Paper Trail: An Immersive Authoring System for Augmented Reality Instructional Experiences

Shwetha Rajaram
University of Michigan
United States
shwethar@umich.edu

Michael Nebeling
University of Michigan
United States
nebeling@umich.edu

ABSTRACT

Prior work has demonstrated augmented reality's benefits to education, but current tools are difficult to integrate with traditional instructional methods. We present Paper Trail, an immersive authoring system designed to explore how to enable instructors to create AR educational experiences, leaving paper at the core of the interaction and enhancing it with various forms of digital media, animations for dynamic illustrations, and clipping masks to guide learning. To inform the system design, we developed five scenarios exploring the benefits that hand-held and head-worn AR can bring to STEM instruction and developed a design space of AR interactions enhancing paper based on these scenarios and prior work. Using the example of an AR physics handout, we assessed the system's potential with PhD-level instructors and its usability with XR design experts. In an elicitation study with high-school teachers, we study how Paper Trail could be used and extended to enable flexible use cases across various domains. We discuss benefits of immersive paper for supporting diverse student needs and challenges for making effective use of AR for learning.

CCS CONCEPTS

• **Human-centered computing** → **Interface design prototyping**; **Mixed / augmented reality**.

KEYWORDS

immersive paper, augmented reality, educational technology, STEM.

ACM Reference Format:
Shwetha Rajaram and Michael Nebeling. 2022. Paper Trail: An Immersive Authoring System for Augmented Reality Instructional Experiences. In *CHI Conference on Human Factors in Computing Systems (CHI '22), April 29-May 5, 2022, New Orleans, LA, USA.* ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3491102.3517486

1 INTRODUCTION

Previous studies have primarily explored the use of augmented reality (AR) in education by building domain-specific systems tailored to specific educational activities, such as visualizing physical properties in science labs [3, 51], teaching hands-on skills [26, 63], and learning languages [12]. Such examples can be valuable both for learning about the potential of AR in particular educational domains and addressing challenges that are unique to each use case. However, the needs of instructors across domains and effective tools that empower instructors to create AR experiences without a technical background or prior training in AR are less well understood [63]. Prior work has contributed new authoring tools to accelerate prototyping and ease development of AR applications; yet, most are targeted at users with a technical or design background [36, 44, 45]. Designing new AR applications remains a difficult and time-consuming task for novice creators [2, 13]. In particular, XR tools have a tendency to impose new workflows [47], which can pose major challenges for instructors to incorporate them with existing instructional methods and materials.

In this work, we present the design and evaluation of Paper Trail, an AR immersive authoring tool we created to study how instructors envision using AR in different educational contexts. As paper remains the preferred medium for many educational activities due to its versatility and availability [54], our system allows instructors to create new AR learning experiences around paper. A large body of research has explored *interactive paper*, aiming to merge the physical and digital worlds while preserving the tangible properties and convenience of paper as a medium [18]. The demonstrated benefits of interactive paper include ease of annotation [5, 34, 64], navigation [17, 54], improved task management [4], and effective spatial organization of information [33]. Some implementations utilize digital pens to capture handwritten content [5, 16, 34, 64] or enable interactivity via paper-based electronics [25, 48, 52]; however, specialized writing supplies and embedded hardware can impose significant limitations in terms of affordability and adoption [18]. A related stream of research explores the use of AR to create what we refer to as *immersive paper* systems [15, 17, 21, 33, 56, 65], which not only utilize paper to locate and spatialize AR experiences, but also as a user interface for manipulating AR content. Adding to both streams of research, we investigate the needs of instructors and how to enable them to create interactive AR content that enhances their existing paper-based teaching resources, exploring potential benefits to instruction and learning.

This paper makes two primary contributions. First, we present the design of Paper Trail, an AR authoring system for instructors to create immersive paper learning materials. Using a scenario-based approach [7], we started by implementing five example use cases for both hand-held and head-worn AR in educational activities across STEM subjects. Analyzing these scenarios and prior work on interactive paper systems and AR prototyping tools, we classified the design space of immersive paper interactions for instructional use into four key tasks along a spectrum from purely

CHI '22, April 29-May 5, 2022, New Orleans, LA, USA

ACM ISBN 978-1-4503-9157-3/22/04…$15.00
https://doi.org/10.1145/3491102.3517486

physical to purely digital interactions: *(1)* enabling tangible interactions with paper, *(2)* capturing & embedding digital content in paper, *(3)* transforming paper-based digital content, and *(4)* converting to purely digital formats. Focusing on tasks in the middle of this spectrum where we saw the greatest need for integrated tool support, we designed Paper Trail to enable instructors to create new AR content from notes and sketches on paper, associate digital media with paper, animate AR content to illustrate dynamic concepts, and use clipping masks to control AR content visibility and guide learning. We refined the system design in two iterations through conducting evaluations with PhD-level student instructors and XR design experts to assess the usability and flexibility of the system in supporting a range of educational scenarios.

As a second contribution, we offer insights from an elicitation study with seven high school instructors with an average teaching experience of 18 years, where we utilized Paper Trail to explore how immersive paper can enhance their current instructional workflows involving both physical and digital tools. In the study, the instructors first used Paper Trail to review an interactive AR instructional handout as a priming exercise for an elicitation task [42], then to brainstorm and prototype new interaction proposals for enhancing their own paper-based teaching materials with AR content. Overall, the instructors found immersive paper to be promising for enhancing students' comprehension and engagement with subject material and providing support for students' diverse learning needs. They gravitated towards hand-held AR as a modality for authoring immersive paper resources, but saw potential in using head-worn AR to preserve natural interactions with paper and facilitate collaboration between students. We discuss challenges and considerations for the future adoption of immersive educational systems like Paper Trail, in particular, the need for new guidelines to effectively design immersive educational materials and instructors' perceptions of immersive paper in relation to their current physical and digital instructional toolchains.

2 RELATED WORK

The benefits of using AR in education established in prior work include improved comprehension of topics involving spatial relationships, memory retention, collaboration, and student engagement [8, 23, 40, 49–51]. The focus of this work is not to demonstrate the learning benefits of AR. Rather, we see our primary contributions in Paper Trail as a new AR authoring tool for instructors and an extension of existing interactive paper systems.

2.1 AR Authoring Tools

Despite a rich literature on XR tools, creating AR experiences remains a difficult task. Ashtari *et al.* [2] identified eight common barriers to entry for novice XR creators, ranging from a lack of non-technical tools for designers to limited guidelines and metrics that constitute good XR experiences. Recent HCI research has focused on creating new XR authoring tools with the common goal of lowering the technical barriers. Nebeling & Speicher's 2018 review groups existing XR tools into five classes [47]. Tools in the highest classes include Unity and Unreal, which are often out of reach for novice XR creators. Tools in the lower classes require less training and provide layers of abstraction and automation support for common programming tasks. Previous techniques to make tools more accessible to a broader spectrum of designers include physical prototyping [44, 45, 59], immersive authoring [30, 68], video-based editing [31, 32], live sharing [26, 46], and asynchronous/asymmetric collaboration [27, 43].

All these techniques were inspirational to Paper Trail. However, we notice two shortcomings in the current AR tools landscape. First, tools are primarily digital, making it hard to bridge the gap from physical to digital content. Some of the exceptions include DART [36], which utilizes pre-scripted behaviors on top of Macromedia Director to take storyboards into AR; ProtoAR [45], which captures paper sketches and Play-Doh models and brings them into AR; ARcadia [24], which offers a tangible AR programming environment using tokens with fiducial markers; 360proto [44], which creates immersive 360 previews from paper sketches in equirectangular format; and Living Paper [10], which supports the authoring of AR stories integrated with a physical storybook. We generalize from these prior works, adapting some of the paper-based AR authoring techniques to develop use cases for AR across educational domains.

Second, while many tools are suitable for non-programmers, most assume a technical or design background that instructors may not have. Notable exceptions include Loki [26], an immersive telepresence system which supports customized learning environments with options for embodiment and a variety of 2D and 3D viewing modes; Meta-AR-App [63], which allows for collaborative authoring employing a pull-based development model for AR educational experiences; and XRStudio [46], which enables mixed reality capture of instructors and live streaming of immersive VR lectures without requiring students to have access to VR devices. Drawing inspiration from these authoring tools designed for instructors, we create a system that capitalizes on paper as a familiar medium, then use our system as a basis for studying how instructors can extend their existing teaching materials using AR.

2.2 Interactive Paper

Our work was inspired by a long trajectory of research on making paper more interactive, which can be grouped into three techniques: *(1)* using digital pen and paper technology, *(2)* integrating additional physical layers via paper-based electronics, and *(3)* augmenting paper with AR layers. We review prominent examples, extracting commonalities in interaction techniques and educational use cases which informed the design of Paper Trail.

Digital Pen Technology. Prior work utilizes digital pens (e.g., Anoto or Neo Smartpen) in combination with patterned paper to merge physical and digital forms of documents and track user interactions with paper [5, 16, 34, 64]. A common interaction technique is using the pen to select designated areas of the paper to convert the physical pages to digital documents [5, 16, 34, 64] or enable digital search functionalities [5]. A few systems also define pen-based command systems to manipulate digital documents [5, 34]. Overall, these works focus on digitizing hand-written content to allow for further manipulation in a desktop interface. In contrast, we aimed to ground digital content creation on paper and integrate digital layers via AR techniques. This approach preserves the tangible properties of paper which have been proven beneficial for education, prototyping, and design [44, 45, 54].

Adding Physical Layers via Paper-based Electronics. We also observe a trend to make paper interactive through paper-based electronics, i.e., integrating additional physical layers with paper [25, 48, 52]. Qi et al. [48] developed a method of creating circuits on any paper surface through conductive sketching, enabling novices to author interactive paper experiences through templates that could be annotated with analog writing tools. Klamka et al's IllumiPaper [25] combines digital pens with conductive paper to display dynamic visual feedback. They explored use cases in education, such as creating interactive exams that provide students with on-demand answer checking. We were inspired by the educational use cases these papers presented, but aimed to enable end users to add interaction to paper without the need for specialized writing supplies or programming skills. We accomplish this by building on the advanced environment and hand tracking capabilities of the latest AR devices, i.e., the iPad Pro and HoloLens 2.

AR & Paper. AR has previously been explored as a method of integrating digital content with physical paper. Early projects, like the DigitalDesk Calculator [65] and PaperWindows [21], used spatial AR enabled by projectors and cameras mounted in the environment to visualize digital content and detect user interactions with paper. PenLight [55] and MouseLight [56] explore applications in the architecture domain; the use of digital pens in combination with small field-of-view, movable projectors enables the capture of writing as well as precise measurements. While these projective AR workspaces are conceptually powerful, we aimed to simplify the technical setup with the latest generation of AR devices, while at the same time investigating the new affordances.

Marker-based AR, which applies computer vision techniques to align AR content to fiducial markers, requires more lightweight hardware than spatial AR, making it more suitable and flexible for ad-hoc use cases in education [22]. HoloDoc [33] uses a head-mounted display and digital pen to create an immersive document analysis workspace for academic reading. Affinity Lens [60] targets the domain of interaction design, enabling data-driven affinity diagramming through augmenting post-it notes with data visualizations. Mackay et al. [38] utilized small mobile devices in combination with paper to create an interactive biology lab notebook for analyzing hand-written and digital experimental data within a single interface. While some of these systems focus on specific learning activities, we took inspiration from their interactions — embedding a variety of media and using existing physical content to create AR experiences — and aimed to develop an immersive authoring tool that extends to a wide range of educational contexts.

3 SYSTEM DESIGN CONSIDERATIONS

To inform the design of our system, we first designed and implemented five target use cases for how AR could enhance paper-based educational activities across different domains. Through implementing these examples on the iPad Pro and HoloLens 2, we were able to experience the benefits and limitations that hand-held and head-worn AR may offer for each learning scenario, creating the foundation of our PAPER TRAIL system (Sec. 4). To identify areas of focus for PAPER TRAIL compared to prior work, we analyzed existing interactive paper and AR prototyping systems and established a design space along the spectrum from purely physical to purely digital techniques. While prior work often studied particular immersive paper techniques or educational activities in depth, we aimed to study how a combination of techniques could enable instructors to enhance a variety of educational activities using AR.

3.1 Target Use Cases

When studying the design of new AR tools, a key issue is that user adoption and familiarity with AR are still low, which poses challenges for common user-centered design approaches (e.g., contextual inquiry with end-users). Before involving instructors, we adopted a scenario-based approach [7] by designing five use cases that explore how AR in combination with paper could support activities central to different STEM domains. Aiming for coverage of a variety of subjects, we selected domains where the research team had experience studying or teaching subjects and saw potential benefits of using AR in certain scenarios. While approaching each scenario in a device agnostic manner, we weighed the benefits and limitations of using hand-held vs. head-worn AR when implementing the scenarios for iPad Pro and HoloLens 2, considering each device's display and tracking capabilities (e.g., FOV, LiDAR). We then analyzed the implemented scenarios to extract system requirements and inform the design of initial interaction techniques to develop further in our PAPER TRAIL system. Please refer to our video for demonstrations of these target use cases.

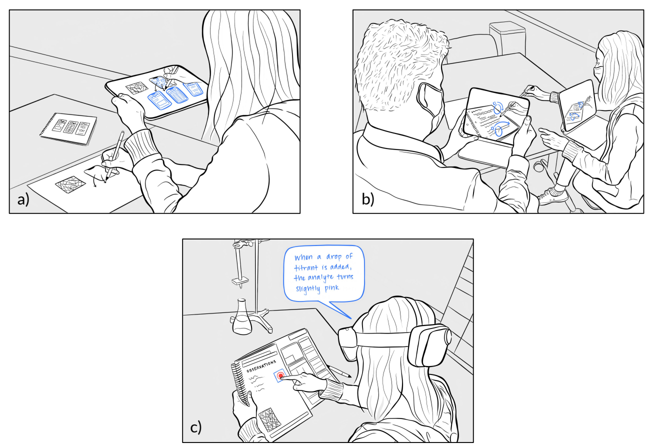

Figure 1: Example use cases of immersive paper. *(a) Interaction Design:* students can create and annotate layered wireframes with both physical and virtual content; *(b) Teaching Orbital Velocity:* an instructor creates an animation by demonstrating how the satellites move around planets on the iPad; *(c) Chemistry Lab Notebook:* while conducting a titration experiment, a student refers to digital representations of the lab procedure and records observations using audio bookmarks, which allow for hands-free interaction.

Interaction Design. Our first scenario explores how paper sketches could be used as a basis to create **layered physical and digital diagrams**, in the context of a wireframing activity for an interaction design course (Fig. 1a). When designing a mobile app, a student captures physical sketches of interface elements as AR objects, then experiments with different layouts by repositioning the

AR content; this is more efficient than sketching alternate designs by hand. Adding to the physical layer of the wireframe, they can use a pen to annotate the screens, drawing arrows to indicate app transitions when certain buttons are clicked.

Teaching Orbital Velocity. Our second scenario explores how an instructor can create **animated content** using just pen and paper in a one-on-one tutoring session (Fig. 1b). To demonstrate the intuition behind satellite motion, the instructor draws a planet and satellite, captures the drawings as AR copies, then creates dynamic visualizations to illustrate the satellite leaving the planet's orbit when it achieves escape velocity. This example is collaborative, so both students and instructors can view the AR objects from their own devices and manipulate digital content.

Chemistry Lab Notebook. Our third scenario explores augmenting paper with a **variety of digital media** for hands-on and field-based learning activities, which often rely on solely physical paper for recording instructions and data. We were inspired by Mackay et al.'s augmented lab notebook [38] and explored a head-worn AR implementation to allow for hands-free AR interaction (Fig. 1c). To compile instructions for a titration lab, students augment the hand-written procedure in their notebooks with digital **photos** and **videos**. While performing the experiment, they use the HoloLens 2 to replay the procedure video and embed digital **audio clips** in their notebooks to record observations.

Figure 2: Example use cases of immersive paper (cont). *(d) Biology Poster:* an instructor augments an existing classroom poster of a cell cross-section to zoom into organelles and illustrate their functions; *(e) MOOC Notebook:* a student utilizes an immersive notebook to take notes for an online course, using video bookmarks to link specific notes to timestamps in the lecture video.

Biology Poster. Our fourth scenario explores how **clipping masks** can be used to integrate background information with existing printed content. An instructor makes use of a physical poster in their classroom which illustrates the cross-section of a cell (Fig. 2d). In order to explain the function of specific organelles, they insert some hand-drawn sketches, photos, and animations. Then, they use digital clipping masks to hide the AR content, so that students can access this information on an as-needed basis. When students inspect the poster using a tablet, they can expand the clipping masks to zoom into organelles and view more details about their functions.

MOOC Notebook. Our fifth scenario explores supporting natural note-taking when interacting with online lecture content for massive open online courses (MOOCs) (Fig. 2e). Using an AR headset, students can view course videos, take notes on paper, and save timestamps of critical moments in the lecture by adding **virtual bookmarks**. The notebook is organized chronologically such that flipping to the next page will load the next video in the course; similar interactions have also been explored by prior work [17].

3.2 Design Space

As a next step, we synthesized prior work on interactive paper and AR prototyping tools into a design space of immersive paper interactions for instructional activities. Focusing on systems that enhance use cases across information work and education using AR, we first categorized existing systems according to common tasks they enable, then mapped these tasks on a spectrum based on whether interactions are mostly grounded in the physical or digital space, in line with previous XR classification frameworks from Milgram & Kishino [41] and Roo & Hachet [53]. Fig. 3 shows the design space from purely physical to purely digital techniques grouped into four dimensions: *(D1)* enabling tangible interactions with paper; *(D2)* capturing & embedding digital content with paper; *(D3)* transforming paper-based digital content; and *(D4)* converting from physical to purely digital formats. In this section, we present the design space and our motivation for either adapting or omitting specific interactions in Paper Trail, considering the feasibility of implementing the interactions in classroom settings and whether they would increase instructors' expressiveness in creating immersive paper teaching resources.

D1: Enabling tangible interactions with paper. The first class of interactions leverage paper as a tangible user interface for manipulating digital or physical components integrated with paper. Systems like the DigitalDesk Calculator [65] and PaperWindows [21] enable **paper-based gesture sets** for navigating projective AR experiences, relying on motion capture systems to track user interactions, e.g., folding or pointing at specific locations on a page. Other approaches include fabricating paper **embedded with interactable components**; IllumiPaper [25] and PaperPulse [52] utilize embedded electronics to enable visual and auditory feedback, while MoveableMaker [1] facilitates the creation of "interactive papercraft" which can be animated through Wizard-of-Oz techniques.

Given that tangible interactions with paper and other physical materials have been the focus of prior work [28, 39], with Paper Trail, we wanted to focus on techniques that enable the transition from physical to AR content, which are often underexplored in educational contexts [46, 63]. However, we aimed to leave paper at the core of interactions to preserve tangible paper-based interactions which are essential in educational contexts (e.g., writing, sketching, making notes in the margins) and enable instructors to create feedback mechanisms and animations similar to digital tools from prior work, but via immersive authoring using AR on top of paper. Since complex hardware setups which are required for tracking paper-based gestures and fabricating custom tangible interfaces may be impractical for instructors to implement in classroom settings, we focused on interaction techniques that require only minimal instrumentation of the environment.

D2: Capturing & embedding digital content in paper. To simplify information professionals' workflows, prior work has contributed interaction techniques for capturing various forms of digital media as AR elements and embedding them in paper. Common techniques for authoring digital content include **capturing handwritten content**, which previous systems like PenLight [55] and

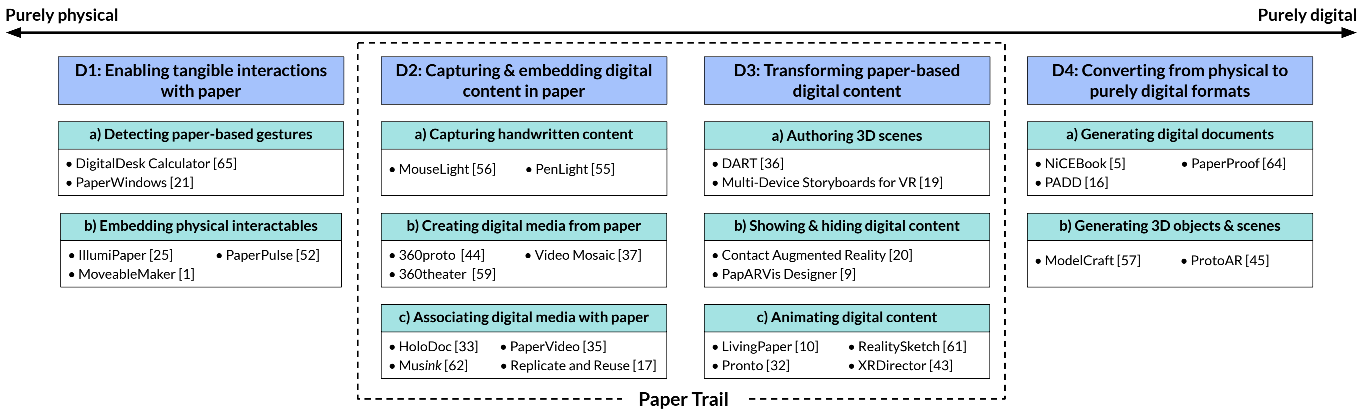

Figure 3: Design space of immersive paper interactions for instructional use cases: Analyzing our target use cases and prior work, we categorized interactive paper and AR authoring systems in terms of common tasks they allow users to accomplish: enabling tangible interactions with paper (D1), capturing physical content and associating it with paper (D2), transforming paper-based digital content including toggling visibility and animations (D3), and converting paper-based content into purely digital formats (D4). Tasks on the left of the spectrum primarily involve interactions with physical content, while tasks on the right side involve primarily digital interactions. With Paper Trail, we present an implementation of immersive paper interactions for educational use cases that covers tasks situated in the middle of the design space for which we saw a common need based on the scenarios we developed previously.

MouseLight [56] primarily accomplished via digital pens, and **creating digital media from paper** (e.g., Video Mosaic [37] generates videos from paper storyboards, 360proto [44] and 360theater [59] generate 3D interactive scenes from paper sketches and dioramas). Prior work has also proposed **associating existing digital media with paper** including photos [17], videos [35], audio clips [62], and web interfaces [33].

We adapted these capture techniques for Paper Trail to enable use cases where creating ad-hoc, digital content may be required (e.g., recording live audio notes in our *Chemistry Lab Notebook* scenario) and to lower the barrier for instructors to create AR content, which remains a challenge with existing prototyping tools [2].

D3: Transforming paper-based digital content. The next class of interactions involve transforming AR content which is embedded in paper or anchored to physical objects. We draw on interaction techniques from prior AR prototyping systems for **authoring 3D scenes** with operations to move, rotate, and scale content [19, 36], **showing or hiding digital content** through scanning a fiducial marker [9, 20], and **animating AR content** via multi-touch gestures or device motion [10, 32, 43, 61]. In adapting these interactions to educational contexts, we saw value in animations to demonstrate motion or sequential processes which are difficult to convey through static content printed on paper (e.g., depicting satellite motion in our *Teaching Orbital Velocity* scenario) and visibility toggling to provide just-in-time information (e.g., further exploring cellular processes in our *Biology Poster* example).

D4: Converting physical content to a purely digital format. Finally, we identified prior systems which translate physical content to a purely virtual format for continued use in another digital tool. Digital pen systems such as NiCEBook [5] and PaperProof [64] enable **conversion to digital text documents**. Prior 3D prototyping tools **generate virtual objects and scenes** from paper representations, e.g., ModelCraft [57] uses paper models to generate initial digital artifacts in the 3D modeling pipeline; ProtoAR [43] converts physical prototypes to fully virtual scenes which can be tested on AR/VR capable devices.

While integrating immersive paper experiences into a pipeline of more powerful digital tools could certainly be useful for instructors, we considered it out of scope for our work. Given that our goal was to enable instructors to enhance their existing paper-based teaching materials with AR, rather than using paper as an intermediary tool to create digital learning resources, we focused our efforts with Paper Trail on tasks in the middle of the spectrum. While many of the features we implemented are not unique to our system, our contribution lies in compiling these features together in a system and using the system in studies with instructors to elicit potential use cases for immersive paper (Sec. 6).

4 PAPER TRAIL SYSTEM

In this section, we introduce Paper Trail, an immersive authoring system for creating paper-based educational experiences. We first discuss system requirements, which our five target use cases and design space helped to establish. Then, we present a system walkthrough and the implementation of Paper Trail, which was further informed by and refined through two initial evaluations with PhD students and AR experts (Sec. 5).

4.1 System Requirements

Based on our process of developing target use cases and analyzing prior work in a design space, we extracted four main requirements for an immersive paper authoring tool like Paper Trail:

R1: Need to repurpose existing physical & digital content. The system must support efficient AR authoring for instructors and students, who may be novice AR users and have limited time, e.g., during live lectures or experiments. In our own scenarios, it was easiest to prototype examples where we could make use of existing physical and digital content (i.e., *Interaction Design, Biology Poster*). Prior work's techniques for associating existing digital interfaces with paper [17, 33, 35, 62] also allows for efficient authoring. These examples inspired Paper Trail's lightweight techniques for capturing and immediately embedding images and outlines (i.e., AR copies of hand-written content) into paper.

R2: Need to enable flexible modes of engaging with learning material. Another key requirement is enabling instructors to support students' learning through multiple representations of course material (e.g., displaying AR animations of formulas in *Teaching Orbital Velocity* and RealitySketch [61], allowing students to record audio observations as an alternative to hand-written notes in *Chemistry Lab Notebook*). This informed our techniques for associating photos, audio, videos, and video bookmarks with paper. Flexible engagement can also constitute accessing learning resources on an as-needed basis (*Biology Poster*, PapARVisDesigner [9]); our implementation of clipping masks to selectively hide and show AR content allows for this user agency.

R3: Need to support fine-grained input in both physical and virtual spaces. Some examples require precise manipulation of AR content (e.g., positioning wireframes in *Interaction Design*), while other examples prioritized interactions with physical objects (e.g., handling chemicals and recording observations in *Chemistry Lab Notebook*, AR-assisted writing in prior work [33, 55, 56]). Therefore, we implemented both hand-held and head-worn interfaces for Paper Trail; the iPad interface enables more fine-grained manipulation of digital content, while the HoloLens enables hands-free interaction with AR content when precise manipulation of physical objects is required.

R4: Need to preserve versatile use of paper. Our scenarios and prior work demonstrate a wide variety of roles that paper can serve, e.g., writing surface (*MOOC Notebook*, [33]), capture surface (*Interaction Design*, [10, 37]), display surface (*Chemistry Lab Notebook*, [9, 17]), prototyping material [44, 59], and artifact to facilitate collaboration (*Teaching Orbital Velocity*). This need to provide flexible support for individual and multi-user tasks led us to develop collaborative authoring techniques and use marker-based AR to maintain stable tracking when paper is moved around, which could be difficult to accomplish through overhead camera and projector setups from prior work [55, 56, 65].

4.2 System Overview and Design Process

Figure 4 provides an overview of the Paper Trail's five main components: capture techniques, performance animations, clipping masks, audio/video clips, and shared content. We developed interfaces for hand-held AR using the iPad Pro and for head-worn AR using the HoloLens 2, supporting all interactions on both devices. This allowed us to study the affordances of both types of AR and their benefits and limitations for different instructional activities.

We iterated on the design of Paper Trail based on two evaluations (described in more detail in Sec. 5). First, we implemented an initial system prototype on the iPad and HoloLens; we tested the iPad implementation in a preliminary study with six PhD-level student instructors, which surfaced user experience improvements and a few potential new features, in particular, creating 3D virtual objects. We also had two AR design experts review both interfaces, which led to further usability improvements.

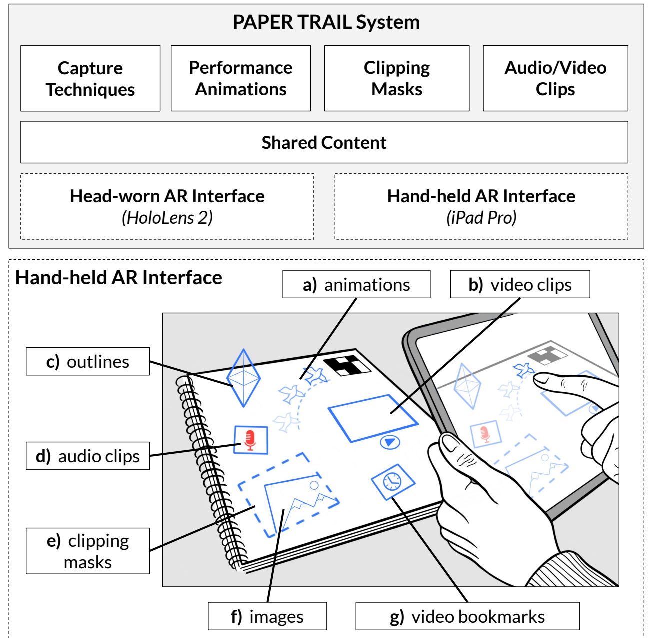

Figure 4: Overview of Paper Trail system: Our immersive authoring tool enables students and instructors to enhance paper with various forms of digital media, including images *(f)*, videos *(b)*, audio clips *(d)*, and outlines i.e., virtual copies of hand-drawn sketches *(c)*. Users can animate AR content for dynamic illustrations *(a)*, selectively show and hide content through clipping masks *(e)*, and create video bookmarks linking to particular timestamps *(g)*. We developed hand-held and head-worn interfaces using the iPad Pro and HoloLens 2, respectively. Paper Trail also enables collaborative experiences for group work or tutoring scenarios.

4.3 System Walkthrough

We present a system walkthrough based on the example of a physics instructor creating an interactive AR handout to check students' understanding of torque and angular momentum. We used this example for brainstorming and evaluating system usability in our formative system evaluations with PhD-level student instructors and XR experts (Sec. 5), as well as for priming in our elicitation study with high school teachers (Sec. 6).

First, our instructor wants to recap the torque formula and demonstrate the direction of vectors. Since the torque vector is perpendicular to the rod printed on the handout, she draws a vector on scrap paper, uses Paper Trail to capture the vector as an AR **outline**, which performs background removal on the photo and makes it blend in with printed content. Then, she aligns the vector to be popping out of the paper (Fig 5a).

Next, the instructor wants students to create dynamic visualizations demonstrating the behavior of two uniform rods when force is applied, as an alternative to answering the question in prose. She

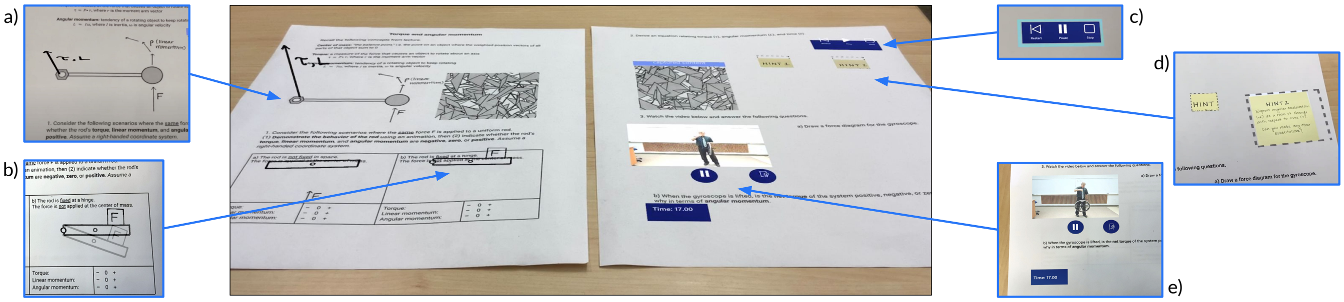

Figure 5: System walkthrough: AR torque handout. To demonstrate Paper Trail's feature set, we created a representative example of a physics instructor reinforcing her students' understanding of torque and angular momentum using an immersive paper handout. Using Paper Trail, the instructor enhances the handout with a hand-drawn arrow to show the torque vector popping out of the page *(a)*, animations to demonstrate torque applied to a fixed rod *(b)*, audio clips *(c)* and clipping masks to provide just-in-time hints *(d)*, and a video of a gyroscope with a bookmark linked to a key moment in the video *(e)*.

captures and embeds outlines of the rods into the handout, then instructs the students to record **animations**. They translate the rod when the force is applied at the center of mass and rotate it when torque is applied about its pivot point (Fig 5b).

To assist students on a difficult formula derivation problem, the instructor wants to embed virtual hints into the page. She writes two hints on post-it notes, uses Paper Trail to capture **images** and position them next to the question. Then, she attaches **clipping masks** to the AR images, such that only the word "Hint" is visible to students. When students need to receive a hint, they can scale up the clipping mask to reveal the rest of the AR hints (Fig 5d). She can also use Paper Trail to record the hints as **audio clips**, to support students are auditory rather than visual learners (Fig 5c).

Lastly, our instructor wants to enable students to easily reference a video demonstrating the motion of a gyroscope. Using Paper Trail, she records a **video** of a physical gyroscope and positions it under the question on the handout. She pauses the video at an important point in the demo and creates a **video bookmark** which references the current timestamp. Students can click the bookmark button to jump to that critical moment in the demo video (Fig 5e).

4.4 Immersive Paper Experiences with Paper Trail

This section describes how Paper Trail enables the creation of immersive paper experiences for hand-held and head-worn AR. The system supports capturing a various kinds of digital content, adding interactivity through animations and clipping masks, and shared experiences (Figure 4).

Enabling hand-held and head-worn AR experiences *(R3, R4).* We developed both a hand-held iPad Pro interface and a head-worn HoloLens 2 interface to enable fine-grained interaction with physical and virtual objects, as per our system requirements (Sec. 4.1). Both interfaces support enhancing paper with the same types of virtual content, but we adjusted the interaction design to optimize for each form factor. Users interact with virtual content via multi-touch gestures on the iPad and midair gestures on the HoloLens; we also enable voice commands on the HoloLens for capturing images and videos, so that the users' hands do not appear in the captured content. Another major difference was to account for the small screen of the iPad vs. the larger interaction space on the HoloLens. We kept all UI elements on a sidebar on the iPad, but on the HoloLens we attached some UI elements to the AR content (e.g., controls for deleting AR objects), as it felt cumbersome to frequently switch contexts between the main menu and AR objects.

Capturing and processing existing instructional material *(R1, R2).* Paper Trail offers a set of four capture techniques which allow users to embed digital content in paper: *(1)* **photos**, *(2)* **outlines** (where background removal is performed on a photo), *(3)* **videos**, and *(4)* **audio clips**. Live capture is enabled via in-built device cameras and microphones, and achieved via interaction with the sidebar menu on the iPad or direct manipulation and voice commands on the HoloLens. Users can duplicate, delete, transform *(translate, rotate, scale)*, and align captured content to be parallel or perpendicular to the paper.

Creating interactive content through animations and clipping masks *(R2).* Paper Trail allows users to record looping **animations** for digital content by translating it along a path or rotating it about a pivot point. Motion paths are demonstrated via multi-touch gestures in the iPad system and via direct manipulation in the HoloLens system. The aim of this feature is to enable instructors and students to visualize complex concepts which can be difficult to express through traditional analog methods, such as printed prose descriptions or static diagrams. With **clipping masks**, we enable users to control which portions of digital content are visible, which can address students' needs for personalized, on-demand learning. We explored this idea in the *Biology Poster* for embedding background information into existing physical resources, and also see potential for using clipping masks to create simple interactive elements on the page, such as flashcards or embedded answer keys.

Cross-referencing video recordings *(R2).* Paper Trail allows users to create **video bookmarks** which reference the current timestamp for video elements in the scene. When a user clicks the bookmark buttons, the video skips to that particular timestamp. This method of navigating digital content is explored through the *MOOC Notebook* example, where students may want a means of linking physical notes to specific points in the lecture, in order to enable quick referencing when notes are later reviewed.

Enabling shared AR experiences *(R4)*. To support multi-user and cross-device experiences, Paper Trail implements collaborative authoring techniques. Captured media is shared across connected devices, and the position and movement is synced. This feature can be used to enable collaborative tasks, such as in our *Teaching Orbital Velocity* example where instructors and students have a shared view of virtual animations, as well as meeting scenarios where teammates can use AR as a means of sharing digital and physical content.

4.5 Implementation

Paper Trail is implemented as a Unity 2019.2.12f1 application using MRTK 2.3.0 to reach the iPad Pro and HoloLens 2. We used Vuforia for marker tracking, as well as Lean Touch[1] for multi-touch interactions on the iPad and for direct manipulation on the HoloLens 2. Photo and video capture is accomplished via the iOS ReplayKit API[2] for Unity on the iPad and via the PhotoCapture[3] & VideoCapture[4] APIs on the HoloLens 2. More information on Paper Trail, including the source code and examples like our AR torque handout, can be found at https://mi2lab.com/research/papertrail.

5 SYSTEM EVALUATIONS WITH STUDENT INSTRUCTORS AND XR EXPERTS

We conducted system evaluations to explore use cases and guide design iterations of Paper Trail: *(1)* a **preliminary study with six PhD-level student instructors**, where we aimed to understand opportunities and limitations when applying the system in various STEM instructional scenarios, and *(2)* a **usability review with two XR experts**, in order to identify ways of improving the user experience. In both studies, participants were given the task of re-creating an immersive paper handout (Fig. 5). In the first study, this task was used to prime participants for brainstorming possible use cases and new system features, while in the second study, the task was used for heuristic evaluation.

5.1 Preliminary Study with PhD-level Student Instructors

With our first formative study, we aimed to understand how our initial implementation of the Paper Trail iPad interface could integrate with PhD students' instructional activities and whether the feature set was sufficient to support a range of topics. We chose to study with PhD students who had prior teaching experience, as they represented both target user groups of our system – instructors and students. We adopted an elicitation study design [67], first priming participants on potential use cases for immersive paper through recreating a handout using Paper Trail, then having them produce AR interaction proposals to support teaching a topic from their own domain.

Method. We recruited participants via university mailing lists and selected 6 PhD students (5 female, 1 male, average age of 24.3 years) from a variety of STEM fields, including physics, mechanical engineering, chemical engineering, chemistry, civil engineering, and computer science. Two participants were familiar with mobile AR/VR devices, and one of these two also had experience with the HoloLens 1. Due to COVID-19, we delivered all necessary equipment to the participants' homes and conducted the study over Zoom. Before the study, we asked participants to prepare a 5-10 minute lesson on a topic from their domain, using their choice of teaching materials, e.g., slides or textbooks.

The study consisted of three tasks: *(1)* **recreating an AR handout** *(20 min)*: following a step-by-step video, participants used the Paper Trail iPad interface to create an AR torque handout with a subset of features from the example described in Sec. 4; *(2)* **teaching a lesson from their domain**, using their prepared instructional materials *(5 min)*; *(3)* **producing proposals for immersive paper interactions** which could support that lesson *(30 min)*.

Results. In Task 1, all participants were able to create the AR torque handout using Paper Trail within the given time limit. A majority of participants saw potential in AR videos for capturing important lecture snippets or visualizing complex topics (P2, P3, P5, P6) and AR animations for conveying movement in diagrams (P2-6) or replaying how a drawing was sketched (P6). For Task 2, the participants' lessons covered a wide range of STEM topics, including viscosity, rheology (material flow), pillars of tissue engineering, balancing chemical equations, calculating forces in a truss, and vector addition. All preferred to teach primarily using paper even though they were given the choice of teaching materials in preparation for the study.

Table 1 shows the immersive paper interaction proposals we elicited during Task 3. Many proposals directly addressed difficulties that participants had while serving as instructors, e.g. providing more context for a lecture topic or making backward references to previous instructional sessions. P3 proposed enabling students to selectively view background content using clipping masks (2.2) or link to past lecture videos (3.3). P5 suggested using AR to embed diagrams within another (2.1) or create layered diagrams (4.3), rather than having to refer to multiple diagrams for a force calculation. Most of these proposals could be accomplished with the current Paper Trail system, with the exception of visualizing 3D content (4.1) and color coding quantities (4.4). To enable creation of 3D content, we implemented a feature to align AR content to be parallel or perpendicular to the paper in our next iteration of the system.

5.2 XR Expert Reviews of Paper Trail's User Experience and Usability

The goal of our second evaluation, a system walkthrough [29] with two XR design experts, was to assess the user experience of the Paper Trail iPad and HoloLens interfaces and obtain feedback to improve the interaction design.

Method. We recruited two XR design experts from an on-campus professional group which specializes in developing educational XR experiences for academic courses at our university; one participant is the director of this group (E1), and the other is an XR software developer (E2). Both participants have been using AR experiences for 2+ years and have experience developing educational apps for either mobile AR or the HoloLens 2.

[1] http://carloswilkes.com/Documentation/LeanTouch
[2] https://docs.unity3d.com/ScriptReference/Apple.ReplayKit.ReplayKit.html
[3] https://docs.unity3d.com/2019.2/Documentation/Manual/windowsholographic-photocapture.html
[4] https://docs.unity3d.com/2018.3/Documentation/Manual/windowsholographic-videocapture.html

Animations	Video
1.1) Illustrating motion paths and speed 1.2) Conveying structural changes 1.3) Making story problems more engaging	2.1) Visualizing complex topics 2.2) Walking through a 3D environments 2.3) Linking to critical moments in a lecture
Clipping Masks	Other
3.1) Expanding definitions for mathematical quantities 3.2) Showing background information 3.3) Viewing detailed diagrams within a larger diagram 3.4) Revealing solutions to problem sets	4.1) Visualizing 3D content 4.2) Overlaying units for equations 4.3) Creating layered diagrams 4.4) Color coding quantities

Table 1: AR Interaction Proposals from Preliminary Study: In our study with PhD-level instructors, participants produced the following proposals for using immersive paper to teach STEM topics. We aggregated the proposals under four types of features: *Animations, Video, Clipping Masks,* and *Other.*

We conducted the expert reviews in a lab setting and structured it into two tasks, one involving the iPad Pro interface and the other involving the HoloLens 2 interface, counterbalancing the order between participants. In these two tasks, we provided step-by-step instructions for the participants to recreate AR torque handout (Sec. 4) and asked them to think-aloud during the task to ask questions or provide feedback. For each device, we discussed how effectively they could accomplish the task using questions based on the System Usability Scale (SUS) [6] in order to reveal insights about the user experience of both interfaces and pinpoint specific usability issues which we could address in another development iteration.

Results. Overall, both experts agreed that the interaction design of the iPad and HoloLens interfaces was intuitive. In particular, they found the iPad interface's capture and animation workflows easy to execute, noting the similarities to familiar mobile apps like the iOS camera. E2 expressed that the iPad interface "could be really effective" for instructors, considering that a new user could recreate the torque handout in under 20 minutes. They found it straightforward to navigate to different features in the HoloLens interface and appreciated the convenience of the voice commands (E2), but questioned whether the HoloLens gestures would also feel intuitive for novice users (E1).

In terms of opportunities for improvement, the lack of visual feedback indicating when a marker was being tracked caused confusion over where captured content would appear (E1, E2). The iPad form factor posed challenges for selecting buttons due to the large width of the device (E1, E2) and heavy weight (E2). With the HoloLens interface, both experts experienced unstable marker and hand-tracking, particularly when interacting with paper laying flat on the table (as opposed to holding the paper at eye-level). This resulted in moving AR content accidentally and struggling to press small buttons. Additionally, captured outlines on the HoloLens were "faint" and hard to see at times (E1, E2). We addressed all of these UX issues in our final design iteration, besides improving upon Vuforia tracking and HoloLens' in-built hand-tracking, which would require custom implementations. Instead, our strategy was to optimize the system design for the existing tracking mechanisms by making the fiducial markers and interactable elements larger.

6 ELICITATION STUDY WITH EXPERIENCED HIGH SCHOOL TEACHERS

After our formative studies and finalizing the system design, we conducted a user study with seven high school instructors. Our goal was to investigate whether and how they could envision using Paper Trail to complement their teaching. We were particularly interested in exploring how Paper Trail's features could generalize to a range of academic subjects and learning activities and what needs the instructors might have for using AR.

6.1 Method

We recruited seven high school instructors (4 female, 3 male, average age = 48.4 years, average teaching experience = 18.7 years) to participate in our user study. We identified potential participants who teach upper-level courses across different subjects, in particular through the Advanced Placement (AP) and International Baccalaureate (IB) programs, from websites of 4 local high schools in the same town as our university. Six out of seven instructors currently teach STEM topics (summarized in Table 2), and P5 is a library media specialist who supports students and other instructors with research and learning technology needs. All instructors identified as novice AR users, with some having one-time experiences with mobile AR (P5) or VR headsets (P1, P3, P4).

The study consisted of three tasks centered around the instructors' use of paper and digital tools in their current instructional workflows: (1) a **walkthrough of a paper-based teaching resource** which the instructors brought with them to the study, (2) a **review of the AR torque handout** using both the iPad Pro and HoloLens 2, and (3) an **elicitation task to propose and prototype AR interactions** for the paper-based resource we discussed in Task 1. Tasks 1 and 2 were used to prime the participants for Task 3, which was conducted in the style of user-driven elicitation [42, 67]. In a debrief session, we conducted a short semi-structured interview around how the participants could see Paper Trail applying to their broader instructional workflow.

We asked the participants to bring an example of a paper-based teaching resource to their study session (e.g., informational handout, worksheet, exam). The study was conducted in a lab setting, following COVID-19 precautions required by our university. Each session lasted 1.5 hrs and participants were compensated with $50 USD for their time.

Task 1: Walkthrough of paper-based instructional resources. The study began with a 15 minute semi-structured interview where the instructors presented the paper-based instructional resource which they brought with them. We asked them to describe how they created the resource and why they chose paper as the medium, how students would utilize it in a learning activity, and

	Academic Subject	Topic Explored in Study	Paper-Based Resource
P1	Integrated Science	Wind turbines & energy conversion	Handout to accompany physical demo
P2	Computer-aided manufacturing	G&M coding for CNC machines	Lecture slides for fabrication activity
P3	AP Calculus	Rectilinear motion	Guided lecture notes
P4	AP Biology	Types and functions of enzymes	Problem set
P5	Media & research skills	Library search tools	Research log to database searches
P6	AP Physics	Roller coasters, springs, power	Problem set
P7	AP Biology	Building macromolecules	Cutting & pasting activity

Table 2: Instructors' Domain Areas and Paper-Based Resources: The high school instructors teach courses in mostly STEM domains, with the exception of P5 who supports students' & instructors' educational technology needs across many subject areas. In our study, they explored a variety of topics, ranging from sustainable energy to physic and math, cellular biology, and programming laser cutters. Their paper-based resources included problem sets or note sheets to demonstrate knowledge of course material (P3-4, P6), handouts accompanying hands-on activities (P1-2, P7), and a research log to record and analyze online search results (P5).

how they would assess student engagement. Thinking beyond this specific paper-based resource, we discussed how the instructors utilize paper in conjunction with analog and digital tools and the benefits and challenges of this combination of tools.

Task 2: Review of AR handout created with Paper Trail. To introduce the Paper Trail system to participants, we utilized the torque and angular momentum example described in Sec. 4 using all system features, as opposed to using a subset of features in the initial evaluations (Sec. 5). We presented the handout from a student's perspective, asking the participants to test out a Unity scene of the torque handout which we created in advance: recording performance animations, expanding clipping masks to reveal hints, and playing the immersive video and audio elements. They experienced the torque handout on both the iPad Pro and HoloLens 2; we counterbalanced the order of devices between participants. Afterwards, we discussed the overall effectiveness of the handout example, using any metrics the participants felt were relevant (e.g., impact on learning, user experience of each form factor).

This task took 30-40 minutes to complete. Due to time restrictions, we used a pre-created AR handout on both devices rather than having participants recreate the handout, like in the prior studies (Sec. 5). This approach enabled us to elicit more holistic feedback on the handout; focusing on the student perspective encouraged the participants to think more broadly about metrics relevant to teaching and learning, rather than primarily the system UX.

Task 3: Prototyping immersive paper resources with Paper Trail. The aim of the third task was to explore how the instructors would want to use AR to support their teaching, using the paper-based teaching resource from Task 1 as a basis for brainstorming. This task adopted some elements of the production, priming, and partners elicitation methodology from Morris et al. to reduce legacy bias [42]. We prompted the instructors to consider the student engagement and challenges with their current paper-based learning activity in Task 1 and used Task 2 to prime them on possible ways for AR to enhance student comprehension of topics and add interactivity to instructional resources.

We first asked the instructors to produce at least three proposals for how they could use AR to enhance their own resource, thinking aloud and annotating their resource using blank paper, post-its, and markers we provided. We encouraged them to think beyond the existing Paper Trail features and the limitations of the iPad and HoloLens form factors. Then, we asked them to select either the iPad or HoloLens system to use for prototyping, considering how the students would utilize this AR experience in the learning activity. We selected 2-3 proposals to prototype and trained the instructors to use specific Paper Trail features as needed.

Debrief. In the debrief, we first compared the prototypical immersive paper resource from Task 3 with the original resource, discussing whether Paper Trail's features were sufficient to implement the participant's interaction proposals and whether they would anticipate a difference in student engagement or learning with the new immersive resource. We ended the study with a discussion on whether AR and Paper Trail in particular could be useful for their teaching in a range of scenarios and what concerns they may have with utilizing AR devices with students.

6.2 Results

Overall, all instructors agreed that immersive paper could be useful for their teaching. They brainstormed use cases around their own instructional resources including problem sets for checking students' understanding of core concepts (P3-4, P6), handouts which accompany physical demos and hands-on lab activities (P1-2, P7), and a research log to record and analyze online search results (P5), as shown in Table 2. Figure 6 shows an overview of our participants' physical and AR prototypes created with Paper Trail. Instructors were generally interested in enhancing their paper resources with AR in order to add interactivity and multiple ways of engaging with learning material beyond reading and writing, to explain dynamic processes through animated AR simulations, and to bridge the gap between digital tools used in conjunction with paper-based activities (e.g., videos and interactive web apps).

In this section, we present six themes from our user study around common types of interaction proposals, pros and cons of hand-held and head-worn AR for authoring and experiencing immersive paper, potential use cases (i.e., evaluating students' predictions, enabling hands-on learning, providing individualized for students' learning needs), and the barrier to entry posed to instructors and students.

T1: A majority of instructors' proposals included transforming and associating digital content with paper, and there was a common desire to integrate immersive paper with existing digital tools. Participants found the Paper Trail system

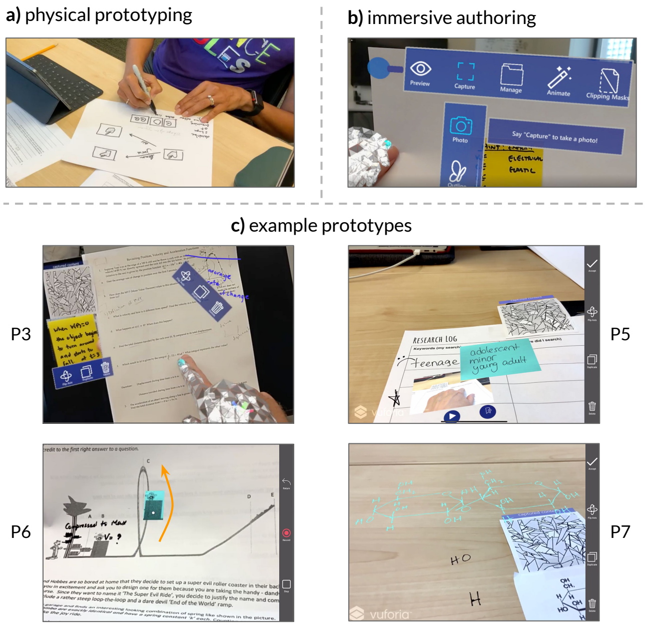

Figure 6: Immersive Paper Prototypes. In Task 3, we first elicited AR interaction proposals from the instructors through think aloud and physical prototyping *(a)*. Then, we asked them to select either hand-held or head-worn AR to author their proposals using Paper Trail *(b)*. In (*c*), we show four of the prototyped examples: P3 created an guided notesheet for rectilinear motion, where students can receive hints and tap on areas of the printed graph to visualize changes in slope. P5 prototyped an immersive research log which enables students to look up hand-written words in an AR thesaurus and view video instructions for the activity. P6 used animations to simulate a cart going through a roller coaster based on variables printed on the page. Finally, P7 prototyped a macromolecule building activity, where students can break off hydroxyl groups and combine molecules to form carbohydrates.

sufficiently expressive to prototype the majority of their interaction proposals (Table 3). The most common proposals included animating static diagrams through AR (proposed by P1-2, P4, P6), embedding photos and videos to display background concepts (P1-5, P7), and using clipping masks to provide just-in-time information (P1, P3, P7). In our design space (Sec. 3.2), these popular interactions can be categorized as associating digital media with paper (D2.c) and transforming AR content through toggling visibility (D3.b) and animations (D3.c), which are all supported by our system.

While these results suggest that we achieved good coverage of the key immersive paper interactions in the middle of the design space, the instructors also proposed a few interactions currently not implemented in Paper Trail, which are italicized in Table 3. Performing calculations or simulating dynamic processes based on handwritten content (P2-3, P6) could be considered an extension of animating AR content in our design space (D3.c), where semantic understanding of paper-based content is required to generate AR animations (e.g., RealitySketch animates AR drawings based on the color and position of physical objects [61]). Instructors also wanted to link to external web sources (P1, P3, P5) and integrate AR buttons for students to digitally submit paper-based assignments (P4-5). To accomplish this, they proposed associating existing digital interfaces with paper (D2.c) or exporting their immersive paper worksheets to purely digital formats to facilitate compatibility with school-wide digital tools like Pear Deck[5] and Kami[6], which offer mechanisms for automated feedback and grading.

T2: Instructors found hand-held AR more practical for creating immersive paper resources and class facilitation, but head-worn AR more natural for experiencing these resources. Five out of seven instructors chose to use the iPad for prototyping in Task 3; as novice AR users, the screen-based interactions were easier and more familiar for them to perform than the HoloLens gestures (P2, P4-7). However, some of these instructors noted that while the iPad felt more usable, it limited their tangible interaction with the paper (P1, P3-5) and required them to "keep bringing yourself out of the experience" (P5). The instructors who selected the HoloLens (P1, P3) viewed head-worn AR as a more viable option for students experiencing immersive paper in co-located classrooms, as it allows for hands-free interaction and imposes "fewer restrictions" when students are collaborating and working with paper and physical demos (P1). However, without a spectator view for head-worn AR, instructors felt their ability to monitor students' progress and existing class facilitation strategies like "scanning the room" would be limited (P1, P4).

T3: Instructors emphasized the value of using immersive paper for scientific predictions and the flexibility to adapt established pedagogical models. Many instructors expressed that AR could be particularly useful for validating and explaining students' predictions directly on paper (P1-2, P5-7), rather than developing specific physical labs or online simulations for hypothesis testing. Some instructors explored this use case in their prototypes, e.g., simulating how a laser cutter would interpret students' handwritten codes before running the codes on a CNC machine (P2) and testing students' hand-drawn roller coaster configurations when it is infeasible to construct a physical setup (P6). However, they emphasized that these AR simulations need to be designed to support students' "individualized exploration" (P6) without simply giving them the answers (P1, P6-7). P1 explained how AR could complement the *predict, observe, explain* pedagogical model [66] which he frequently uses in science courses; in the *predict* phase, he would first instruct students to think through a concept using paper and pencil, then incorporate immersive content in the *observe* and *explain* phases to validate their predictions. P7 "usually likes [the students] to make mistakes" when learning about macromolecules, and wanted to preserve this learning opportunity by using AR to illuminate students' "preconceptions."

T4: Direct manipulation of AR content enables tangible learning opportunities. Some instructors used their paper-based activities from Task 1 to accompany hands-on, lab-based activities to enable students to engage with complex content in new ways (P1-2, P7); however, they found it challenging to "perfectly mimic the paper world" in adapting their existing hands-on lessons to

[5]https://www.peardeck.com/googleslides
[6]https://www.kamiapp.com

Animations (P1, P2, P4, P6)		**Videos** (P2, P3, P5, P7)	
1.1) Visualizing motion in static diagrams	P1, P4, P6	**2.1)** Demonstrating dynamic content	P2, P3
1.2) *Simulating hand-drawn dynamic processes*	P2, P6	**2.2)** Delivering activity instructions	P5, P7
Buttons (P3, P4, P5, P6)		**Photos** (P1, P3, P4)	
3.1) *Performing calculations based on diagrams*	P3, P5, P6	**4.1)** Providing accommodations	P1
3.2) *Submitting answers to questions*	P4, P5	**4.2)** Providing background info	P3, P4
Clipping Masks (P1, P3, P7)		**Outlines** (P2, P5, P7)	
5.1) Providing hints for problem sets	P1, P7	**6.1)** Testing configurations of objects	P2, P7
5.2) Providing answer keys	P3	**6.2)** Indicating best & worst search terms	P5
Audio Clips (P1, P4)		**Links to External Sources** (P1, P3, P5)	
7.1) Explaining static diagrams	P1	**8.1)** *Linking to past course material*	P1
7.2) Delivering activity instructions	P4	**8.2)** *Integrating dictionaries / calculators*	P3, P5

Table 3: AR Interaction Proposals from Elicitation Study with Instructors: We aggregated the instructors' interaction proposals and ordered the categories in terms of how frequently they were suggested. The italicized proposals (1.2, 3.1-2, 8.1-2) are not currently supported by our implementation of Paper Trail.

online formats online learning during the COVID-19 pandemic (P1). Instructors saw potential for immersive paper to provide tangible learning opportunities even with mostly online instruction through enabling direct manipulation of AR content. In particular, they expressed that performance animations in the torque handout could be a valuable mechanism for students to demonstrate knowledge (P2, P4-5, P7), saying that this feature "takes the understanding to a different dimension" (P2). P7's prototyped example explored direct manipulation to construct AR macromolecules, as an alternative to an in-person building activity.

T5: Immersive paper is a promising modality for supporting students' diverse learning styles. A major challenge that all our participants encounter when selecting instructional tools is catering to students' individual learning needs (P1-7). Some students are uncomfortable with digital tools and tend to "get lost in the tech rather than being able to focus on the content" (P4), while other students "just don't have a good attitude towards paper" (P5) and feel self-conscious about their handwriting and drawing skills (P2). Instructors felt that Paper Trail could help overcome this challenge by "engaging learners in multiple formats" (P4) and providing a range of options for content delivery through printed content and embedded AR media (P3, P5-7). It could also provide a choice of modalities for demonstrating their understanding of concepts (e.g., students might feel more comfortable answering a question through performance animations than writing prose). P1 also noted the potential of immersive paper to provide accommodations for students with learning differences by personalizing their paper-based content with additional instructions and hints.

T6: There is a tradeoff between immersive paper's technical barrier to entry and the potential benefits it could provide. A common concern with utilizing AR devices and Paper Trail in the classroom was experiencing frustration when the technology does not work (P1-7). Drawing on their experience with online learning during the COVID-19 pandemic, instructors anticipated "kids that would shut down" if they struggled to use the technology (P4) or get distracted by the novelty of AR (P1, P3). From an instructor perspective, they would need to invest time and effort to "diagnose problems quickly" (P1) and learn to redesign their existing lesson plans, considering how AR could best support students' learning goals (P4, P7). P5, who supports and consults with teachers on technology needs, expressed that even well-designed AR content would be "ineffective if [students] struggle with the means to access it" and stressed the importance of weighing the costs and benefits of integrating new technologies into instructional workflows.

7 DISCUSSION

Our studies around Paper Trail are promising in that they demonstrate our system's general ability to support a range of educational scenarios. Our participants found Paper Trail sufficiently expressive to accomplish a majority of their interaction proposals and suggested extensions to the system's functionality to further enable instructors (Table 3). Instructors found value in even minimal usage of AR (e.g., demonstrating vectors coming out the of the page in our torque handout) and proposed basic use cases in their own prototypes (e.g., simply moving AR content around to test out different configurations for molecules and machine codes). While not all findings reported here are unique to Paper Trail, from the instructors' point of view, our general approach of enhancing existing instructional activities based on paper achieved similar benefits to the tailored AR experiences developed in prior research [3, 50, 51, 63].

In this section, we reflect on challenges and opportunities which immersive paper may pose in educational settings and compare immersive paper with alternative tools in instructors' workflows.

7.1 Challenges and Opportunities in Adopting Immersive Paper for Instruction

In our user studies, we utilized Paper Trail as a basis for instructors to imagine how the combination of AR and paper (i.e., *immersive paper*) could support their existing lesson plans and analyze potential concerns which may arise when using immersive paper in the classroom. We discuss two categories of concerns: *(1)* challenges related to immersive paper, where Paper Trail should be regarded as one of many possible implementations, and *(2)* challenges with the usage of AR technologies more broadly, e.g., limited device availability and the learning curve for novice users.

Focusing on immersive paper, our instructors had open questions around how to best translate students' learning goals into

AR interactions and repurpose existing teaching materials. P7 identified many paper-based lesson plans which could benefit from immersive content, but required "more time to process how to do it" effectively. This raises a need for more concrete design guidelines for adapting instructional material to immersive formats such that they preserve analog learning strategies. Throughout our study, we observed common design strategies which we see as initial guidelines on creating immersive instructional experiences. For example, instructors saw value in engaging students with multiple immersive representations of lecture content, using animations to simulate and validate scientific hypotheses [66], and guiding students' attention by embedding hints via clipping masks. These design strategies align with guidelines from prior work for designing AR learning experiences [23, 50].

The majority of challenges raised by the instructors go beyond immersive paper and pertain to AR technologies more broadly, including the limited availability of AR devices in educational settings [18] and the time investment required from both students and teachers to learn to use AR. As our instructors experienced during the COVID-19 pandemic, even when digital technologies are mandated by schools, there may still be students who struggle and prefer analog alternatives. However, P2 expressed that AR could be a promising modality to engage students who are more accustomed to digital rather than paper-based tools, arguing that "it's the expectation that you integrate technology" into the curriculum to "represent what's happening in the real world." Considering the rapid pace with which AR devices are developing and becoming more widespread and accessible to students and instructors [23, 40, 46, 51], we argue that our implementation of immersive paper would not be rejected on the basis of these general challenges with AR, but additional research is needed to lower the barrier to entry so that instructors can develop meaningful alternatives for students who are not comfortable or able to use AR devices.

We adopted a priming task of recreating an AR handout to introduce our user study participants, all of whom were novice AR users, to examples of immersive paper interactions and reduce legacy bias as recommended by prior elicitation studies [42]. However, priming the instructors using Paper Trail may have contributed to design fixation around our system features and participant response bias [11] regarding the benefits that immersive paper could pose for education. In an attempt to mitigate this, we explicitly asked instructors to reflect on limitations of immersive paper and concerns with using AR in the classroom, but additional research may be required to more objectively evaluate the value of immersive paper in educational contexts.

7.2 Design Alternatives to Immersive Paper in Education

Guided by our target use cases and design space (Sec. 3), we focused our exploration with Paper Trail on enabling educational use cases which make use of both physical and digital interactions grounded in paper. While all of our participants felt that immersive paper could be a valuable modality for their own teaching, they also discussed instructional scenarios which are potentially better suited for purely physical or digital tools. In this section, we discuss how these alternative tools compare to immersive paper and limitations in our investigation of AR/VR alternatives.

Instructors expressed they may opt for purely analog learning activities when it seemed less effective to digitally mimic the physical world, e.g., chemistry and physics activities where mastering hands-on lab techniques is a core learning goal or collaborative activities where paper helps to mediate and democratize students' design process. They saw value in extending these tangible modalities with immersive paper to simulate complex concepts beyond the capabilities of physical setups and translate physical designs to higher fidelity digital formats; however, they also raised concerns that AR could disrupt benefits of standalone paper activities, like supporting students' focus and memory [54] and enabling instructors to scan the room to monitor students' progress. If choosing to complement physical activities with immersive paper, they would select head-worn AR rather than hand-held devices to allow students to more freely communicate and collaborate around physical setups. This raises a need for effective techniques for instructors and students to share content in head-worn AR, in order to preserve instructors' class facilitation strategies like scanning the room to gauge students' progress.

We discussed purely digital tools mainly in the context of remote teaching during the COVID-19 pandemic, when it was infeasible to distribute physical materials to students. Our participants initially felt limited in adapting tangible activities to online formats, but discovered new benefits in educational management tools such as Pear Deck[7] and Kami[8] for automating existing analog processes for grading, collecting learning analytics to assess students' progress, and providing feedback on assignments. From an instructor standpoint, further developing interactions on the digital side of our design space to more closely integrate immersive paper with school-wide, mandated digital tools could be a valuable avenue for future work. However, from a student perspective, instructors argued that embedding elements of existing digital apps with paper worksheets (e.g., embedding AR graphing calculators or interactive polls) would be a more effective design strategy to preserve the learning benefits of paper and support a wider range of learning styles. We find it promising that our participants viewed immersive paper as an opportunity to bridge the gap between distinct physical & digital tools by bringing the most promising aspects of web-based tools to AR, since enabling instructors to repurpose existing resources was one of our core requirements in developing Paper Trail (Sec. 4.1).

We see our focus on combining AR and paper as a strength of the user study, as it allowed instructors to envision and prototype use cases which complement their existing workflows, rather than aiming to replace their familiar tools. However, this raises a potential limitation in that we did not explicitly elicit instructors' perceptions on stronger versions of AR, e.g., mid-air digital content [53] and augmented virtuality [41, 58], or use cases in VR. To an extent, this has been the subject of prior work on immersive educational technologies [8, 12, 23, 46, 49, 51], but additional research may be required to assess the benefits of strong AR and VR use cases in comparison with immersive paper.

[7]https://www.peardeck.com/googleslides
[8]https://www.kamiapp.com

8 CONCLUSION

With Paper Trail, we contribute insights around the design of immersive paper educational experiences using the latest generation of AR devices and example use cases across a variety of educational domains. Through system evaluations with PhD student instructors and XR design experts, we refined the design of Paper Trail for an elicitation study with high school instructors, where we investigated how they could envision using immersive paper to complement their existing educational activities. The instructors' feedback was promising in that they saw potential for immersive paper to support students' diverse learning needs and bridge the gap between strictly physical or digital educational tools in their existing workflows.

Due to the COVID-19 pandemic, we were limited in our ability to conduct field studies with instructors and students; to some extent, this was the focus of prior work which aimed to investigate interactive paper in educational contexts [25, 48] and assess the educational value of AR compared to traditional, non-immersive modalities. [50, 51]. In an attempt to mitigate this limitation, we studied with highly experienced teachers (average of 18.7 years experience) who have taught a wide range of grade levels, prompting them to consider a variety of students' learning preferences during the interview portions and when choosing a device for prototyping. Since we primarily studied with STEM instructors, the immersive paper use cases in our study may be limited in their generalizability to other domains, e.g., language learning [12] or music education [14, 62]. Future work could deploy an immersive paper authoring tool such as Paper Trail in high school or undergraduate courses to more comprehensively study opportunities and challenges for immersive paper from the student perspective, as well as develop best practices for when and how to utilize immersive paper for specific learning activities in a wider variety of domains.

ACKNOWLEDGMENTS

We thank our study participants for sharing their experiences and insights to improve the design of Paper Trail. We thank Chen Chen for assistance on the literature review and Iulian Radu for providing feedback on the paper. We are grateful to our anonymous reviewers for their time and valuable advice for developing the design space and improving the presentation of our work.

REFERENCES

[1] Michelle Annett, Tovi Grossman, Daniel J. Wigdor, and George W. Fitzmaurice. 2015. MoveableMaker: Facilitating the Design, Generation, and Assembly of Moveable Papercraft. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology, UIST 2015, Charlotte, NC, USA, November 8-11, 2015*. ACM, New York, NY, USA, 565–574. https://doi.org/10.1145/2807442.2807483

[2] Narges Ashtari, Andrea Bunt, Joanna McGrenere, Michael Nebeling, and Parmit K. Chilana. 2020. Creating Augmented and Virtual Reality Applications: Current Practices, Challenges, and Opportunities. In *CHI '20: CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, April 25-30, 2020*. ACM, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376722

[3] Elham Beheshti, David Kim, Gabrielle Ecanow, and Michael S. Horn. 2017. Looking Inside the Wires: Understanding Museum Visitor Learning with an Augmented Circuit Exhibit. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, Denver, CO, USA, May 06-11, 2017*. ACM, New York, NY, USA, 1583–1594. https://doi.org/10.1145/3025453.3025479

[4] Olha Bondarenko and Ruud Janssen. 20. Documents at Hand: Learning from Paper to Improve Digital Technologies. In *Proceedings of the 2005 Conference on Human Factors in Computing Systems, CHI 2005, Portland, Oregon, USA, April 2-7, 2005*. ACM, New York, NY, USA, 121–130. https://doi.org/10.1145/1054972.1054990

[5] Peter Brandl, Christoph Richter, and Michael Haller. 2010. NiCEBook: supporting natural note taking. In *Proceedings of the 28th International Conference on Human Factors in Computing Systems, CHI 2010, Atlanta, Georgia, USA, April 10-15, 2010*. ACM, New York, NY, USA, 599–608. https://doi.org/10.1145/1753326.1753417

[6] John Brooke. 1995. SUS: A quick and dirty usability scale. *Usability Eval. Ind.* 189 (11 1995).

[7] John M. Carroll. 1999. Five Reasons for Scenario-Based Design. In *Proceedings of the Thirty-Second Annual Hawaii International Conference on System Sciences-Volume 3 - Volume 3 (HICSS '99)*. IEEE Computer Society, USA, 3051.

[8] Peng Chen, Xiaolin Liu, Wei Cheng, and Ronghuai Huang. 2017. A review of using Augmented Reality in Education from 2011 to 2016. In *Innovations in Smart Learning*, Elvira Popescu, Kinshuk, Mohamed Koutheair Khribi, Ronghuai Huang, Mohamed Jemni, Nian-Shing Chen, and Demetrios G. Sampson (Eds.). Springer Singapore, Singapore, 13–18.

[9] Zhutian Chen, Wai Tong, Qianwen Wang, Benjamin Bach, and Huamin Qu. 2020. Augmenting Static Visualizations with PapARVis Designer. In *CHI '20: CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, April 25-30, 2020*. ACM, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376436

[10] Stephanie Claudino Daffara, Anna Brewer, Balasaravanan Thoravi Kumaravel, and Bjoern Hartmann. 2020. Living Paper: Authoring AR Narratives Across Digital and Tangible Media. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems, CHI 2020, Honolulu, HI, USA, April 25-30, 2020*. ACM, New York, NY, USA, 1–10. https://doi.org/10.1145/3334480.3383091

[11] Nicola Dell, Vidya Vaidyanathan, Indrani Medhi, Edward Cutrell, and William Thies. 2012. "Yours is better!": participant response bias in HCI. In *CHI Conference on Human Factors in Computing Systems, CHI '12, Austin, TX, USA - May 05 - 10, 2012*. ACM, New York, NY, USA, 1321–1330. https://doi.org/10.1145/2207676.2208589

[12] Fiona Draxler, Audrey Labrie, Albrecht Schmidt, and Lewis L. Chuang. 2020. Augmented Reality to Enable Users in Learning Case Grammar from Their Real-World Interactions. In *CHI '20: CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, April 25-30, 2020*. ACM, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376537

[13] Maribeth Gandy and Blair MacIntyre. 2014. Designer's augmented reality toolkit, ten years later: implications for new media authoring tools. In *The 27th Annual ACM Symposium on User Interface Software and Technology, UIST '14, Honolulu, HI, USA, October 5-8, 2014*. ACM, New York, NY, USA, 627–636. https://doi.org/10.1145/2642918.2647369

[14] Jérémie Garcia, Theophanis Tsandilas, Carlos Agón, and Wendy E. Mackay. 2014. Structured observation with polyphony: a multifaceted tool for studying music composition. In *Designing Interactive Systems Conference 2014, DIS '14, Vancouver, BC, Canada, June 21-25, 2014*. ACM, New York, NY, USA, 199–208. https://doi.org/10.1145/2598510.2598512

[15] Raphaël Grasset, Andreas Dünser, Hartmut Seichter, and Mark Billinghurst. 2007. The mixed reality book: a new multimedia reading experience. In *Extended Abstracts Proceedings of the 2007 Conference on Human Factors in Computing Systems, CHI 2007, San Jose, California, USA, April 28 - May 3, 2007*. ACM, New York, NY, USA, 1953–1958. https://doi.org/10.1145/1240866.1240931

[16] François Guimbretière. 2003. Paper augmented digital documents. In *Proceedings of the 16th Annual ACM Symposium on User Interface Software and Technology, Vancouver, Canada, November 2-5, 2003*. ACM, New York, NY, USA, 51–60. https://doi.org/10.1145/964696.964702

[17] Aakar Gupta, Bo Rui Lin, Siyi Ji, Arjav Patel, and Daniel Vogel. 2020. Replicate and Reuse: Tangible Interaction Design for Digitally-Augmented Physical Media Objects. In *CHI '20: CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, April 25-30, 2020*. ACM, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376139

[18] Feng Han, Yifei Cheng, Megan Strachan, and Xiaojuan Ma. 2021. Hybrid Paper-Digital Interfaces: A Systematic Literature Review. In *DIS '21: Designing Interactive Systems Conference 2021, Virtual Event, USA, 28 June, July 2, 2021*. ACM, New York, NY, USA, 1087–1100. https://doi.org/10.1145/3461778.3462059

[19] Rorik Henrikson, Bruno Rodrigues De Araújo, Fanny Chevalier, Karan Singh, and Ravin Balakrishnan. 2016. Multi-Device Storyboards for Cinematic Narratives in VR. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology, UIST 2016, Tokyo, Japan, October 16-19, 2016*. ACM, New York, NY, USA, 787–796. https://doi.org/10.1145/2984511.2984539

[20] Juan David Hincapié-Ramos, Sophie Roscher, Wolfgang Büschel, Ulrike Kister, Raimund Dachselt, and Pourang Irani. 2014. CAR: Contact Augmented Reality with Transparent-Display Mobile Devices. In *Proceedings of The International Symposium on Pervasive Displays* (Copenhagen, Denmark) *(PerDis '14)*. Association for Computing Machinery, New York, NY, USA, 80–85. https://doi.org/10.1145/2611009.2611014

[21] David Holman, Roel Vertegaal, Mark Altosaar, Nikolaus F. Troje, and Derek Johns. 2005. Paper windows: interaction techniques for digital paper. In *Proceedings of the 2005 Conference on Human Factors in Computing Systems, CHI 2005, Portland, Oregon, USA, April 2-7, 2005*. ACM, New York, NY, USA, 591–599. https://doi.org/10.1145/1054972.1055054

[22] Eva Hornecker and Thomas Psik. 2005. Using ARToolKit Markers to Build Tangible Prototypes and Simulate Other Technologies. In *Human-Computer Interaction - INTERACT 2005, IFIP TC13 International Conference, Rome, Italy, September 12-16, 2005, Proceedings (Lecture Notes in Computer Science, Vol. 3585)*. Springer, Berlin, Heidelberg, 30–42. https://doi.org/10.1007/11555261_6

[23] María-Blanca Ibáñez and Carlos Delgado-Kloos. 2018. Augmented reality for STEM learning: A systematic review. *Computers & Education* 123 (2018), 109–123. https://doi.org/10.1016/j.compedu.2018.05.002

[24] Annie Kelly, R. Benjamin Shapiro, Jonathan de Halleux, and Thomas Ball. 2018. ARcadia: A Rapid Prototyping Platform for Real-time Tangible Interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, CHI 2018, Montreal, QC, Canada, April 21-26, 2018*. ACM, New York, NY, USA, 409. https://doi.org/10.1145/3173574.3173983

[25] Konstantin Klamka and Raimund Dachselt. 2017. IllumiPaper: Illuminated Interactive Paper. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, Denver, CO, USA, May 06-11, 2017*. ACM, New York, NY, USA, 5605–5618. https://doi.org/10.1145/3025453.3025525

[26] Balasaravanan Thoravi Kumaravel, Fraser Anderson, George W. Fitzmaurice, Bjoern Hartmann, and Tovi Grossman. 2019. Loki: Facilitating Remote Instruction of Physical Tasks Using Bi-Directional Mixed-Reality Telepresence. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology, UIST 2019, New Orleans, LA, USA, October 20-23, 2019*. ACM, New York, NY, USA, 161–174. https://doi.org/10.1145/3332165.3347872

[27] Balasaravanan Thoravi Kumaravel, Cuong Nguyen, Stephen DiVerdi, and Bjoern Hartmann. 2020. TransceiVR: Bridging Asymmetrical Communication Between VR Users and External Collaborators. In *UIST '20: The 33rd Annual ACM Symposium on User Interface Software and Technology, Virtual Event, USA, October 20-23, 2020*. ACM, New York, NY, USA, 182–195. https://doi.org/10.1145/3379337.3415827

[28] Susan Lechelt, Frederik Brudy, Nicolai Marquardt, and Yvonne Rogers. 2021. EvalMe: Exploring the Value of New Technologies for In Situ Evaluation of Learning Experiences. In *CHI '21: CHI Conference on Human Factors in Computing Systems, Virtual Event / Yokohama, Japan, May 8-13, 2021*. ACM, New York, NY, USA, 59:1–59:14. https://doi.org/10.1145/3411764.3445749

[29] David Ledo, Steven Houben, Jo Vermeulen, Nicolai Marquardt, Lora Oehlberg, and Saul Greenberg. 2018. Evaluation Strategies for HCI Toolkit Research. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, CHI 2018, Montreal, QC, Canada, April 21-26, 2018*. ACM, New York, NY, USA, 36. https://doi.org/10.1145/3173574.3173610

[30] Gun A. Lee, Claudia Nelles, Mark Billinghurst, and Gerard Jounghyun Kim. 2004. Immersive Authoring of Tangible Augmented Reality Applications. In *3rd IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR 2004), 2-5 November 2004, Arlington, VA, USA*. IEEE Computer Society, New York, NY, USA, 172–181. https://doi.org/10.1109/ISMAR.2004.34

[31] Germán Leiva and Michel Beaudouin-Lafon. 2018. Montage: A Video Prototyping System to Reduce Re-Shooting and Increase Re-Usability. In *The 31st Annual ACM Symposium on User Interface Software and Technology, UIST 2018, Berlin, Germany, October 14-17, 2018*. ACM, New York, NY, USA, 675–682. https://doi.org/10.1145/3242587.3242613

[32] Germán Leiva, Cuong Nguyen, Rubaiat Habib Kazi, and Paul Asente. 2020. Pronto: Rapid Augmented Reality Video Prototyping Using Sketches and Enaction. In *CHI '20: CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, April 25-30, 2020*. ACM, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376160

[33] Zhen Li, Michelle Annett, Ken Hinckley, Karan Singh, and Daniel Wigdor. 2019. HoloDoc: Enabling Mixed Reality Workspaces that Harness Physical and Digital Content. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, CHI 2019, Glasgow, Scotland, UK, May 04-09, 2019*. ACM, New York, NY, USA, 687. https://doi.org/10.1145/3290605.3300917

[34] Chunyuan Liao, François Guimbretière, and Ken Hinckley. 2005. PapierCraft: a command system for interactive paper. In *Proceedings of the 18th Annual ACM Symposium on User Interface Software and Technology, Seattle, WA, USA, October 23-26, 2005*. ACM, New York, NY, USA, 241–244. https://doi.org/10.1145/1095034.1095074

[35] Roman Lissermann, Simon Olberding, Benjamin Petry, Max Mühlhäuser, and Jürgen Steimle. 2012. PaperVideo: interacting with videos on multiple paper-like displays. In *Proceedings of the 20th ACM Multimedia Conference, MM '12, Nara, Japan, October 29 - November 02, 2012*. ACM, New York, NY, USA, 129–138. https://doi.org/10.1145/2393347.2393372

[36] Blair MacIntyre, Maribeth Gandy, Steven Dow, and Jay David Bolter. 2004. DART: a toolkit for rapid design exploration of augmented reality experiences. In *Proceedings of the 17th Annual ACM Symposium on User Interface Software and Technology, Santa Fe, NM, USA, October 24-27, 2004*. ACM, New York, NY, USA, 197–206. https://doi.org/10.1145/1029632.1029669

[37] W. Mackay and D. Pagani. 1994. Video Mosaic: Laying out Time in a Physical Space. In *Proceedings of the Second ACM International Conference on Multimedia* (San Francisco, California, USA) *(MULTIMEDIA '94)*. Association for Computing Machinery, New York, NY, USA, 165–172. https://doi.org/10.1145/192593.192646

[38] Wendy E. Mackay, Guillaume Pothier, Catherine Letondal, Kaare Bøegh, and Hans Erik Sørensen. 2002. The missing link: augmenting biology laboratory notebooks. In *Proceedings of the 15th Annual ACM Symposium on User Interface Software and Technology, Paris, France, October 27-30, 2002*. ACM, New York, NY, USA, 41–50. https://doi.org/10.1145/571985.571992

[39] Paul Marshall. 2007. Do tangible interfaces enhance learning?. In *Proceedings of the 1st International Conference on Tangible and Embedded Interaction 2007, Baton Rouge, Louisiana, USA, February 15-17, 2007*. ACM, New York, NY, USA, 163–170. https://doi.org/10.1145/1226969.1227004

[40] Jorge Martín-Gutiérrez, Peña Fabiani, Wanda Benesova, María Dolores Meneses, and Carlos E. Mora. 2015. Augmented reality to promote collaborative and autonomous learning in higher education. *Computers in Human Behavior* 51 (2015), 752–761. https://doi.org/10.1016/j.chb.2014.11.093 Computing for Human Learning, Behaviour and Collaboration in the Social and Mobile Networks Era.

[41] Paul Milgram and Fumio Kishino. 1994. A Taxonomy of Mixed Reality Visual Displays. *IEICE Transactions on Information and Systems* 77 (1994), 1321–1329.

[42] Meredith Ringel Morris, Andreea Danielescu, Steven Mark Drucker, Danyel Fisher, Bongshin Lee, m. c. schraefel, and Jacob O. Wobbrock. 2014. Reducing legacy bias in gesture elicitation studies. *Interactions* 21, 3 (2014), 40–45. https://doi.org/10.1145/2591689

[43] Michael Nebeling, Katy Lewis, Yu-Cheng Chang, Lihan Zhu, Michelle Chung, Piaoyang Wang, and Janet Nebeling. 2020. XRDirector: A Role-Based Collaborative Immersive Authoring System. In *CHI '20: CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, April 25-30, 2020*. ACM, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376637

[44] Michael Nebeling and Katy Madier. 2019. 360proto: Making Interactive Virtual Reality & Augmented Reality Prototypes from Paper. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, CHI 2019, Glasgow, Scotland, UK, May 04-09, 2019*. ACM, New York, NY, USA, 596. https://doi.org/10.1145/3290605.3300826

[45] Michael Nebeling, Janet Nebeling, Ao Yu, and Rob Rumble. 2018. ProtoAR: Rapid Physical-Digital Prototyping of Mobile Augmented Reality Applications. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, CHI 2018, Montreal, QC, Canada, April 21-26, 2018*. ACM, New York, NY, USA, 353. https://doi.org/10.1145/3173574.3173927

[46] Michael Nebeling, Shwetha Rajaram, Liwei Wu, Yifei Cheng, and Jaylin Herskovitz. 2021. XRStudio: A Virtual Production and Live Streaming System for Immersive Instructional Experiences. In *CHI '21: CHI Conference on Human Factors in Computing Systems, Virtual Event / Yokohama, Japan, May 8-13, 2021*. ACM, New York, NY, USA, 107:1–107:12. https://doi.org/10.1145/3411764.3445323

[47] Michael Nebeling and Maximilian Speicher. 2018. The Trouble with Augmented Reality/Virtual Reality Authoring Tools. In *IEEE International Symposium on Mixed and Augmented Reality, ISMAR 2018 Adjunct, Munich, Germany, October 16-20, 2018*. IEEE, New York, NY, USA, 333–337. https://doi.org/10.1109/ISMAR-Adjunct.2018.00098

[48] Jie Qi and Leah Buechley. 2014. Sketching in circuits: designing and building electronics on paper. In *CHI Conference on Human Factors in Computing Systems, CHI'14, Toronto, ON, Canada - April 26 - May 01, 2014*. ACM, New York, NY, USA, 1713–1722. https://doi.org/10.1145/2556288.2557391

[49] Jaziar Radianti, Tim A. Majchrzak, Jennifer Fromm, and Isabell Wohlgenannt. 2020. A systematic review of immersive virtual reality applications for higher education: Design elements, lessons learned, and research agenda. *Computers & Education* 147 (2020), 103778. https://doi.org/10.1016/j.compedu.2019.103778

[50] Iulian Radu. 2014. Augmented reality in education: a meta-review and cross-media analysis. *Pers. Ubiquitous Comput.* 18, 6 (2014), 1533–1543. https://doi.org/10.1007/s00779-013-0747-y

[51] Iulian Radu and Bertrand Schneider. 2019. What Can We Learn from Augmented Reality (AR)?. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, CHI 2019, Glasgow, Scotland, UK, May 04-09, 2019*. ACM, New York, NY, USA, 544. https://doi.org/10.1145/3290605.3300774

[52] Raf Ramakers, Kashyap Todi, and Kris Luyten. 2015. PaperPulse: An Integrated Approach for Embedding Electronics in Paper Designs. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, CHI 2015, Seoul, Republic of Korea, April 18-23, 2015*. ACM, New York, NY, USA, 2457–2466. https://doi.org/10.1145/2702123.2702487

[53] Joan Sol Roo and Martin Hachet. 2017. One Reality: Augmenting How the Physical World is Experienced by combining Multiple Mixed Reality Modalities. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology, UIST 2017, Quebec City, QC, Canada, October 22 - 25, 2017*. ACM, New York, NY, USA, 787–795. https://doi.org/10.1145/3126594.3126638

[54] Abigail J. Sellen and Richard H. R. Harper. 2003. *The Myth of the Paperless Office*. MIT Press, Massachusetts.

[55] Hyunyoung Song, Tovi Grossman, George W. Fitzmaurice, François Guimbretière, Azam Khan, Ramtin Attar, and Gordon Kurtenbach. 2009. PenLight: combining a mobile projector and a digital pen for dynamic visual overlay. In *Proceedings of the 27th International Conference on Human Factors in Computing Systems, CHI 2009, Boston, MA, USA, April 4-9, 2009*. ACM, New York, NY, USA, 143–152. https://doi.org/10.1145/1518701.1518726

[56] Hyunyoung Song, François Guimbretière, Tovi Grossman, and George W. Fitzmaurice. 2010. MouseLight: bimanual interactions on digital paper using a pen and a spatially-aware mobile projector. In *Proceedings of the 28th International Conference on Human Factors in Computing Systems, CHI 2010, Atlanta, Georgia, USA, April 10-15, 2010*. ACM, New York, NY, USA, 2451–2460. https://doi.org/10.1145/1753326.1753697

[57] Hyunyoung Song, François Guimbretière, Chang Hu, and Hod Lipson. 2006. ModelCraft: capturing freehand annotations and edits on physical 3D models. In *Proceedings of the 19th Annual ACM Symposium on User Interface Software and Technology, Montreux, Switzerland, October 15-18, 2006*. ACM, New York, NY, USA, 13–22. https://doi.org/10.1145/1166253.1166258

[58] Maximilian Speicher, Brian D. Hall, and Michael Nebeling. 2019. What is Mixed Reality?. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, CHI 2019, Glasgow, Scotland, UK, May 04-09, 2019*. ACM, New York, NY, USA, 537. https://doi.org/10.1145/3290605.3300767

[59] Maximilian Speicher, Katy Lewis, and Michael Nebeling. 2021. Designers, the Stage Is Yours! Medium-Fidelity Prototyping of Augmented & Virtual Reality Interfaces with 360theater. *Proceedings of the ACM on Human-Computer Interaction* 5, EICS (2021), 1–25.

[60] Hariharan Subramonyam, Steven Mark Drucker, and Eytan Adar. 2019. Affinity Lens: Data-Assisted Affinity Diagramming with Augmented Reality. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, CHI 2019, Glasgow, Scotland, UK, May 04-09, 2019*. ACM, New York, NY, USA, 398. https://doi.org/10.1145/3290605.3300628

[61] Ryo Suzuki, Rubaiat Habib Kazi, Li-Yi Wei, Stephen DiVerdi, Wilmot Li, and Daniel Leithinger. 2020. RealitySketch: Embedding Responsive Graphics and Visualizations in AR through Dynamic Sketching. In *UIST '20: The 33rd Annual ACM Symposium on User Interface Software and Technology, Virtual Event, USA, October 20-23, 2020*. ACM, New York, NY, USA, 166–181. https://doi.org/10.1145/3379337.3415892

[62] Theophanis Tsandilas, Catherine Letondal, and Wendy E. Mackay. 2009. Mus*ink*: composing music through augmented drawing. In *Proceedings of the 27th International Conference on Human Factors in Computing Systems, CHI 2009, Boston, MA, USA, April 4-9, 2009*. ACM, New York, NY, USA, 819–828. https://doi.org/10.1145/1518701.1518827

[63] Ana M. Villanueva, Zhengzhe Zhu, Ziyi Liu, Kylie Peppler, Thomas Redick, and Karthik Ramani. 2020. Meta-AR-App: An Authoring Platform for Collaborative Augmented Reality in STEM Classrooms. In *CHI '20: CHI Conference on Human Factors in Computing Systems, Honolulu, HI, USA, April 25-30, 2020*. ACM, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376146

[64] Nadir Weibel, Adriana Ispas, Beat Signer, and Moira C. Norrie. 2008. Paperproof: a paper-digital proof-editing system. In *Extended Abstracts Proceedings of the 2008 Conference on Human Factors in Computing Systems, CHI 2008, Florence, Italy, April 5-10, 2008*. ACM, New York, NY, USA, 2349–2354. https://doi.org/10.1145/1358628.1358682

[65] Pierre Wellner. 1991. The DigitalDesk calculator: tangible manipulation on a desk top display. In *Proceedings of the 4th Annual ACM Symposium on User Interface Software and Technology, UIST 1991, Hilton Head, South Carolina, USA, November 11-13, 1991*. ACM, New York, NY, USA, 27–33. https://doi.org/10.1145/120782.120785

[66] Richard White and Richard Gunstone. 1992. *Probing Understanding*. Routledge, London, 208. https://doi.org/10.4324/9780203761342

[67] Jacob O. Wobbrock, Meredith Ringel Morris, and Andrew D. Wilson. 2009. User-defined gestures for surface computing. In *Proceedings of the 27th International Conference on Human Factors in Computing Systems, CHI 2009, Boston, MA, USA, April 4-9, 2009*. ACM, New York, NY, USA, 1083–1092. https://doi.org/10.1145/1518701.1518866

[68] Haijun Xia, Sebastian Herscher, Ken Perlin, and Daniel Wigdor. 2018. Spacetime: Enabling Fluid Individual and Collaborative Editing in Virtual Reality. In *The 31st Annual ACM Symposium on User Interface Software and Technology, UIST 2018, Berlin, Germany, October 14-17, 2018*. ACM, New York, NY, USA, 853–866. https://doi.org/10.1145/3242587.3242597