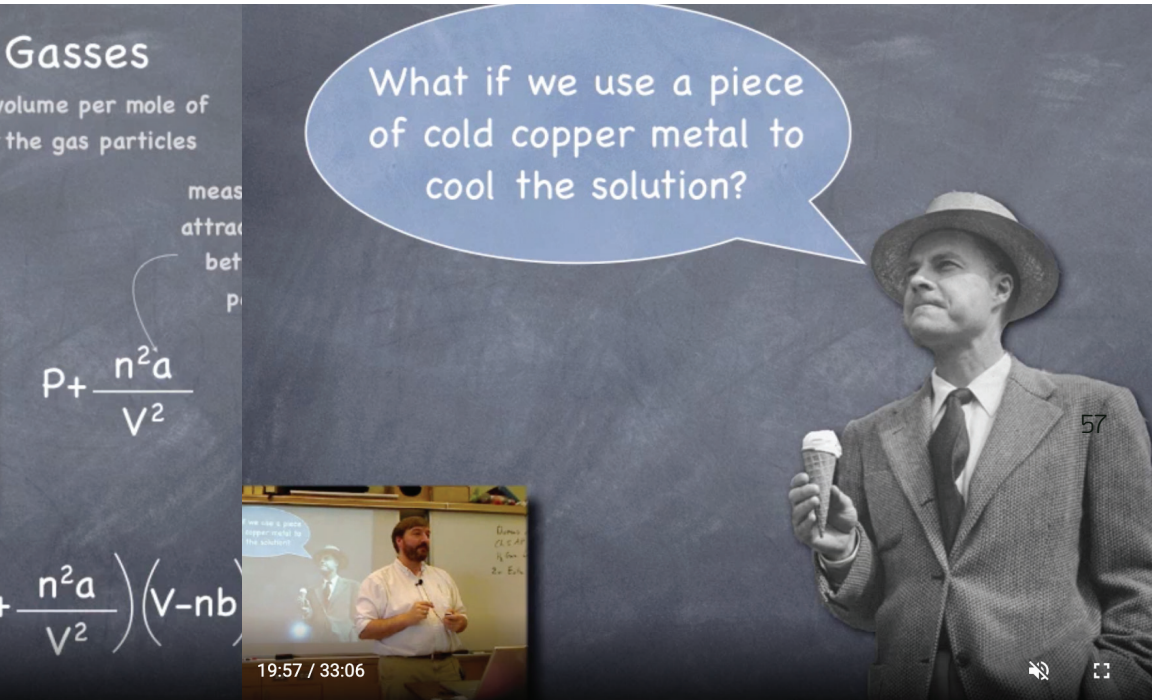
(Glimme, A, 2011)

The scope of the problem was narrowed to in-class instruction, specifically focusing on content storytelling. This meant that the design of TeachXR would focus on how to enable teachers to discover and create content to illustrate a complex topic quickly during a lecture. As a result of analyzing Aaron's course content and discussing with him, the AR activity was defined as in-class storytelling of Calorimetry and Enthalpy content.

4.4 DEVELOP

Multiple ideations were sketched and storyboarded of the TeachXR experience (Figures 5 and 6). Aaron provided feedback on those sketches to reduce the ideation scope, resulting in another round of iterations at slightly increased fidelity, as wireframes in Figma (Figures 7-10). The second iteration was presented to five individuals with various relevant backgrounds: Emmy Trieu—a high school biology teacher at Oakland School of the Arts, Rajan Vaish—a Senior Research Scientist at Snap Research, Bala Thoravi—a Ph.D. Candidate studying Virtual/ Augmented Reality at UC Berkeley, Michael Neimark—an expert in the fields of virtual reality and new media art, and Adityia Vishwanath— CEO of Inspirit, a 3D and VR science toolkit for teachers.

The design was iterated based on feedback from the five experts, resulting in an updated Figma wireframe. The iterated design was then presented to both Aaron and Emmy for another round of feedback and to confirm design direction.

Aaron reviewing TeachXR prototype for feedback

Many diverging ideas were brought up during the ideaiton of the desktop tools' AR customization interaction—some of which required technical feasibility testing. For example, it was very difficult to determine the best interactive experience for teachers to customize animations of 3D content. To test and narrow possible solutions, low-fidelity interactive prototypes of the AR customization tool were built in Unity using the physics engine. These prototypes were presented to Aaron a total of four times through iterations to discover best methods of designing complex creator interactions such as animation editing, molecule selection, object size, and more.

To test the TeachXR design, an augmented reality experience was designed with Aaron based decisions he would have made while using the customization tools in TeachXR. The result is an AR experience which is based on the information that Aaron teaches for his Unity 6 Calorimetry and Enthalpy class. Multiple ideations of the AR experience were sketched (Figures 30 and 31) and discussed with Aaron for feedback. After narrowing ideations, two iterations of the AR experience were built in Unity using Unity animation and Vuforia image tracking.

To test the second iteration, Aaron Glimme presented the AR experience to his class of 37 11th grade AP chemistry students (16-17 years old) to aid Aaron in his explanation of phase change. The AR tool was built onto a Samsung S9 mobile device, which was projected onto a projector to increase visibility. An observation was conducted to get feedback from students and test their learning outcomes, which was followed by a final interview with Aaron. The observation and interview highlighted several necessary improvements, which were implemented into the final design.

Deliver.

The final design includes a high fidelity interactive experience of the TeachXR desktop tool, built using Figma, and a mid fideltiy prototype of the AR experience designed by Aaron, built onto a Samsung S9 mobile device using Unity and Vuforia. Designs of both experiences were presented to Aaron Glimme, two other high school chemistry teachers, and Aditya Vishwanath for final feedback. The final designs with also be presented and defended to three leader of industry, as part of the graduation requirements of the Berkeley Master of Design program.

TeachXR mock-up

Aaron teaching with TeachXR tool

Five

e

Chapter 5: Iterative Work

5.1 PROCESS

This section is split into two parts, the first describes the process of designing the TeachXR desktop tool. The second outlines the process of designing the AR experience designed by Aaron, as a possible outcome of the TeachXR customization tool.

The decision to create a desktop tool and an AR experience was a direct result of initial research. Before even defining a problem statement, a literature review and an interview with Aaron was conducted to better understand the problem space. The two main findings were that: students struggle to learn 3D concepts and that teacher customization preferences vary. This led to two design goals: 1. Create a tool that empowers teachers to create, share, and prepare XR lessons for their classrooms— including guidelines and instructions for lesson planning. 2. Create an AR activity with Aaron as an example of what could come out of the customization tool.

1. TeachXR Desktop Tool

2. Aaron's AR Activity

66

Sketching and storyboarding.

Initial brainstorming sketchs of TeachXR

The first step of creating a teacher tool was to create storyboards and sketches of possible solutions. Figure 5 shows a very high level storyboard. Figure 6 shows the other more specific ideation sketches.

5.2 TEACHXR DESKTOP TOOL
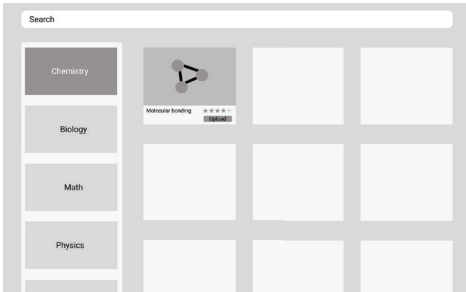
Explore Iteration 1
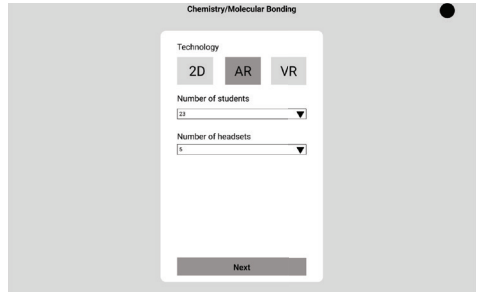
Settings Iteration 1
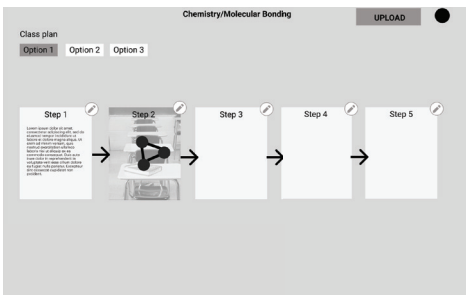
Instructions Iteration 1
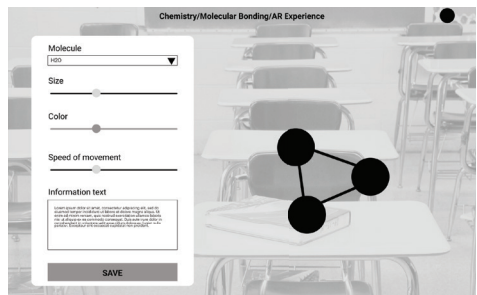
XR Editting Iteration 1

Based on those storyboards, possible solutions were narrowed to four low fidelity screens built in Figma (Figure 7-10). These screens were presented to Aaron who was positive about the direction of the tool and provided iterative feedback about filtering and customization.

The Figma screens were iterated to create a second version (Figures 11-14) that reflected Aaron's feedback. This iteration was an interactive Figma prototype to be used by Aaron Glimme, Emmy Trieu and Aditya Vishwanath during observation sessions. These observations enabled the discovery of several improvements that may not have been recognized otherwise. Some key areas for improvement include: filtering of experiences on the explore page, user navigation after an experience is selected, and additional features to be added to the XR editing.
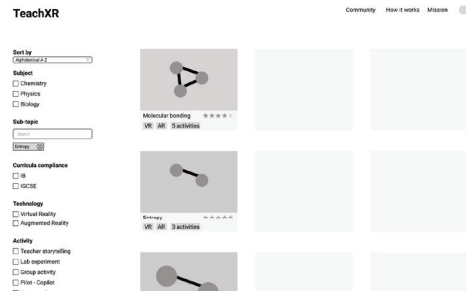
Explore Iteration 2
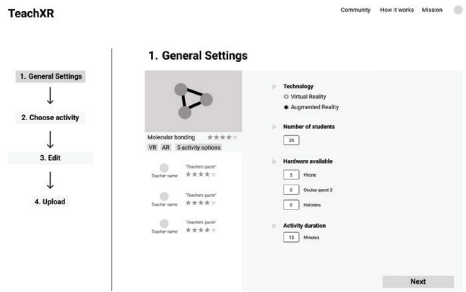
Settings Iteration 2
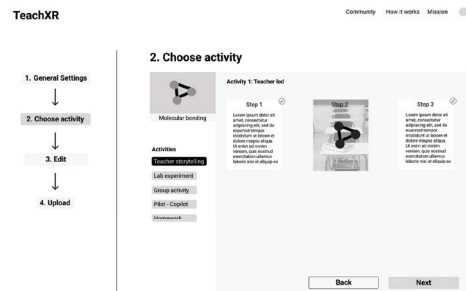
Instructions Iteration 2
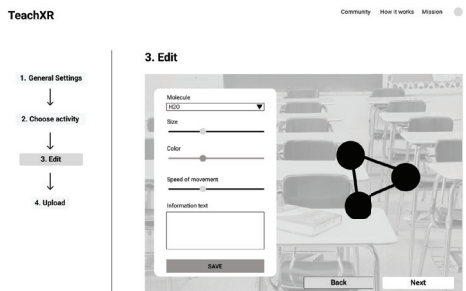
XR Editting Iteration 2

5.2 TEACHXR DESKTOP TOOL

It also became clear that increased interactivity was necessary for testing of the customization screen so that interaction of text, object size, and molecule selection could be assessed. A low fidelity desktop experience was built with real-time interactivity in Unity (Figure 32).

Aaron interacted with the experience and determined that it was necessary to add animation to this interaction. It was decided that the most simple way for a teacher to implement animation would be for motion to be a direct result of chemistry formulas. For example, if a teacher wanted to show particle motion at different temperatures, they could adjust the temperature of the environment using the specific heat capacity formula, which would result in faster moving particles. This interaction was built at low fidelity to show how the motion of one particle would change in responsive to three values in the specific heat capacity formula (Figure 33).

Testing the interaction of XR editting.
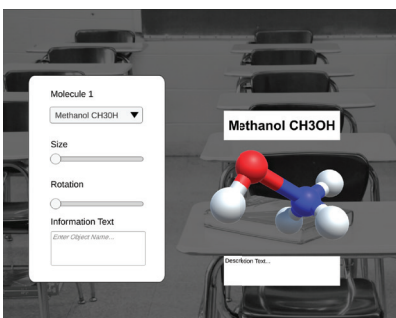
Test for interactive size, rotation, and text
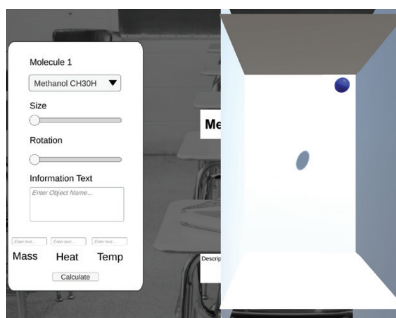
Test for heat capacity formula animation
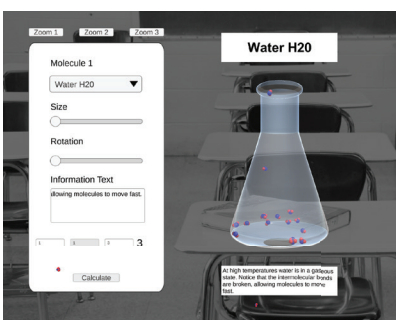
Test for three zoom levels

C# code for heat capacity formula animation

These low-fidelity Unity prototypes confirmed the use of formulas for animations, the selection of molecules using a drop down menu, and the description text input. Additionally, the size and rotation editing tools were removed, as they would be better adjusted on the actual AR experience. All of these decisions were implemented into the third iteration of the interactive Figma TeachXR prototype.

5.2 TEACHXR DESKTOP TOOL

In addition to the changes discovered from the Unity builds, filtering options were also increased, navigation was designed a more familiar way. This final low fidelity prototype was presented to Aaron, which led to the discovery of minute interaction design iterations, and significant user interface improvements to be implemented into the final design.
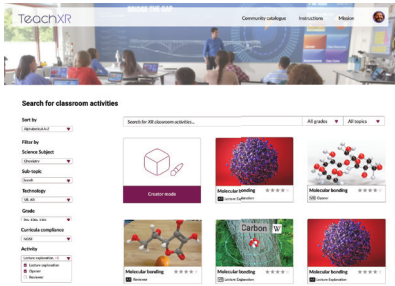
Explore Iteration 3
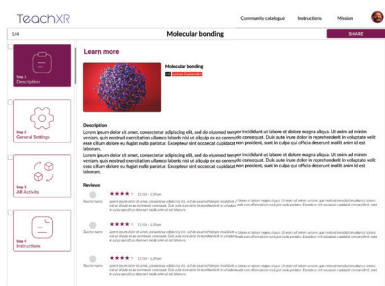
Description Iteration 3
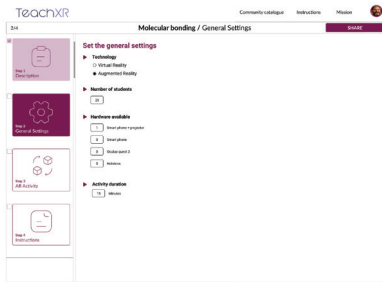
Settings Iteration 3
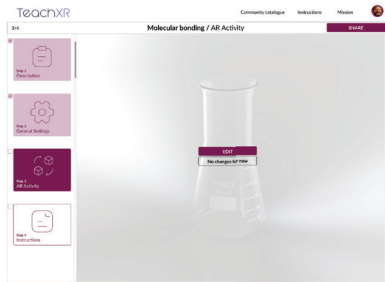
Optional UX Editting Iteration 3
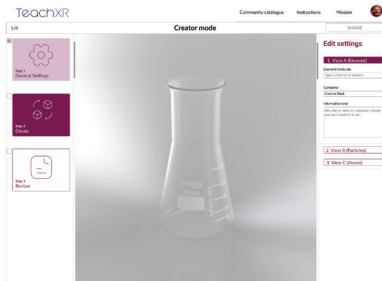
Macroscopic View XR Editting Iteration 3
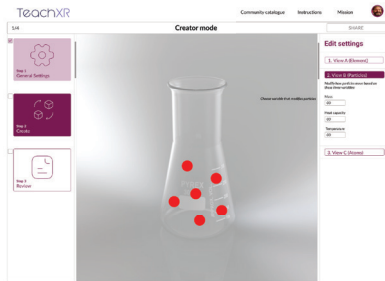
Molecular View XR Editting Iteration 3
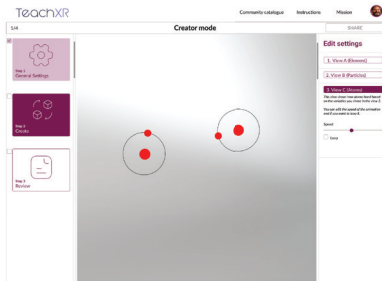
Atomic View XR Editting Iteration 3
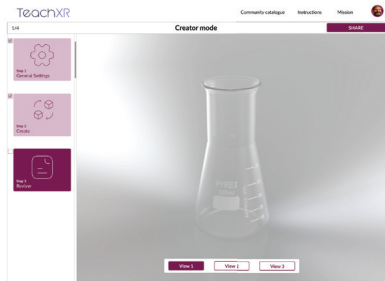
XR Editting Review Iteration 3

Aaron conducting experiment in class
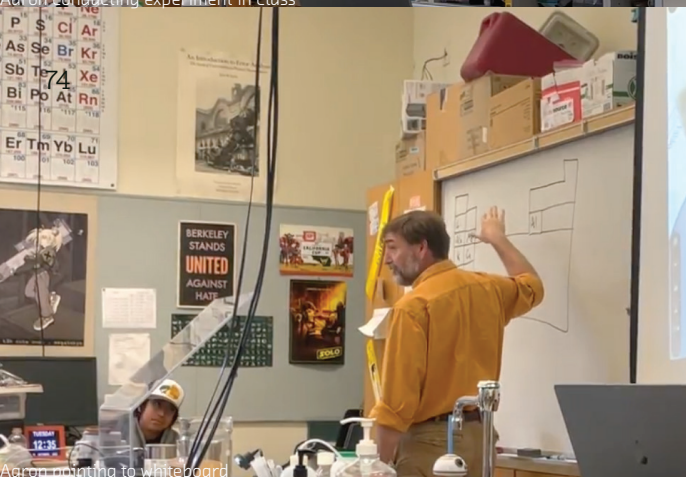
Aaron pointing to whiteboard
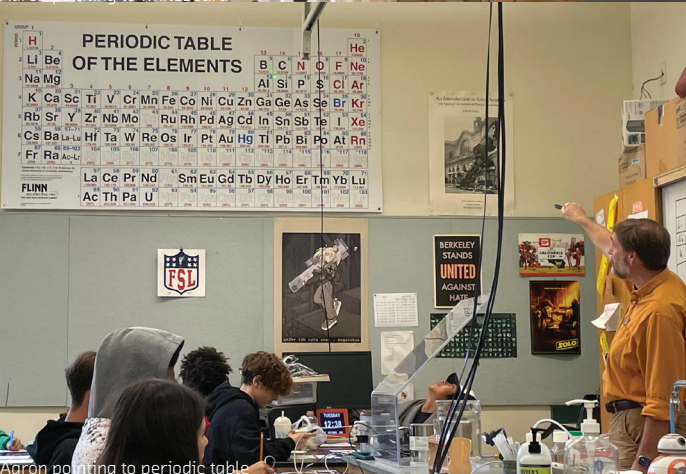
Aaron pointing to periodic table

5.3 AARON'S AR EXPERIENCE

To better understand how Aaron would use an AR experience to enhance his storytelling, an observation of Aaron's CP and AP classes was conducted. A key discovery during this observation was that Aaron explains connections between three different types of visualizations to illustrate concepts that are hard to explain. Those three methods of visualization were: 1. The lab experiment, which was recorded and projected on the wall (Figure 27), 2. the whiteboard (Figure 28), and 3. the periodic table on another wall (Figure 29).

Two main problems of this presentation style were discovered: 1. Students in the back were not able to see the lab which led to a lack of focus. 2. The students understanding of these complex and abstract concepts were reliant of Aaron's oral explanation.`

Learning Aaron's teaching style.

5.3 AARON'S AR EXPERIENCE

Two possible solutions for improving Aaron's explanation of enthalpy were sketched and presented to Aaron for feedback. The first solution (Figure 30) was a mobile AR app for students to see what Aaron was doing at their own desks. The second solution (Figure 31) was a mobile AR app for Aaron to use while projecting the recording of a lab experiment. This enables him to augment additional information on top of the lab recording to show microscopic invisible concepts.

Aaron revealed preference for the second ideation saying that it would be better for students to see the real lab rather than an augmented version of the lab at their desk. The second ideation would be a "better version of reality," because it shows invisible information on top of what is really happening. Aaron was very excited about this ideation and said, "I would change the way I present this entire unit, and would use this to introduce the concepts of phase change instead."
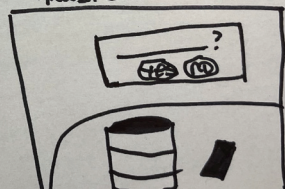
Storyboarding possible solutions.

Today: —————————→ XR
Students watch demos

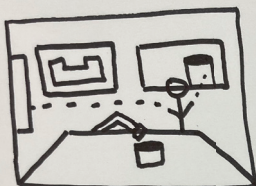Replicate demos in their desk

77
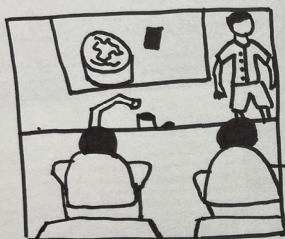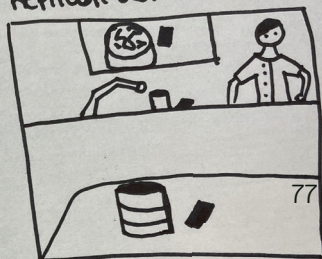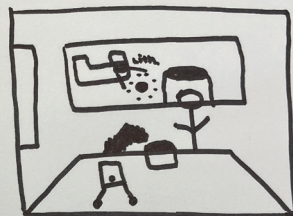
Questions+ = "Review sheet"

Aaron's AR Sketch 1

Today —————————→ XR

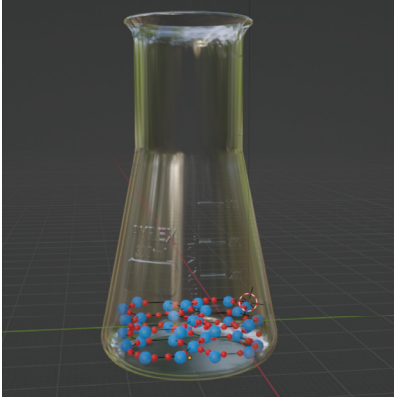Teacher bounces
between 3 visuals
to explain connections

Augment video to
connect visuals +
show even more.

Aaron's AR Sketch 2

5.3 AARON'S AR EXPERIENCE

Animation of solid h20 molecule

Three image trackers in Unity

Aaron explained that rather than changing temperature in real time to show phase change, he would prefer to have three states of temperature (solid, liquid and gas) displayed on his desk in the physical world for comparison. Based on this information, three image targets were designed to coincide with each phase state (Figure 35). When Aaron scans each of the images, the associated particle motion would appear and be augmented on top of the physical object to show the molecular level of that phase state. Animations of the different phases were designed to show particle motion (Figure 32) and exported into Unity to appear in AR as image recognition (Figure 33 and 34).

Testing image trackers for h20 at solid and liquid

Visualizing three different states.

5.4 FINAL TEST IN AARON'S CLASS

Aaron using AR tool during a lecture

Testing

All of the information gathered during the design process was culminated into a high fidelity Figma prototype of the TeachXR tool, and a mid-fidelity AR mobile application of the Aaron's AR enthalpy experience. Most of the design decisions were confirmed (which will be outlined in the final design portion of this paper), but some design choices showed room for improvement. For example, the images presented in the customization part of the TeachXR tool (Figure 36) should directly correlate with the outcome of the AR tool (Figure 33).

Three explaining AR content on projector

in class.

Six

Chapter 6: Final Work

The final design is composed of two parts: 1. The TeachXR desktop tool which enables teachers to prepare XR lessons for their classroom including guidelines and instructions for lesson planning (interactive Figma prototype). 2. An AR activity that is designed by Aaron as if it were built from the customization portion of the TeachXR desktop tool, to provide an example of what could come out of the customization tool. (Deployed on an Android Samsung S9, built using Unity).

The aesthetic of the TeachXR brand portrays a welcoming and inclusive feeling to encourage teachers with little technical expertise to use the tool. TeachXR is also meant to illustrate with undertones of bold, unique, and innovative emotions as this tool can disrupt the education industry in a positive and exciting way.

Bold, yet inclusive.

6.2 DESKTOP TOOL

The final design of the TeachXR desktop tool consists of 11 interactable screens, all of which were designed as a result of the information gathered from interviews and observations throughout this study. There are two main paths that teachers are expected to take using this tool: Creator Mode or Explore Mode. Creator mode enables teachers to make an XR experience from scratch, while Explore mode allows teachers to find activities built by their community to use and optionally edit. It is expected that most teachers would use pre-built activities, making slight edits to meet their specific needs.

6.2a CREATOR MODE

From the explore page, if a teacher wants to build an experience from scratch they would click the "Create Experience" button on the top right corner.

Creator
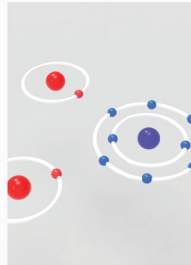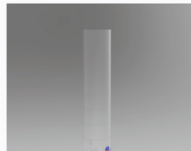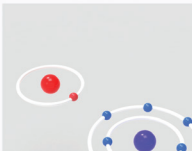
TeachXR Explore page, with "Create Experinece" button highlighted

Mode.

6.2a CREATOR MODE

Step 1
Description

Step 2
Settings

Step 3
XR Activity

Step 4
Instructions

Step 5
Save

TeachXR navigation bar

After selecting an activity, the next four steps set teachers up to use the activity. The steps are: 1. Description, 2. Settings, 3. AR Activity, 4. Instructions, and 5. Save. These steps are on the left side of the screen, replicating the interface of powerpoint slides to increase a teacher's familiarity with the interaction. Each step is color-coordianted to indicate which step that the teacher is on, which they have completed, and which are uncompleted.

The description page allows teachers to add information about the activity. The setting page allows teachers to indicate the type of technology that they have access to, the number of students participating, and the time available so that others can understand how this activity is meant to be used.
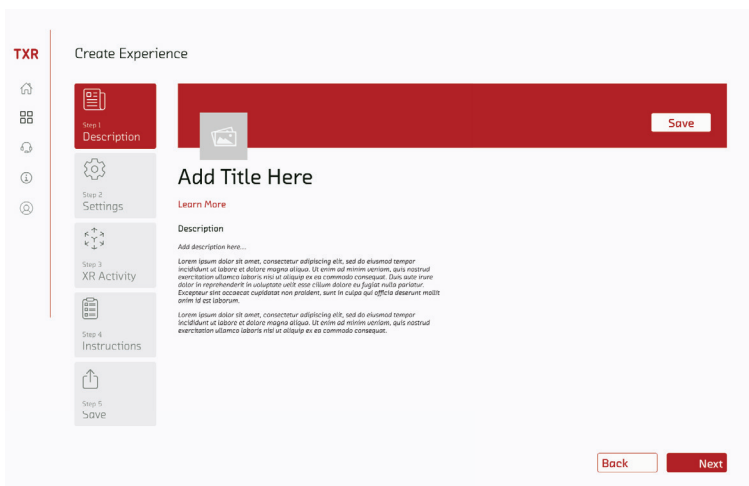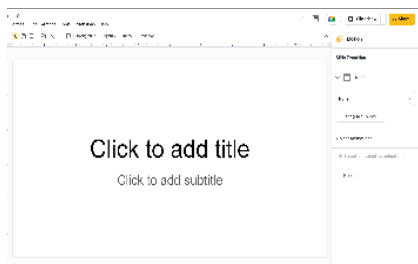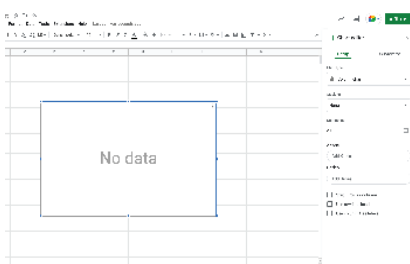
TeachXR Description page—creator mode
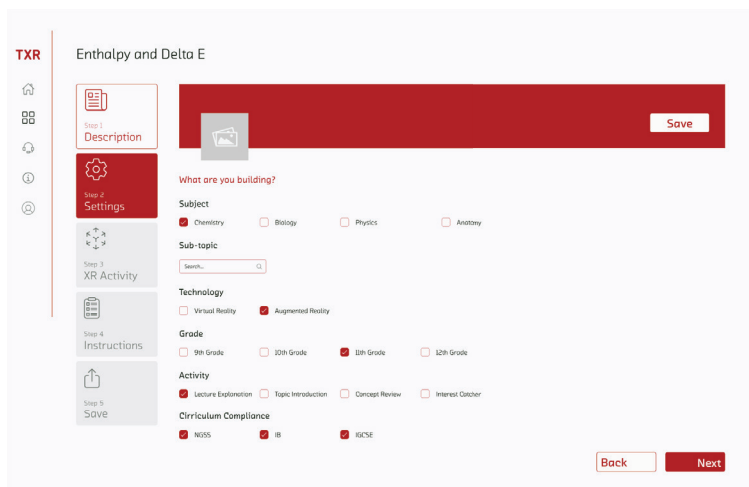
TeachXR Settings page—creator mode

6.2a CREATOR MODE

(Google Slides, n.d.)

(Google Sheets, n.d.)

When teachers arrive at the AR activity section, they will see a render of the XR activity with activity setting on the left side of the screen. This design is similar to the interaction of editing tools in Google Slides (Google Slides, n.d.) or Google Sheets (Google Sheets, n.d.). This is meant to increase teacher familiarity with interactive content.

TeachXR XR activity

The sidebar is split into three sections: 1. Macroscopic view, 2. Molecular view, 3. Atomic View, followed by a review page. From interviews and observations with Aaron, we discovered that to explain chemistry concepts, teachers need to show the relationship between the content in different zoom levels. Most significantly they need to show relationships between macroscopic, molecular, and atomic levels of content.

Each zoom level contains different editable information based on the content that it shows. The settings chosen in each zoom level will effect all zoom levels. Teachers are also able to turn any of the zoom levels on or off with a toggle button depending on their storytelling preferences for that activity. The settings chosen in each zoom level will effect all zoom levels—even if one zoom level is turned off, the settings can still be editted to affect other zoom levels.

TeachXR XR activity editor—creator mode

6.2a CREATOR MODE

Macroscopic View

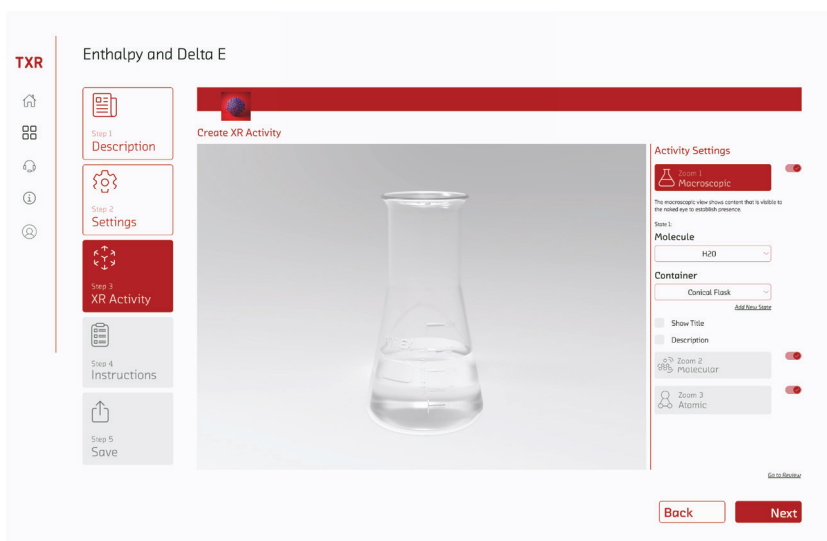The macroscopic view shows content that is visible to the naked eye. This view is mainly to establish presence so that teachers (and students observing teachers) understand what is being zoomed into. The editable features of this zoom level include, type of molecule, type of container and optional title/description text. Molecules and containers can be selected from a drop down menu and title/ description text can be added with text input that can be toggled on or off, with layout automatically organized on the screen. Teachers can also add new states to compare interactions of multiple different molecules or different containers at the same time.
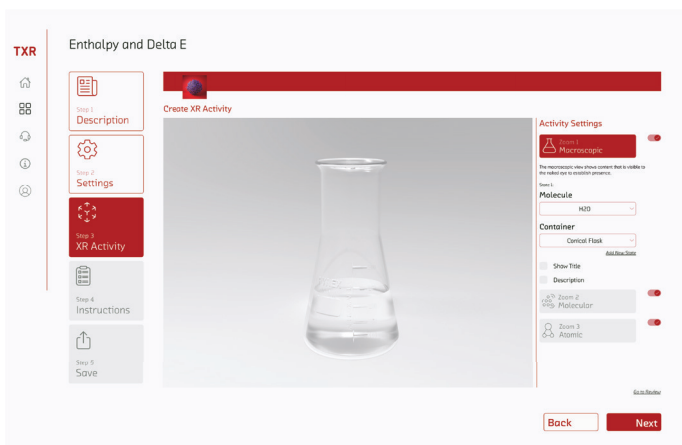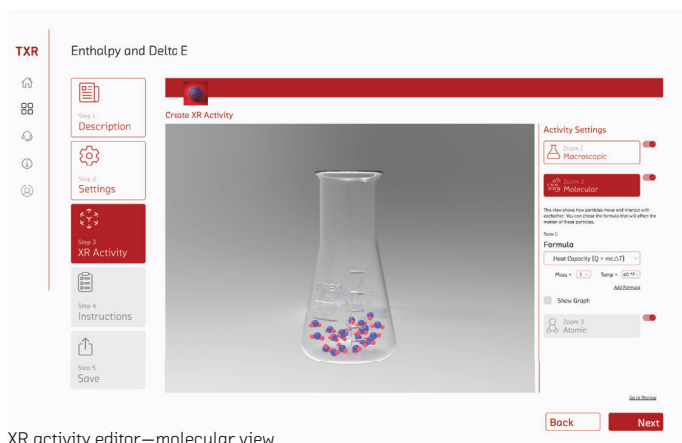
XR activity editor—macroscopic view
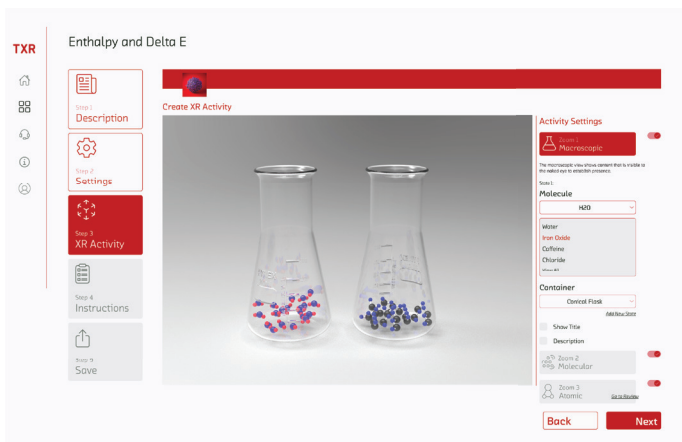
XR activity editor—add new state

Molecular View

XR activity editor—molecular view
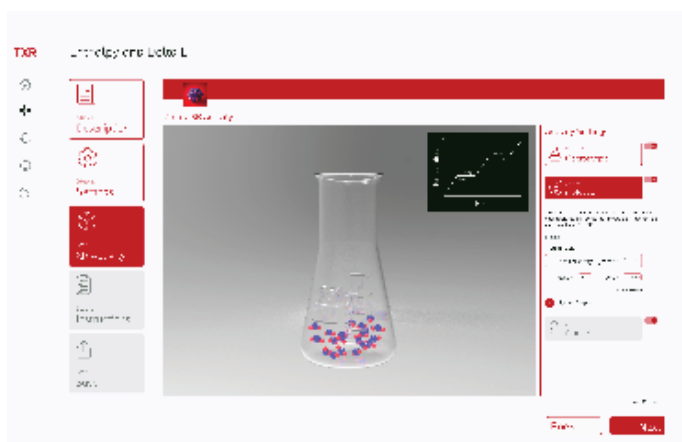
XR activity editor—show graph

The molecular view shows how particles move and interact with eachother, to illustrate motion properties of the molecules as they would exist in the container—both chosen in the macroscopic zoom level. In the molecular view teachers can select from a dropdown list of formulas to effect the motion of the particles. For example, a teacher would use the heat capacity formula to illustrate enthalpy. Each factor of the formula can be adjusted using a dropdown menu. Teachers can also toggle on or off a graph, to illustrate where the selected values fall on a graph associated with the selected formula. In this example, the red dot indicates that at 40 degrees, H20 is a liquid.

6.2a CREATOR MODE

Atomic View

XR activity editor—atomic view

The atomic view illustrates molecules at the atomic level, to show an animation of how atoms bond to form molecules. In this view, teachers can edit the speed of the animation and whether or not the animation is looped.

Review

XR activity editor—review

The final step of the XR creation is the review, which enables teachers to ensure that they are satisfied with the activity that they have editted.

6.2a CREATOR MODE

Instructions

Next, teachers will arrive at the instructions step. Here, teachers can access text and video instructions to learn how to use the technology and how they might implement the XR activity into their classroom.

TeachXR Instructions page

Save

TeachXR Save page
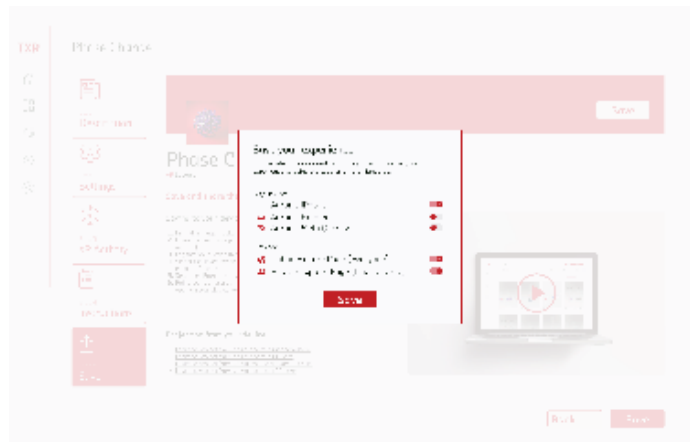
TeachXR Save pop-up

The final step is to save the activity. If teachers want to skip to this step, they can also access it from either the description or settings page by clicking the save button at the top right corner. This page describes how a teacher can save and access the activity on their personal device with clear written instructions and an informational video. Links to information about projecting the activity from their phone onto a classroom projector are also provided on this page.

When the save button is pressed, a pop-up window appears, prompting teachers to select where they would like to save their activity. This window includes a list of devices to save the activity onto as well as locations to share the activity either privately or publicly with other teachers.

6.2b EDIT MODE

The heart of edit mode is in the explore page—from there, teachers can choose from a list of activities built by other teachers, and make slight edits to meet their own personal needs.

The explore page is designed to make it easy for teachers to find the right activity for to tell their story. The search bar and filters at the top of the page are intended to simplify the process for teachers to find lessons based on their prioritized criteria. The filter options were recommended by real teachers based on the needs that themselves and their colleagues generally search for—including subject, technology, grade, curricula compliance, activity type, and more. Ratings are also made visible as many teachers informed us to that value ratings from other teachers when finding instructional content online.

Edit
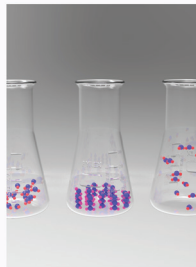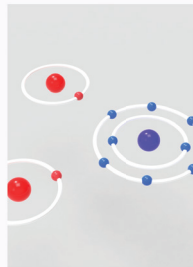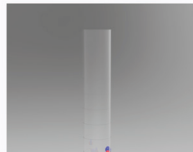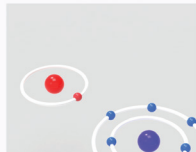
TeachXR Explore page, with "Phase Change" button highlighted

Mode.

6.2b EDIT MODE

Description/Settings

From here, teachers will see the same five steps that exist in the creator mode: 1. Description, 2. Settings, 3. AR Activity, 4. Instructions, and 5. Save. However, the description page will not be editable and it will display reviews by previous teachers who have used the activity. The settings page will only display settings that are editable.
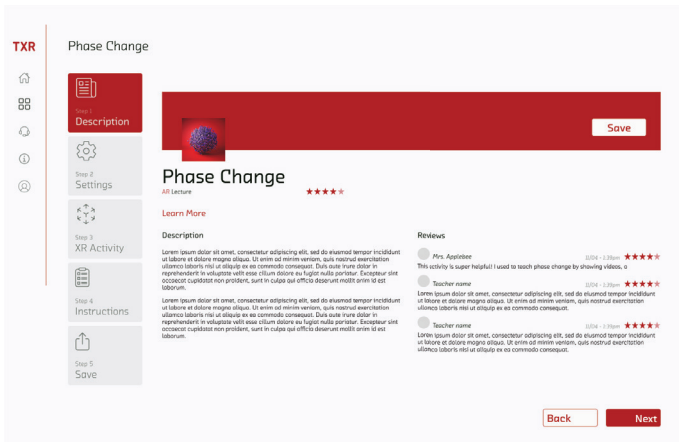
TeachXR Description page—edit mode
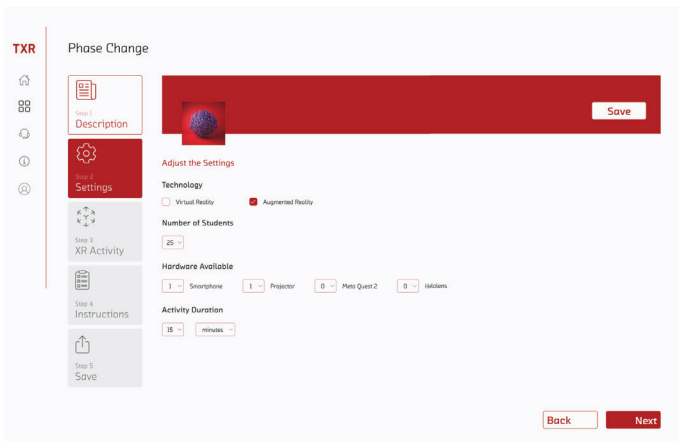
TeachXR Settings page—edit mode

XR Editing
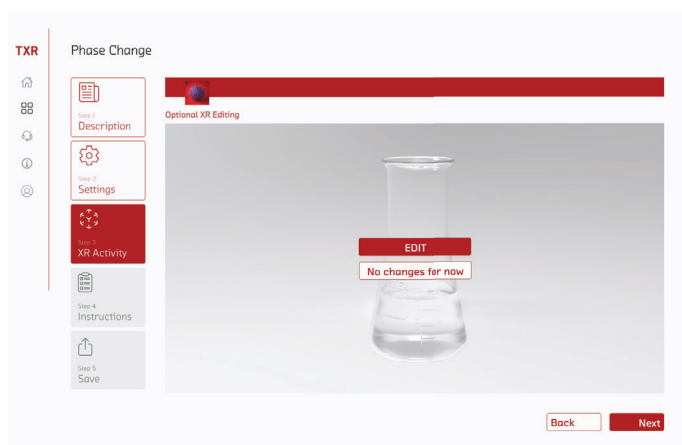
TeachXR Optional XR activity editor—creator mode

In edit mode, when a teacher arrives at the XR activity step, they
will be asked whether or not they would like to edit the XR activity.
Editing is an option and not a requirement because it is not
expected that all teachers will be interested in editing the actual
AR content. If the teacher does not chose to edit the content they
will skip to the Instructions step.

6.2b EDIT MODE

XR Editing
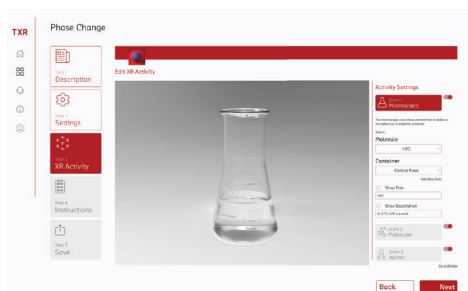
XR activity editor—macroscopic view
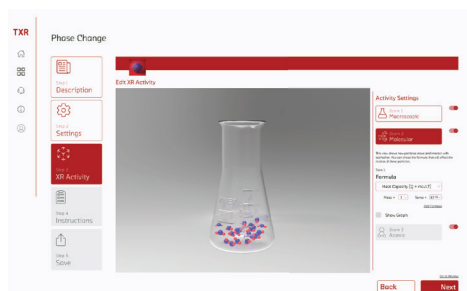
XR activity editor—molecular view
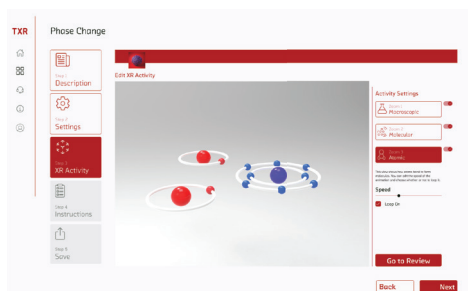
XR activity editor—atomic view
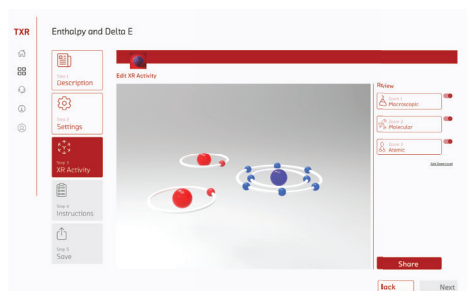
XR activity editor—review

The editting of the XR activity is nearly identical to editting the XR activity in the creator mode. The only difference is that the activity settings are already set to specific values, but that are still adjustable.

XR Editing

The instructions and save pages
are also consistent with the creator
mode, as that information is based
on how to use TeachXR, rather than
how to use the specific XR activity.
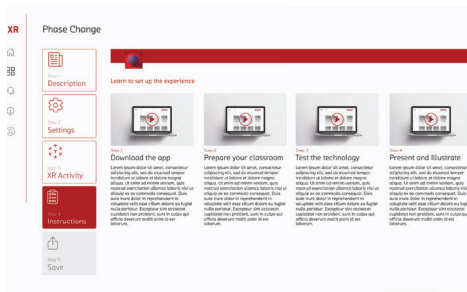
TeachXR Instructions page—edit mode
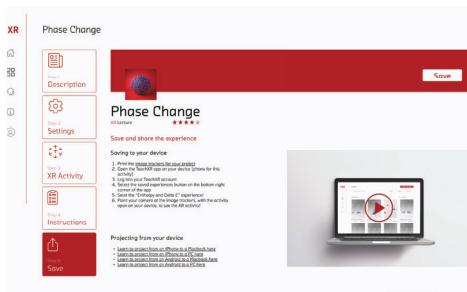
TeachXR Save page—edit mode

6.3 AARON'S AR ACTIVITY

The AR experience was designed as a possible outcome of the TeachXR tool as if it had been designed by Aaron Glimme. This app is designed for Aaron to illustrate phase change at a molecular level. The experience was built on an Android in Unity using the AR Core template and Vuforia Engine onto an Android Samsung S9. Aaron uses the activity for storytelling by mirroring the visualization from a mobile device to a laptop, and then projecting the laptop view onto a classroom projector. Molecules in this app are color coded to be consistent with common practices in science diagrams and illustrations.

Aaron's

TeachXR final mock-up
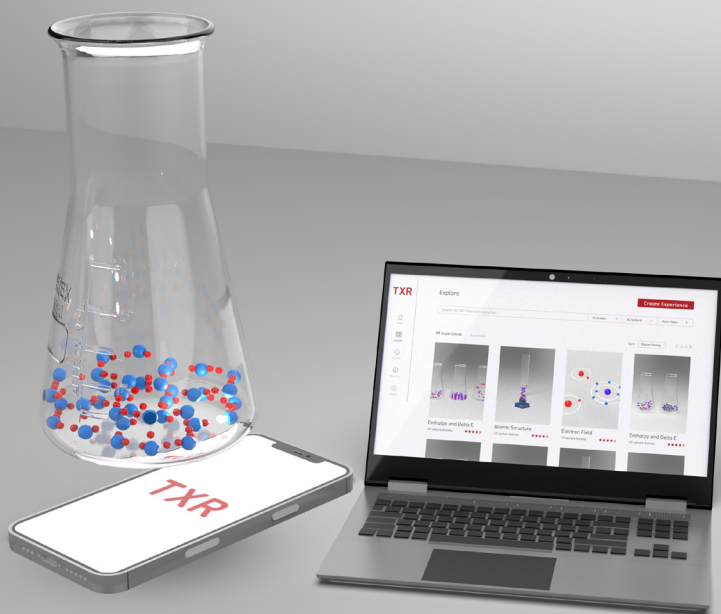
AR.

H2O in a conical flask at 3 temperatures.

He chose to only illustrate the molecular level to match his lecture material. Using edit mode, Aaron chose to show three states of h2o in a conical flask at the macroscopic level of editing. At the molecular level of editing, Aaron chose to use the heat capacity formula to show h2o in a conical flask at the three different temperatures—resulting in a solid, liquid, and gas state. The atomic zoom level is turned off, in accordance with Aaron's preferences.

TXR

Enthalpy and Delta E

Create XR Activity

Step 1
Description

Step 2
Settings

Step 3
XR Activity

Step 4
Instructions

Step 5
Save
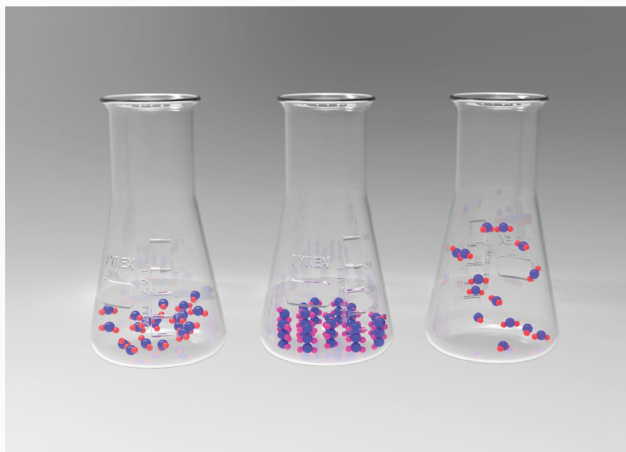
Activity Settings

Zoom 1
Macroscopic

Zoom 2
Molecular

This view shows how particles move and interact with eachother. You can chose the formula that will effect the motion of these particles.

State 1:
Formula

Heat Capacity (Q = mc△T)

Mass = 1   Temp = 40 °F

State 1:
Formula

Heat Capacity (Q = mc△T)

Mass = 1   Temp = 0 °F

State 1:
Formula

Heat Capacity (Q = mc△T)

Mass = 1   Temp = 100 °F

Add Formula

☐ Show Graph   Go to Review

Back   Next

Settings selected by Aaron in XR activity editor

107

6.3 AARON'S AR ACTIVITY

Three image trackers are detected
using an AR image Tracker Manager
component. When activated,
each image tracker displays a
corresponding animation prefab
which displays either the molecule
movement of h2O at a solid, liquid,
or gaseous state. Aaron places the
image trackers below a conical
flask, so that each animation is
displayed directly into the conical
flask, showing molecule movement in
real-time.

Screenshot from Unity editor of three image trackers with conical flasks

Animations of the different states are consistent with how h2O molecules would move in the real world. In the solid state, molecules are organied in a hexagonal shape to create hydrogen bonds and vibrate around eachother. In the liquid state, some molecules are broken from the hydrogen bonds and move faster in a larger distance of space while other remain vibrating. In the gaseous state, all hydrogen bonds are broken, so molecules are able to move faster across the entire conical flask.
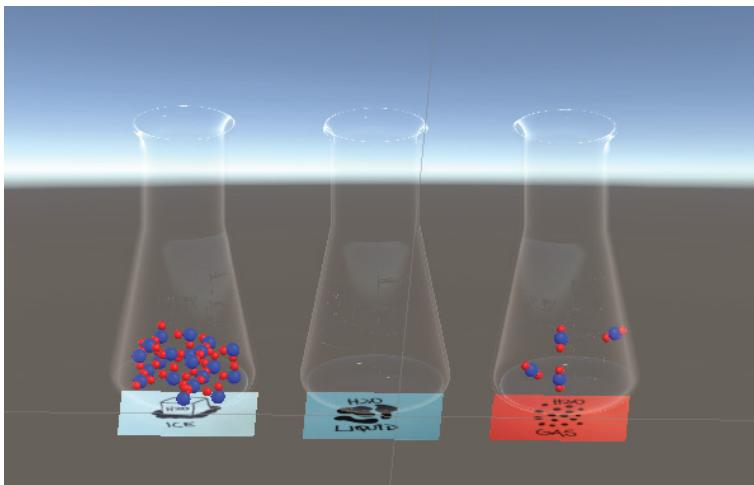
Screenshot from Unity editor of three image trackers with active molecules

Sev

ven

Chapter 7: Final Thoughts

7.1 DISCUSSION

The purpose of this study was to
answer the question, "How might
we enable high school teachers to
use XR to enhance storytelling?"
Throught the exploration of this
question, many key discoveries were
made teachers' abilities, needs, and
expectations around implementing
new technology in their classrooms.

XR for teachers, not students.

XR for Teachers, not Students

While reviewing literature, it became clear that almost all XR educational content was directed towards students (Bower et al., 2014; Schutera et al., 2021; Southgate, 2019). Research supports the assumption that students' learning styles differ from one student to another. Early on in this thesis project we were inspired to customize the learning experience for each students' learning style, however through teacher interviews we discovered that students' learning styles do not differ as much as students' learning paces. In addition, differences in students' learning paces are more strongly correlated with the content being learned rather than differences between individual students. In other words, some concepts take longer for students to learn than others—these difficult concepts being consistent among the majority of students (Vermunt & Vermetten, 2004) Based on this finding, we chose to create a tool that helps teachers explain concepts that are harder for students to learn, rather than helping students learn the concepts independently. In some instances it may be better for students to use educational technology independently, such as when they are reviewing concepts at home or testing knowledge. However, it was discovered that students learn better with a teacher present than they do with technology alone (U.S. DEPARTMENT OF EDUCATION, 2017). It is critical for future educational technology to also empower teachers to use innovating technology to help students learn.

7.1 DISCUSSION

Understanding Teachers' Assumptions

When designing a tool for teachers to use, is important to understand teachers' common practices and their expectations of how they may interact with technology.

Most teaches design lectures today using powerpoint, keynote, or Google Slides presentation programs (Google Slides, n.d.). These presentations contain a combination of text, images, animations, and videos, and often are designed completely by the teacher. Generally, these presentations contain minimal text, that when presented in class, is accompanied by a teachers' oral explanation. Content in these lectures are generally based on textbook information, concepts required by school boards, and/or materials found online. Based on the fact that teachers general use Powerpoint, Keynote, and Google Slides, we can assume that teachers understand the interactions in these programs and expect other educational technologies to be designed similarly.

To find materials online, many teachers use platforms such as Teachers Pay Teachers (Teachers Pay Teachers, n.d.)., Youtube (Youtube, n.d.)., or even Pinterest (Pinterest, n.d.)`. Teachers Pay Teachers has recently grown increasing popularity for enabling teachers to support eachother by sharing, exploring, and using educational content from other teachers. A key feature of this platforms success is its' efficient search and filtering tools, which includes: grade, topic, subtopic, and curricula compliance. From this information, we can determine that teachers are interested in sharing and borrowing content from other teachers, and that efficient search and filtering capabilities are essential for enabling teachers to do so.

When designing a tool for teachers, it is important to keep in mind teachers' common practice and replicate interactions that they might expect. The most notable design features to be replicated include: 1. The side left panel presentation outline on Powerpoint, Keynote, and Google Slides. 2. The right side panel editing tools on Google Slides. 3. The organization of explore content on Pinterest and Youtube. 4. The filtering options on Teachers Pay Teachers.
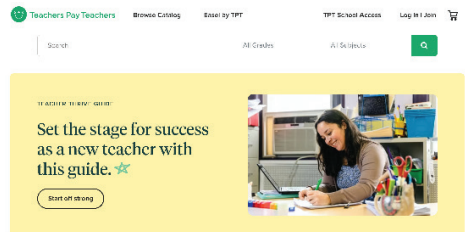
(Teachers Pay Teachers, n.d.)
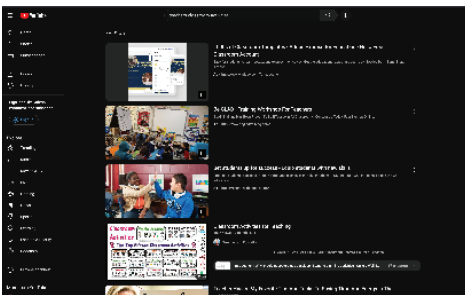
(Youtube, n.d.)

(Pinterest, n.d.)

XR should focus on enabling teachers to show the invisible.

Teacher Needs with Using XR Discoveries

When designing a tool to help teachers use XR technology, it is important to take into account which information teachers are interested in displaying XR. From interviews and observations, it was discovered that teachers are interested in using XR to display information that exists in the physical world, but is not visible to the naked eye. In contrast, teachers are opposed to replicating information that exists in the physical world and is visible to the naked eye. For example, Aaron explained that he would not be interested in replicating a physical lab experiment in AR for students to see upclose on their smartphone because the content displayed in AR would be less accurate than what the students can see in the lab experiment occurring the physical world. However, Aaron was excited about the opportunity to overlap virtual information on top of the lab experiment so that students can see the real experiment occurring with information about invisible objects atop the lab. Based on this information, future XR educational technology should focus on visualizing information that is difficult to see with the naked eye, enabling teachers to explain illustrate invisible content.

([Man looking at AR through lens of a phone screen], n.d.)

7.1 DISCUSSION

Teacher Needs with Using XR Discoveries

It is also critical for designers of XR educational technologies to consider how teachers would be most comfortable using this technology in their classrooms. The teachers which we interviewed were very concerned about their ability to access devices necessary to use XR in their classrooms. For this reason, they prefer to use devices that they already have access to. Most teachers have access to smartphones, computers, and projectors but they do not have access to innovative XR headsets.

Teachers were not comfortable with students using smartphone devices to access XR information while lecturing about novel content. When teachers present information and project it on a screen, students are all listening to the teacher and watching the same screen. As a result, teachers are able to control what students see as they are explaining certain concepts, to ensure that students are absorbing information accurately. However, when content is not novel, teachers were more open to students using personal devies to access XR content. This is because accessing personal content during repeated exposure allows students to absorb information in a new way, compared to via a presentation that is controlled by the teacher. Because this study focused on teacher storytelling, we did not investigate best practices for enabling students to relearn information at a deeper level. Future work that focuses on students use of XR to relearn information at a deeper level should design around individual activities such as laboratory experiments at homework.

Can Teachers Be Creators Too?

From interviewing multiple teachers it became clear that each teacher prefers a different level of customization of lecture content. Some teachers prefer to directly replicate successful presentations found online while others prefer to create presentations from scratch, and many others fall somewhere in the middle. For this reason, it is important for content to be designed in a way that can be accessed at varying levels of customization. User testing confirmed that the best method to implement varying levels of customization is by creating basic ready-to-use templates that can immediately used or meticulously edited.

Teachers can create XR activities, but only if given support.

7.2 FUTURE WORK

This study builts a foundation for future work to continue exploring how to empower teachers to tell their stories using a third dimension. It was designed as a case study, which means that most data collection was solely extracted from one teacher. This allowed us to discover and address many of Aaron's specific needs that might have been missed if we were focusing on gathering information from different sources. However, this raises many questions. What challenges do other teachers face? What technologies would other teachers be most comfortable using? Moreover, are the teaching practices in the US similar to those in other countries or would design need to be altered to meet the needs of a more diverse population? It is essential for future work to test the discoveries of this study with more teachers from diverse backgrounds before discoveries can be extrapolated to a larger sample size.

(Teachers Pay Teachers, n.d.)

(Oxfam Australia, 2017)

Due to the limitation of this project we were only able to design one outcome of the TeachXR tool, an AR app build on an Android and presented via projection. However, some content would be better taught in a fully immersive 3D environment. How might the design of TeachXR be different for VR content or for headset devices? What types of environment would be suitable for VR content? Would students take turns using the headset or would they all use the headset at the same time? If this project should continue, all of these questions and more should be addressed before implementing VR into the TeachXR experience.

The final major point of contention is that this study addresses how TeachXR can aid in teaching chemistry topics. However, XR has been proven to be helpful with learning other subjects such as biology, physics, history, etc. Future work should consider how TeachXR would be implemented into these different academic spaces.

7.3 CONCLUSION

This thesis project starts a conversation about the complexities of explaining complex, invisible science topics and introduces a solution designed with and for high school science teachers. The solution was tested through a case study of Aaron Glimme, a chemistry teacher at Berkeley High School. Two artifacts were built as a result of this study: 1. A desktop tool called TeachXR, which provides guidelines to empower high school teachers to create and share XR activities for their classrooms (interactive desktop Figma prototype). 2. An AR activity designed with and for Aaron, to enhance his storytelling of phase change, as a possible outcome of the TeachXR tool (build on an Android Samsung S9).

Findings from this study demonstrate that high school teachers are interested and capable of implementing XR technology into their classrooms. It is clear that teachers can use this technology to illustrate hard-to-see 3D concepts, while still maintaining control over the classroom. However, to empower teachers to use this intimidating technology, it is essential to replicate successes from current educational content platforms, and create a community for teachers to share and review evolving content.

In sum, we have created and engaging and effective tool to inform and empower high school teachers to use XR technologies as a storytelling tool. TeachXR creates a future where XR technologies are accessible and exciting for teachers. In this future teachers have the power to build, share, and edit 3D content for their personal storytelling purposes—teachers are not only given the tools to teach XR but also to create it themselves! Future work should use TeachXR as an example of how to rewrite the narrative of common educational tools to focus on empowering teachers with technology, rather than replacing teachers with technology. A future with TeachXR means that teachers' storytelling abilities are only limited to the imagination—no experience is too dangerous, expensive, invisible, or even impossible for a teacher to illustrate.

View of Aaron's AR app through mobile device, with TXR prototype in background

TeachXR

7.4 BIBLIOGRAPHY

- Balanskat, A., Bannister, D., Hertz, B., Sigilliò, E., & Vuorikari, R. (2013). Overview and analysis of 1:1 learning initiatives in Europe. Joint Research Centre of the European Commission. https://data.europa.eu/doi/10.2791/20333
- Ball, M. (2022a, July 18). The Metaverse Will Reshape Our Lives. Let's Make Sure It's for the Better. Time. https://time.com/6197849/metaverse-future-matthew-ball/
- Ball, M. (2022b). The Metaverse: And How It Will Revolutionize Everything. Liveright Publishing Corporation. https://wwnorton.com/books/9781324092032
- Barak, M., & Hussein-Farraj, R. (2009, February 12). Computerized Molecular Modeling as Means for Enhancing Students' Understanding of Protein Structure and Function.
- Bates, A. (1984). Broadcasting in Education: An Evaluation: An Evaluation. Constable and Company Ltd.
- Bates, A. (2015). Chapter 6.2 A short history of educational technology. In Teaching in a Digital Age (2nd ed.). Tony Bates Associates Ltd. https://opentextbc.ca/teachinginadigitalage/chapter/section-8-1-a-short-history-of-educational-technology/
- Belcher, N. (2018, February 28). A Brief History of U.S. Science Education—Leading to Modeling Instruction. Medium. https://ntbelcher.medium.com/a-brief-history-of-u-s-science-education-leading-to-modeling-instruction-3a9bdbd801f2
- Belcher, N. (2018, February 28). A Brief History of U.S. Science Education—Leading to Modeling Instruction. Medium. https://ntbelcher.medium.com/a-brief-history-of-u-s-science-education-leading-to-modeling-instruction-3a9bdbd801f2
- Ben-Zvi, R., Eylon, B., & Silberstein, J. (n.d.). Students' visualization of a chemical reaction. Education in Chemistry, 24(4), 73–94.
- Bower, M., Howe, C., McCredie, N., Robinson, A., & Grover, D. (2014). Augmented Reality in education – cases, places and potentials. Educational Media International, 51(1), 1–15. https://doi.org/10.1080/09523987.2014.889400
- Ciências Express. (2019). Realidade aumentada para android. (feira de ciencias) Chemistry Simulator AR [Screenshot]. Youtube. https://www.youtube.com/watch?v=PxX3ZTGS_sg
- Cope, W., & Kalantzis, M. (2007). The International Journal of Learning: Annual Review. 14(1), 75–80.

- Dawson, V. (2008). Use of Information Communication Technology by Early Career Science Teachers in Western Australia. International Journal of Science Education, 30(2), 203–219. https://doi.org/10.1080/09500690601175551

- Ditzler, C., Hong, E., & Strudler, N. (2016). How Tablets Are Utilized in the Classroom. Journal of Research on Technology in Education, 48(3), 181–193. https://doi.org/10.1080/15391523.2016.1172444

- Doymus, K. (2008). Teaching chemical bonding through jigsaw cooperative learning. Research in Science & Technological Education, 26(1), 47–57. https://doi.org/10.1080/02635140701847470

- Eberlein, T., Kampmeier, J., Minderhout, V., Moog, R. S., Platt, T., Varma-Nelson, P., & White, H. B. (2008). Pedagogies of engagement in science. Biochemistry and Molecular Biology Education, 36(4), 262–273. https://doi.org/10.1002/bmb.20204

- EDGAR Full Text Search. (n.d.). SEC.Gov. Retrieved October 17, 2022, from https://www.sec.gov/edgar/search/?r=el#/q=metaverse&dateRange=custom&startdt=2022-01-01&enddt=2022-10-16

- FatCamera. (n.d.). Working Together On A Project. Getty Images. https://www.gettyimages.ca/detail/photo/working-together-on-a-project-royalty-free-image/1136174847?adppopup=true

- Ferrantraite. (2015). Teacher explaining molecules in Highschool Science Lab. iStock. https://www.istockphoto.com/photo/teacher-explaining-molecules-in-highschool-science-lab-gm484202532-71514443

- Furht, B. (Ed.). (2006). Augmented Reality. In Encyclopedia of Multimedia (pp. 29–31). Springer US. https://doi.org/10.1007/0-387-30038-4_10

- Gabel, D. (1999). Improving Teaching and Learning through Chemistry Education Research: A Look to the Future. Journal of Chemical Education, 76(4), 548. https://doi.org/10.1021/ed076p548

- Glimme, Aaron. (2011). Unit 5, Lecture 1- The Ideal Gas Law [Screenshot]. LearnAPChemistry.com. http://www.learnapchemistry.com/videos/unit5/u5l1.html

- Glimme, Aaron. (2011). Unit 6, Lecture 2- Enthalpy and Heat [Screenshot]. LearnAPChemistry.com. http://www.learnapchemistry.com/videos/unit6/u6l2.html

- Google Slides. (n.d.). [Google Slides blank presentation with animation settings open]. [Screenshot]. Retrieved December 12, 2022, https://docs.google.com/presentation/d/1jCS-ATAL4R4c38EHOpThNFrtw1VmcTRx9Ca99TthYoo/edit#slide=id.p

7.4 BIBLIOGRAPHY

- Google Sheets. (n.d.). [Google Sheets blank sheet with chart editor open]. [Screenshot]. Retrieved December 12, 2022, https://docs.google.com/spreadsheets/d/1nin05bNTVfUw5bbTCflZPDANYnBl1ipT2fvb2zyoVLY/edit#gid=0
- Ground Picture. (n.d.). Shot of a professor and two science students wearing VR goggles. Shutterstock. https://www.shutterstock.com/image-photo/shot-professor-two-science-students-wearing-519325897
- Griffiths, A. K., & Preston, K. R. (1992). Grade-12 students' misconceptions relating to fundamental characteristics of atoms and molecules. Journal of Research in Science Teaching, 29(6), 611–628. https://doi.org/10.1002/tea.3660290609
- Grunwalk Associates LLC, Vockley, & Lang. (2011). Teachers Increasingly Rely on Media and Technology (Deepening Connections) [Survey]. PBS Education. https://grunwald.com/pdfs/PBS-GRUNWALD_2011_ANNUAL_ED_TECH_STUDY.pdf
- Johnston, A. P. R., Rae, J., Ariotti, N., Bailey, B., Lilja, A., Webb, R., Ferguson, C., Maher, S., Davis, T. P., Webb, R. I., McGhee, J., & Parton, R. G. (2018). Journey to the centre of the cell: Virtual reality immersion into scientific data. Traffic (Copenhagen, Denmark), 19(2), 105–110. https://doi.org/10.1111/tra.12538
- Johnstone, A. H. (1993). The development of chemistry teaching: A changing response to changing demand. Journal of Chemical Education, 70(9), 701. https://doi.org/10.1021/ed070p701
- Kalantzis, M., & Cope, B. (2015). Learning and New Media. The SAGE Handbook of Learning, 373–387.
- Lamb, R., Antonenko, P., Etopio, E., & Seccia, A. (2018). Comparison of virtual reality and hands on activities in science education via functional near infrared spectroscopy. Computers & Education, 124, 14–26. https://doi.org/10.1016/j.compedu.2018.05.014
- Larmand, A. (2022). Using Virtual Reality Systems in Education [Photograph]. Enduporium. https://www.eduporium.com/blog/eduporium-weekly-ar-anad-vr-in-education/
- Liou, W.-K., & Chang, C.-Y. (2018). Virtual reality classroom applied to science education. 2018 23rd International Scientific-Professional Conference on Information Technology (IT), 1–4. https://doi.org/10.1109/SPIT.2018.8350861

- Maresky, H. S., Oikonomou, A., Ali, I., Ditkofsky, N., Pakkal, M., & Ballyk, B. (2019). Virtual reality and cardiac anatomy: Exploring immersive three-dimensional cardiac imaging, a pilot study in undergraduate medical anatomy education. Clinical Anatomy, 32(2), 238–243. https://doi.org/10.1002/ca.23292
- Mazuzan, G. (1994). The National Science Foundation: A Brief History. National Science Foundation. https://search.library.wisc.edu/catalog/9910188433302121/cite
- Mdthub. (2018). Use of an overhead projector for music education [Screenshot]. Youtube. https://www.youtube.com/watch?v=_edmWzv3lcA
- Murray, K. (n.d.). Boy explores virtual reality solar system. Getty Images. https://www.gettyimages.in/detail/photo/boy-explores-virtual-reality-solar-system-royalty-free-image/604582331?adppopup=true
- Nouvelage, Elijah. (n.d.). Visitors use augmented reality apps to discover features of the new Apple Park at the Apple Visitor Center in Cupertino, California. NBC News. Retrieved on December 12, 2022 from https://www.nbcnews.com/mach/science/4-surprising-ways-augmented-reality-will-revolutionize-your-life-ncna830911
- Oakwood Friends School. (2018, April 26). Science class circa 1950-60s. This [Image attached] [Status update]. Facebook. https://www.facebook.com/oakwoodfriends/posts/science-class-circa-1950-60s-tbt-oakwoodfriends-quakered-handsonscience/10156168817253796/
- Oke, O. K., & Alam, G. M. (2010). Comparative evaluation of the effectiveness of 2 and 3D visualizations in students' understanding of structures of organic molecules. Int. J. Phys. Sci., 7.
- Oxfam Australia. (2017). Oxfam VR Film: Evelyn's Story. [Screenshot]. Youtube. https://www.youtube.com/watch?v=jZUnUCWqwFw
- [Photograph of double diamond design process]. (n.d.). Retrieved on November 6, 2022 from https://germinateapps.com/greenhouse/sprout/do-you-double-diamond
- [Photograph of looking through a phone screen to see man visualizing planets in AR]. (n.d.). Retrieved on December 12, 2022 from https://xrcreatives.in/online-augmented-reality-workshop-for-using-ar-for-teaching-purposes/
- [Photograph of students conducting lab experiment in science class]. (n.d.). Retrieved November 5, 2022, from https://primeschool.pt/highschooldiploma.
- [Photograph of students looking at molecular diagram in augmented reality]. (n.d.). Retrieved on November 6, 2022 from https://zspace.com/blog/10-reasons-to-use-ar-and-vr-in-k-12-classrooms

7.4 BIBLIOGRAPHY

- [Photograph of students wearing VR headings in class]. (n.d.). Retrieved on November 6, 2022, from https://www.bayareaparent.com/articles/summer-camp/high-tech-camps/article_0a2705b2-48db-557d-8a70-1ffa92d2fb71.html
- [Photograph of teacher showing students AR chemistry content]. (n.d.). Retrieved on November 6, 2022 from https://www.microsoft.com/en-us/education/school-leaders/showcase-schools
- [Photograph of woman pointing to illustration of ancient civilization, viewed through virtual reality]. (n.d.). Virtual Reality for Education. Retrieved on December 12, 2022 from http://virtualrealityforeducation.com/microsoft-hololens-holotours-making-history-come-alive/#prettyPhoto
- [Photograph of woman in VR headset standing next to a man, in an office]. (2020). https://www.theceshop.com/agent-essentials/blog/5-reasons-why-real-estate-agents-should-use-vr
- [Photograph of woman looking at computer frustrauted]. (n.d.). Retrieved November 4, 2022, from https://usechalkboard.com/avoid-stress-setting-up-business-entrepreneurs
- Pinterest. (n.d.). [Pinterest homepage, displaying explore functionality]. [Screenshot]. Retrieved on December 12, 2022 from https://www.pinterest.com/search/pins/?q=teachers%20classroom%20activities&rs=typed
- RSplaneta. (n.d.) Boy with virtual reality glasses holds the Sun in his room. Concept of using modern technologies for learning. Shutterstock. Retrieved on December 12, 2022 from https://www.shutterstock.com/image-photo/boy-virtual-reality-glasses-holds-sun-1550055194
- Rupp, M. A., Odette, K. L., Kozachuk, J., Michaelis, J. R., Smither, J. A., & McConnell, D. S. (2019). Investigating learning outcomes and subjective experiences in 360-degree videos. Computers & Education, 128(1), 256–268.
- Ruthven, K., Hennessy, S., & Deaney, R. (2005). Incorporating Internet resources into classroom practice: Pedagogical perspectives and strategies of secondary-school subject teachers. Computers & Education, 44(2005), 1–34. https://doi.org/10.1016/j.compedu.2003.11.001
- Samsung. (n.d.). [Teacher using Samsung SMART Board to instruct students]. Retrieved November 5, 2022 from https://www.samsung.com/us/business/displays/interactive/explore/

- Schutera, S., Schnierle, M., Wu, M., Pertzel, T., Seybold, J., Bauer, P., Teutscher, D., Raedle, M., Heß-Mohr, N., Röck, S., & Krause, M. J. (2021). On the Potential of Augmented Reality for Mathematics Teaching with the Application cleARmaths. Education Sciences, 11(8), 368. https://doi.org/10.3390/educsci11080368

- Smisthsonian. (n.d.). A visitor uses an augmented reality app in the Hall of Bones at the Smithsonian. NBC News. Retrieved on December 12, 2022 from https://www.nbcnews.com/mach/science/4-surprising-ways-augmented-reality-will-revolutionize-your-life-ncna830911

- Southgate, E. (2019). Virtual Reality for Deeper Learning: An Exemplar from High School Science. 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), 1633–1639. https://doi.org/10.1109/VR.2019.8797841

- SpaceTime Enterprises. (n.d.). SpaceTime Enterprises hopes to offer virtual reality astronaut experiences by beaming back live images of the Earth from space. Retrieved on November 6, 2022 from https://www.theguardian.com/science/across-the-universe/2018/may/17/space-tourism-for-the-people-become-a-virtual-reality-astronaut

- Teachers Pay Teachers. (n.d.) [Teachers Pay Teachers homepage, displaying search functionality]. [Screenshot]. Retrieved on December 12, 2022 from https://www.teacherspayteachers.com/

- Trahan, M. H., Smith, K. S., & Talbot, T. B. (2019). Past, Present, and Future: Editorial on Virtual Reality Applications to Human Services. Journal of Technology in Human Services, 37(1), 1–12. https://doi.org/10.1080/15228835.2019.1587334

- UCI Open. (2012). Organic Chemistry 51C. Lecture 09. Reactions of Carboxylic Acids, Esters, Amides, & Nitriles [Screenshot]. Youtube. https://www.youtube.com/watch?v=T7qI2hBmRTE

- U.S. DEPARTMENT OF EDUCATION. (2017). Reimagining the Role of Technology in Education: 2017 National Education Technology Update. https://tech.ed.gov/files/2017/01/NETP17.pdf

- UNC Photo Lab Collection, North Carolina Collection Photo Archives, Wilson Library. (1957). [Photograph of lecture in Venable Hall at University of North Carolina, featuring a huge periodic table]. UNC A to Z. https://uncatoz.com/entry/venable-and-murray-halls/

- Youtube. (n.d.). [Youtube search for "teachers classroom activities"]. [Screenshot]. Retrieved on Decemer 12, 2022 from https://www.youtube.com/results?search_query=teachers+classroom+activities

7.4 BIBLIOGRAPHY

- Wickes, L., W. (1909). Immigrants in night school. [Photograph]. National Child Labor Committee collection. https://hdl.loc.gov/loc.pnp/nclc.04549
- Vermunt, J. D., & Vermetten, Y. J. (2004). Patterns in Student Learning: Relationships Between Learning Strategies, Conceptions of Learning, and Learning Orientations. Educational Psychology Review, 16(4), 359–384. https://doi.org/10.1007/s10648-004-0005-y
- Walan, S. (2020). Embracing Digital Technology in Science Classrooms—Secondary School Teachers' Enacted Teaching and Reflections on Practice. Journal of Science Education and Technology, 29(3), 431–441. https://doi.org/10.1007/s10956-020-09828-6
- Wells, M., Hestenes, D., & Swackhamer, G. (1998). A modeling method for high school physics instruction. American Journal of Physics, 63(7), 606. https://doi.org/10.1119/1.17849
- Wu, H.-K., Krajcik, J. S., & Soloway, E. (2001). Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. Journal of Research in Science Teaching, 38(7), 821–842. https://doi.org/10.1002/tea.1033
- Vintage Images. (n.d.). 1930s 1940s Man Teacher Professor is a photograph. Fine Art America. September 28, 2017.
- Zapbox. (n.d.). [Photograph of young boy looking at planetary information through low-cost AR glasses]. Retrieved on December 12, 2022 from https://steemhunt.com/@salmanbukhari54/zapbox-mixed-reality-for-everyone?ref=bluegums