Towards Immersive Visualization for Large Lectures: Opportunities, Challenges, and Possible Solutions

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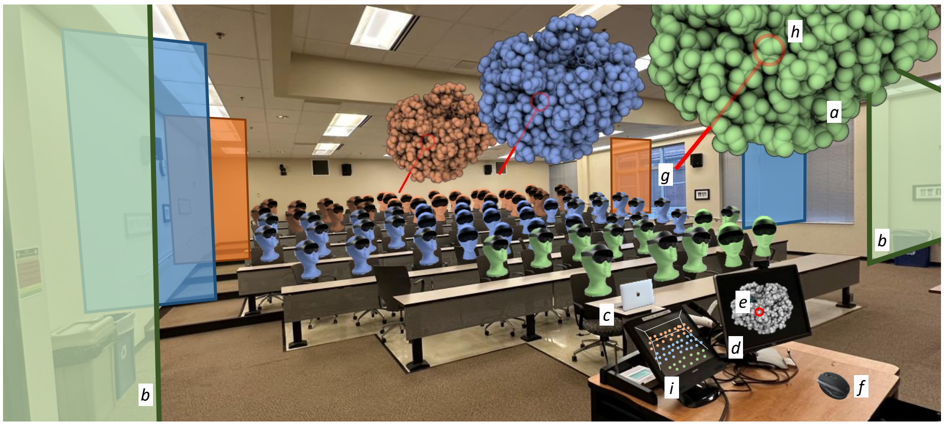

Figure 1: *Immersive Visualization for Large Lectures (IVLL) concept. The class of 80 students visualizes a 3D molecule model with the help of mixed-reality (MR) headsets. The classroom is partitioned by rows into three groups of students (green, blue, and orange). Each group has its own 3D visualization (e.g., a for the green group), as well as two additional virtual 2D displays, e.g., for textual information or 2D diagrams (b). A student in a group only sees the 3D and 2D visualizations intended for their group. The see-through MR headset lets students see important elements of the real world, such as their laptop (c), the instructor, and other students. The instructor sees the visualization on the classroom computer display (d) and points to it (e) using a mouse (f). The instructor pointing is replicated in 3D with a virtual laser pointer for each group (g for the green group). The instructor and the students see the 3D dataset from the same side, so the students see the instructor's pointing location (h, hidden from the viewpoint of this illustration). The instructor can also control the partitioning of the class (i), with great flexibility, from one student per group to one group per class. (Molecule © www.acellera.com/mmsml-workshop-2022/)*

Abstract

In this position paper, we discuss deploying immersive visualization in large lectures (IVLL). We take the position that IVLL has great potential to benefit students and that, thanks to the current advances in computer hardware and software, IVLL implementation is now possible. We argue that IVLL is best done using mixed reality (MR) headsets, which, compared to virtual reality (VR) headsets, have the advantages of allowing students to see important elements of the real world and avoiding cybersickness. We argue that immersive visualization can be beneficial at any point on the student engagement continuum. We argue that immersive visualization allows reconfiguring large lectures dynamically, partitioning the class with great flexibility in groups of students of various sizes, or accommodating 3D visualizations of monumental size. We inventory the challenges that have to be overcome to implement IVLL, and we argue that they currently have acceptable solutions, opening the door to developing a first IVLL system.

CCS Concepts

• ***Applied computing*** $\rightarrow$ ***Interactive learning environments; Collaborative learning;***

1. Introduction

This is a position paper that discusses a potential implementation of an immersive visualization in large lectures (IVLL). Computing technology and applications of computer graphics have been used in education for decades, as noted in reviews and surveys [MZR*20, BWF*17, BWF18]. However, recent advances in

DOI: 10.2312/eged.20231017

the widespread accessibility of modern technologies, such as virtual [NWL*21] and augmented [GPB19] reality, hold great promise for advancing education even further. Technology allows for the distribution of digital learning materials at a low cost to learners. Technology also allows personalizing education for individual learners by taking into account each learner's characteristics, as well as their progression over time. Moreover, technology powers eloquent visualizations of data and processes studied, supporting insight forming, deep understanding, and creativity [MYG*13]. Visualization has long been seen as an essential tool in education [DPL21], from lines drawn in the sand by the mathematics teachers of Antiquity to graphing calculators used by middle school students and to visualizations of complex particle system simulations in support of research aimed at harnessing nuclear fusion as a safe source of energy. Moreover, visualizations combined with user interactions and physics-based simulations have shown progress in teaching difficult concepts in physics [WWM*21, YWM*19, NMN*18, WMQ*18], but also abstract mathematical concepts, such as transformations [FMF*18].

Nowadays, most visualizations are presented to the user on a 2D display, such as a computer monitor, a projection screen, or, evermore often, on a cell phone screen. However, no matter the resolution and brightness of these displays and the rendering power of the graphics processors driving them, visualization on 2D displays suffers from fundamental limitations [EBDC*19]. One is that 2D displays are limited to monoscopic visualization, without disparity between the left and right eye images, depriving the viewer of depth cues, which are an important aid for parsing and understanding complex 3D visualizations. Another limitation is that the display surface area is small, and navigating the view direction and viewpoint to map the display surface to different parts of the dataset requires manipulating complex interfaces and bookkeeping to be able to find and revisit desired focus points. Furthermore, the small display is not easily shared by multiple learners, precluding direct collaboration. Mobile devices often use directional filters, making them suitable only for one person.

These limitations of visualization on 2D displays are alleviated in immersive visualization, where the user wears a head-mounted display (HMD) that allows them to examine the dataset from within. The HMD presents the user with different images for the left and right eyes, computed by taking into account the user's interpupillary distance, which allows the user to perceive depth. HMDs replace the physical screen with virtual screens anchored to the virtual world, thereby significantly increasing the number and size of display surfaces. For example, the user could be surrounded by a 3m tall 360° cylindrical display with a 1m radius. The user browses the large virtual display with natural motions such as rotating their head or body. Moreover, multiple users can collaborate by being placed in the same virtual environment with a large virtual display.

Researchers have been developing systems that support immersive visualization through HMDs for over fifty years. Whereas such systems were initially expensive, bulky, and with low resolution, limited field of view, low brightness, and limited rendering capabilities, recent HMDs are compact. While there are differences in their refresh rate and display resolution, they offer good performance at price points that no longer impede the mass deployment of immersive visualization in education. For example, the Quest 2 is a $400 (as of February 2023) all-in-one VR system with inside-looking-out tracking. The headset is not just a terminal that displays images but rather a computer that renders images and tracks the user and their hands with six degrees of freedom without the help of an external tracker. Seizing the opportunity presented by the leap-forward advances in VR technology, education and technology researchers are working on integrating immersive visualization into education [KLRWP17]. Most efforts focus on laboratory settings, where VR can provide authentic laboratory educational experiences without the expense, the usage contention, and the potential danger that can be associated with physical laboratory equipment [HdMVGMM19].

Little research effort has been devoted to bringing the benefits of immersive visualization to large lectures. The availability of quality online educational content has not made traditional lectures obsolete, and the availability of robust video teleconferencing systems has not made University campuses obsolete. Learners continue to seek and value the delivery of educational material by instructors with the aid of visualizations, which reduces the effort of knowledge acquisition. Learners continue to seek and value the motivational support and the *esprit de corps* forming of conventional on-campus education. These factors, coupled with the exploding popularity of majors such as computer and data science, large lectures are here to stay, and immersive visualization could be a tool for improving their educational effectiveness.

In this position paper, we discuss the opportunities, challenges, and possible solutions for bringing immersive visualization into large, on-campus lectures. We take the position that *immersive visualization in large lectures* (IVLL, see Fig. 1) has important potential benefits and that concretizing these benefits is now possible. Specifically, we discuss the type of immersive visualization best suited for large lectures (Sec. 2), IVLL configurations in support of various levels of student engagement (Sec. 3), support for the dynamic reconfiguration of large lectures (Sec. 4), and IVLL implementation (Sec. 5).

2. Virtual versus Mixed Reality

We define immersive visualization as a type of visualization where the computer-rendered imagery surrounds the user, *and* where users can select the desired view naturally by moving their head, *and* where the images perceived by the user's left and right eyes have the appropriate disparity, based on the user's interpupillary distance and the distance to the entities visualized [FO15].

One type of immersive visualization is virtual reality (VR), where the entire field of view of the user is covered with synthetic imagery. In other words, the user does not see the real world anymore; instead, they only see a rendering of a virtual environment (VE). VR has the advantage of conveying to the user a strong sense of presence in the VE. The user loses all visual contact with the real world, which conveys a strong illusion of being transported into the virtual world. The VR interface's ability to convey a strong sense of presence has great potential in education. It can make the visualization believable, memorable, intriguing, and striking, qualities that can spark and sustain the learner's curiosity, focus, inquisitiveness, and motivation. However, VR has important fundamental limitations.

One limitation [GP18] is that the user does not see elements of the real world that are important for the task at hand. In the context of education, the learner would benefit from seeing the instructor and other learners, as well as, for example, their laptop, to take notes. Showing the other learning activity participants in VR can be done using avatars, i.e., computer animation characters that serve as placeholders for the instructor and students. One challenge with avatars is that the advantage of familiarity with the real-world appearance of the instructor and the other students is lost. It has to be rebuilt by learning which avatar belongs to whom, possibly with name tags floating above each avatar. Another challenge is that a VR headset tracks only the user's head pose, and many other degrees of freedom of a human-like avatar have to be inferred using heuristics and inverse kinematics.

Another limitation is cybersickness, which is believed to be triggered by discrepancies between the images and the accelerations users perceive as they move through the VE [WKBC19]. One issue is motion-to-photon latency–whereas the accelerations triggered by physical motion are perceived with little delay, the VR pipeline has to track the change in pose, render the VE for each eye for the new pose, and update the two displays. Another issue is that natural locomotion through the VE by walking is not always possible, because the VE is typically larger than the physical space hosting the VR application, and because walking is a natural but not an ergonomic interface. Because of this, the one-to-one mapping between the user's motion in the real and virtual world has to be temporarily suspended to "teleport" (i.e., fly, reposition) the user to a new location in the VE, without a matching user motion in the real world.

A second type of immersive visualization is mixed reality (MR), where the synthetic imagery is integrated into the user's view of the real world. The user still sees some parts of the real world in real-time, and the synthetic imagery is anchored to the real world. In other words, the synthetic imagery appears fixed in the real world as the user moves their head. MR avoids many of the shortcomings of VR. With MR, the user can see the parts of the real world that are important, such as their own laptop, their own hands, the instructor, or the other students. Furthermore, seeing the real world greatly reduces the risk of cybersickness, as the visualization of the real world changes as the user expects it in response of the user's head motions. However, delivering an MR immersive visualization is technologically challenging.

First, the user has to see not just the rendered imagery, but also the real world. One approach is to let the user see the real world directly, through a transparent screen in front of their eyes, and to integrate the rendered imagery into the field of view of the user by reflection off the transparent screen, like a helicopter helmet heads-up-display (HUD) that lets the pilot see important elements of the cockpit dashboard without having to look down. An example of such an optical see-through mixed reality headset is Microsoft's HoloLens 2 [Mic23]. Optical see-through headsets have shortcomings such as a small field of view and a lack of true opacity, i.e., a dark rendered image will not be visible over a bright real-world background [LSG*03]. For example, the HoloLens 2 has a field of view of $43^\circ \times 29^\circ$, so the user has to examine the virtual world through a small rectangle at the center of their visual field, which they have to rotate to align it with regions of interest, whose location could be unknown.

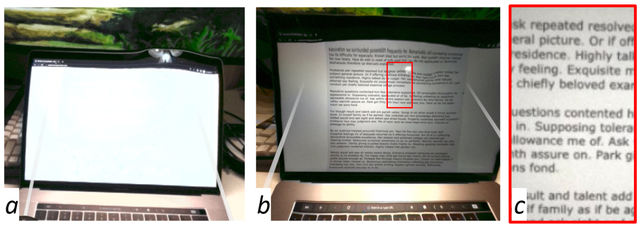

Figure 2: *Images shown to a user who wears a Quest Pro MR headset and looks at a laptop screen. The images can suffer of incorrect exposure (laptop screen in a) and of distortion due to incorrect depth estimation (top laptop screen edge in a and b). A correctly exposed image captured from close range, i.e., 20cm, is sufficient for text readability (b and magnified fragment c).*

Another approach to let the user see the real world is to capture it with back-facing video cameras mounted on the front of the headset and to display the video feeds in real-time on the conventional LED or LCD displays of a VR headset. An example of such a see-through video headset is Meta's recently released Quest Pro [MP23a]. Such video see-through MR headsets have the advantage of a lager field of view and true opacity. An important shortcoming is that the user does not see the real world directly with their own eyes, but rather through a video feed, which could bring back the cybersickness concern due to latency. Furthermore, see-through video headsets suffer from insufficient resolution, which is capped by the camera and display resolutions, from insufficient dynamic range, which can only adapt to either the bright or the dark parts of a scene, and from the offset between the back-facing video cameras used to acquire the real world, and the user left and right eyes from which the real world has to be visualized. Fig. 2 illustrates these challenges. The laptop screen that is brighter than the background is completely overexposed (a). When the user moves their head close to the laptop to not see the background, the exposure of the headset cameras adapts to the bright screen, making it readable (b), as shown in the magnified fragment (c). In order to compensate for the offset between the acquisition and the visualization viewpoints, the headset software reprojects the video frames to the viewpoints of the user's eyes. However, correct reprojection requires accurate depth, i.e., scene geometry. Any depth acquisition error results in a distortion of the reprojected frames; see the top of the laptop screen (a and b).

Second, tracking has to be more accurate. Consider a virtual world whose cardinal points are initially aligned with those of the real world. As the user moves through the VE, small tracking errors compound, and after a while, the real and virtual worlds become misaligned. However, this is of no concern since VR makes complete abstraction of the real world, and this misalignment does not hinder the VR application. The tracking has to be just accurate enough to power a natural user interface where view selection is

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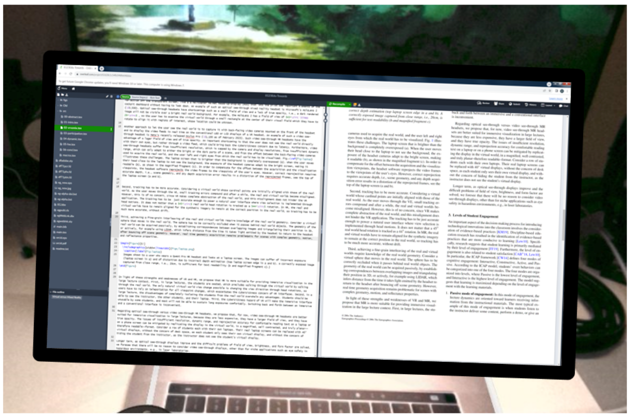

Figure 3: *The low-resolution, overexposed, and distorted image of the laptop screen from Fig. 2a is replaced with a rendering of a Virtual laptop screen that is easier to read.*

implemented through head motions. It does not matter that a 45° real-world head rotation is tracked as a 44° rotation. In MR, the real and virtual worlds have to remain aligned for the synthetic imagery to remain at the correct position in the real world, so tracking has to be much more accurate, without drift.

Third, achieving a fine-grain interleaving of the real and virtual worlds requires knowledge of real-world geometry. Consider a virtual sphere that moves in the real world. The sphere has to be correctly occluded when it passes behind real-world objects. The geometry of the real world can be acquired passively, by establishing correspondences between overlapping images and triangulating their position in 3D or actively, for example, using depth cameras or LIDAR, which infers distance from the time it takes light emitted by the headset to return to the headset after bouncing off scene geometry. However, real-time geometry acquisition remains problematic for scenes with complex geometry, motion, and reflectance properties.

In light of these strengths and weaknesses of VR and MR, we propose that MR is more suitable for providing immersive visualization in a large lecture context. First, the students are seated in large lectures, which preclude walking through the virtual world by walking through the real world. The only natural virtual world view change possible is changing the view direction through head rotations, so users have to rely on teleportation for all viewpoint changes, which exacerbates the cybersickness concern of VR interfaces. Second, in a large lecture, the disadvantages of completely isolating the students from the real world overwhelm any advantages. Students should be able to see the instructor, the other students, and their laptops. Third, the cybersickness hazard of VR will make the immersive interface unusable by some students, and most will not be able to sustain long exposures comfortably. Switching back and forth between an immersive and a conventional interface is inconvenient.

Regarding optical see-through versus video see-through MR headsets, we propose that, for now, video see-through MR headsets are better suited for immersive visualization in large lectures because they are less expensive, have a larger field of view, and have true opacity. The issues of insufficient resolution, dynamic range, and reprojection accuracy for comfortable reading text on a laptop or a phone screen can be mitigated by replicating the display in the virtual world in a magnified, well-contrasted, and truly planar–therefore readable–format (Fig. 3). Consider a row of students, each with their own laptops. Their real laptop screens can be replaced with larger virtual displays without the concern of desk space, as each student only sees their own virtual display, and without the concern of hiding the student from the instructor, as the instructor does not see the student's virtual display.

Longer term, as optical see-through displays improve and the difficult problems of the field of view, brightness, and form factor are solved, we foresee that there will be no reason to consider see-through video displays other than for niche applications such as eye safety in hazardous environments, e.g., in laser laboratories.

3. Levels of Student Engagement

An important aspect of the decision-making process for introducing technological innovations into the classroom involves the consideration of evidence-based practices [KM19]. Discipline-based education research has resulted in the identification of evidence-based practices that are more conducive to learning [Lew10]. Specifically, research suggests that student learning is primarily mediated by their level of engagement [FF19]. Furthermore, the level of engagement is also related to student satisfaction [CAB*18, Lew10]. In particular, the ICAP framework [CW14] defines four modes of cognitive engagement: Passive, Active, Constructive, and Interactive. According to the ICAP model, students' overt behaviors can be categorized into one of the four modes. The four modes are organized into levels, where Passive is the lowest level of engagement, and Interactive is the highest level of engagement. The model suggests that learning is maximized depending on the level of engagement with the learning materials.

Passive mode of engagement. In this mode of engagement, the lecture dynamics are oriented toward learners receiving information from the instructional materials. The most typical example of this mode of engagement is when students listen to the instructor deliver some content, perform a demo, or give an explanation. As a response to this form of instruction, students would be paying attention. Compared to laboratory settings or small lectures, large lectures rely significantly on this mode of engagement, and immersive visualization holds the promise for the instructor to grab and maintain the students' attention and to convey information more eloquently and poignantly, through large size displays, depth perception, and immersion into the dataset. Whereas conventional visualization can only give students a good view of a demonstration carried out by someone else, IVLL gives students the sense they participate in the demonstration. With IVLL, students do not just see the videos of someone else's field trip, they feel part of the field trip. Students do not just see a video recording of an experiment carried out in a distant lab, they feel present in the lab.

Active mode of engagement. This mode of engagement involves some specific action or manipulation of the learning materials. For instance, in the same scenario provided of the instructor delivering a lecture, students, instead of just paying attention to the information provided to them, would undertake a specific action such as taking notes, underlining text in a handout, pointing, gesturing, or rotating artifacts. An example of how IVLL can facilitate this mode of engagement is by allowing students to manipulate their own copy of a 3D visualization. For example, while explaining complex and abstract concepts during lecture time, instructors can show an example of a molecule. Student engagement would involve rotating the molecule to notice the bonds in the molecule, zooming in to further explore characteristics of the elements, changing some colors within the visualization to highlight features of the molecule, or deconstruct the molecule by moving its parts centrifugally to obtain an "exploded" visualization.

Constructive mode of engagement. This mode of engagement involves instances when students generate additional products, materials, or outputs beyond what is provided originally to them. These products, outputs, or materials should involve adding new ideas to existing ones. That is, the outcome should go beyond what is provided by the instructor. For instance, in the same scenario of an instructor delivering a lecture, evidence of constructive behavior could take the form of reflective notes, diagrams connecting ideas, self-explanations of content, and the creation of advanced organizers like tables and concept maps. Constructive behaviors involve a higher level of engagement than active behaviors. Continuing the computational molecular biology example, IVLL could allow students to spend five minutes in a lecture trying to find the molecule receptor sites whose geometry matches that of a ligand or of a drug molecule. Using their own 3D visualization of the components, students rotate and translate the components in search of a match, solving the geometric puzzle interactively, with the benefit of the depth cues and of the natural interface afforded by the immersive visualization.

Interactive mode of engagement. This mode of engagement includes learners being constructive and, at the same time, working with one another. This form of engagement in a lecture format requires instructional changes from the course instructor. The course instructor should elicit that students work with one another. For example, the instructor can pose a challenge for the students to solve, ask them to solve a problem or generate a plan for approaching a solution. Evidence of interactive behaviors would involve students working with peers having verbal discussions, equally exchanging ideas, and jointly contributing to generating a new product or output. Interactive behaviors involve a higher level of engagement than constructive behaviors. IVLL supports this form of instruction by placing a group of students in the same virtual space, where they see the same 3D visualization with which they can interact collaboratively. For example, students could work in groups–and not individually–to find the receptor site that matches a drug molecule. Engaging students interactively in a large lecture using immersive visualization could also be beneficial in the context of engineering design. For example, students can be asked to take five minutes to tune the height of the starting point of a roller coaster such that the coaster's velocity does not exceed a maximum value, while completing the course with hills and vertical loops. The immersive visualization can allow the group of students to ride their virtual roller coaster and to demonstrate their design to the class, possibly racing other groups in parallel.

Research has identified that teachers and instructors have experienced substantial difficulties designing, implementing, and eliciting interactive engagement [CAB*18]. We argue that immersive visualizations can support all these levels of student engagement. Furthermore, interactive and immersive visualizations can uniquely support interactive forms of engagement, especially in the context of a large lecture, overcoming the challenges of some large courses not having a laboratory component.

4. Dynamic Reconfiguration of Large Lectures

Immersive visualization allows for visualization anywhere in the 3D space surrounding the user, on virtual 2D and 3D displays of any size, without the enormous initial investment and subsequent maintenance costs of large physical displays. The ability to display anywhere presents three opportunities: (1) to customize the visualization for individual learners, (2) to customize the visualization based on the specifics of the dataset to be visualized, and (3) to partition the body of students dynamically into groups as required for each part of the lecture with its specific level of interaction.

Immersive visualization provides depth perception, which is more striking when the entities to be visualized are close to the student. As such, instead of showing the dataset "in front of the classroom" the same way for all students, the dataset can be presented in different locations for different subgroups of students. In Fig. 1, the dataset is shown in three different locations for each third of the class, which reduces the maximum distance from the dataset to a student, providing stronger depth cues. How far the dataset is from a student and how large the 3D display, i.e., the bounding box containing the visualization, are visualization parameters that can be easily changed. For example, each student could see their own visualization of the molecule from Fig. 1, in front of them, floating above their desk.

Whereas some datasets can be visualized effectively in a virtual fish tank in front of one or a few students, the visualization of some datasets has to convey their monumental scale. In Fig. 4, the innovative building of Dubai's Museum of the Future might be best appreciated by architecture students when rendered in a 20m format. For that, the immersive visualization can virtually retract the roof of the classroom to make room for the visualization. The virtual hole in the ceiling, complete with hole edge thickness and night sky visualization, accentuates the illusion that the building truly soars above the classroom.

Finally, institutions of higher education invest substantially to support active learning in special classrooms that allow collaboration in small groups of students [TMA19, HdMVGTM*19, THT*20]. Such special active learning classrooms require desks arranged in clusters to allow face-to-face discussion within the group, a replication of physical displays for each group to have access to their own display, as well as the ability to be reconfigurable to vary the group size or even to revert to a conventional lecture format. Meeting all these requirements is expensive, and typically the number of active learning classrooms is limited to one or two per campus. With each student wearing an MR headset and with a swivel chair, students can form and disband groups easily. In Fig. 5, groups of four students work together on a shared 2D virtual display, but

Figure 4: *Display surface extension using immersive visualization (concept). An MR headset can display anywhere around the user, even beyond the physical boundaries of the classroom. Here the MR visualization creates a virtual hole in the classroom ceiling to allow for the large format display of the 3D visualization of Dubai's Museum of the Future in an architecture lecture (Museum photo © Denys Gromov).*

they could just as easily jointly examine a 3D visualization that is located on the desk between them. Larger groups of six or eight students are also possible by extending the number of chairs on each side of the shared desk to three or four.

5. IVLL Implementation

Co-location. One IVLL implementation challenge is co-location, i.e., the alignment of the virtual worlds of all the students in a group such that they see the shared visualizations at the same location relative to the real world. Current MR headsets such as the Quest Pro track the user in an "inside-looking-out" fashion, i.e., without reliance on external trackers, using solely onboard cameras that observe the scene. The current frames are processed to search for salient scene features, the current scene features are matched to earlier features, and feature correspondences are used to infer the current position and orientation of the headset. Meta now supports the sharing of features among multiple devices operating simultaneously in the same physical environment, which allows placing multiple devices in the same coordinate system. Whereas co-location has been demonstrated for two or a small number of headsets, as needed, for example, in an MR ping-pong application, co-locating hundreds of headsets requires a bottom-up hierarchical approach that starts out by co-locating pairs of headsets, then groups of four and so on until all headsets are co-located.

Scene geometry. Another challenge is knowledge of the scene geometry. Knowing the geometry of the classroom at a high level, i.e., that of all fixed elements such as walls and fixed rows of desks

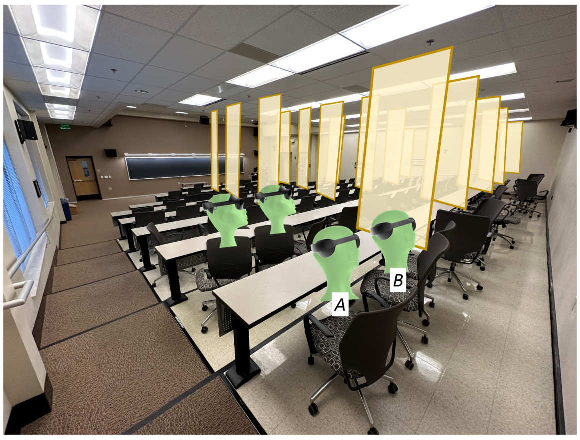

Figure 5: *Classroom partitioning using immersive visualization (concept). Here groups of four students are formed with two students of the lower row turning around to collaborate with two students from the row above. A single group is shown for illustration clarity. Each group has a shared virtual display, which each group member sees at the same location in the classroom. A group sees only its own display and not those of the other groups.*

is needed to be able to place the additional virtual displays. For example, in Figs. 1, 5, and 4, virtually retracting the ceiling and placing the displays on the sides of the classroom and the displays that divide the class into groups requires knowing where the ceiling, walls, and desks are. Such a high-level model of a classroom can be obtained based on the known geometry of repeated objects, e.g., desks, and based on manual modeling. Since the high-level model of the classroom doesn't change, it can be acquired as a preprocess and then reused.

For a fine-grain interleaving of the real and virtual worlds, one needs knowledge of the classroom geometry in real-time. For example, in Fig. 5, the virtual display shown to student A should be overdrawn by student B, for correct depth compositing. Similarly, if the group examines a 3D dataset visualized on the shared desk, a student's hand should occlude the 3D visualization. State-of-the-art MR headsets do acquire and update a proxy geometric model of the scene in real-time. Furthermore, MR headsets now track the user's hands to support a natural interface for direct manipulation of the dataset. Another piece of information that can be exploited is the knowledge of where the (tracked) student heads are, which allows defining conservative bounding boxes. Therefore, providing correct visibility sorting between virtual world elements and user hands and between user bounding boxes and background 2D displays is tractable.

Headset removal. A fundamental challenge in any collaborative VR, MR, and AR application that relies on headsets is rendering the participants without the headset that hides their faces and reduces communication and increases collaborative effectiveness. There are three options. One is not to attempt to remove the headset in order to stay clear of the uncanny valley that could trap an imperfect solution. A second is to replace a user with an avatar, i.e., a computer animation character that moves in sync with the user. A third option is to attempt to inpaint the headset, based on a video of the user without the headset from which appropriate source frames are selected based on tracking data, or based on a trained network similar to those used to generate deepfake videos [SLT*19, SWR*21]. Rendering the eye movement can be done based on eye tracking [FSK17], capabilities that some of the current [MP23a] and probably most of the future headsets will incorporate.

User interface design. An essential element of a successful deployment of immersive visualization in large lectures is the design of a user interface that allows the students to conveniently benefit of the advantages of immersive visualization. For passive immersive visualization, the headset grouping and visualization should be controlled by the instructor. Students should receive assistance to find the visualization in space, leveraging prior work on attention guidance [RBH19]. The user interface should also convey to each student the group that they are part of, for example, by placing a red sphere 5cm in diameter above the head of each student part of the group, which can be done leveraging the known position of the tracked student's heads.

Safety. The choice of the MR interface over the VR interface should minimize cybersickness concerns [WKBC19]. Nonetheless, current headsets still have a form factor that could lead to fatigue after extended use. The concern of inadvertent collisions with other students as well as objects in the real world is also greatly diminished by using the MR interface that shows most real-world objects, and by the fact that students are seated. However, virtual objects could hide real objects, and the real-world geometry changes should be monitored in real-time, and the system should revert to only real and no virtual-world visualization when danger is detected. For example, if a student places a coffee cup "inside" the (virtual) visualization of a dataset, the visualization should disappear and the object infringing upon the 3D display space should be highlighted for removal.

Networking requirements. In order to support large lectures with hundreds, possibly thousands, of students, the communication between headsets and between the system and the headsets should be kept at a minimum by pre-downloading the data onto the headsets to limit the communication to data needed to establish co-location and to commands issued by the instructor for configuring the classroom, for driving the visualization, and for advancing to the next visualization step or dataset.

Implementation cost. An important challenge is the cost associated with the headsets. At the time of this writing, a Meta Quest 2 costs $400 [MP23b] and a Meta Quest Pro costs $1,500 [MP23a] after both headsets were initially available for less, i.e., $200 and $1,100, respectively. If IVLL, in particular, and immersive visualization in education, in general, is successful, it is conceivable that students would cover the cost of acquiring their own headset, the same way all students now have a laptop, as required by their institution. Students owning the headset is a model preferable to the institution lending or renting the headsets because it avoids the semester start and ends overhead of checking out and returning headsets and because it incentivizes students to take better care of their headsets. It is also conceivable that this large-scale adoption of MR headsets will see their prices fall. The classroom does not require any permanently installed special hardware. An IVLL classroom does not even require the conventional computer, projectors, and screens. The instructor should be able to deliver the IVLL experience from their laptop.

Digital content creation. Some of the IVLL benefits, such as dynamically partitioning the class into student groups, each with its own virtual 2D display, are within reach of the current instructional materials. Fully realizing the IVLL promise requires creating content that takes advantage of the 3D and interactive aspects of the visualization. Computer simulations, depth cameras, online 3D models repositories such as TurboSquid and Unity Asset Store, and traditional modeling software tools such as Maya, 3ds Max, and Unity3D provide the raw material for the creation of effective 3D educational content. The assembly and curation of such content have to be a community-level effort involving researchers, educators, and the private sector.

6. Conclusions

We have discussed deploying immersive visualization in large lectures (IVLL). We have taken the position *that IVLL has great potential to benefit students* and that *IVLL implementation is possible*.

We have argued that delivering the immersive visualization experience to students is *best done using mixed reality* (MR) headsets, which, compared to virtual reality (VR) headsets, have the advantages of allowing students to see important elements of the real world such as the other students, the instructor, and their own laptop, and of significantly reducing the risk of cybersickness. Within MR technologies, we have argued that for now and for the immediate future, see-through video headsets have an advantage over optical see-through headsets for their larger fields of view and support of true opacity.

We have argued that immersive visualization can be *beneficial at any point on the student engagement continuum*, including for passive, active, constructive, and interactive engagement levels. We have argued that immersive visualization *allows reconfiguring large lectures dynamically*, to partition the class with great flexibility into groups of students of various sizes, or to make room to accommodate 3D visualizations at a monumental scale.

We have also inventoried the challenges that have to be overcome to implement IVLL, including the virtual co-location of a large number of students, the acquisition of scene geometry, the virtual headset removal to allow collaborators to see each other's faces for effective communication, the design of the user interface to allow the instructor to direct hundred-user immersive visualization collaborative sessions, the management of the network bandwidth requirements, the equipment cost, and the creation of digital content that takes advantage of IVLL. We have concluded that all of these *implementation challenges have acceptable solutions* and that developing a first IVLL system is a tractable–albeit complex– engineering endeavor. We hope that our paper inspires and guides funding agencies, administrators, researchers, and educators toward investing, implementing, and evaluating immersive visualization in large lectures.

7. Acknowledgments

This material is based upon work supported by the National Science Foundation under Grants No 2212200 and 2219842.

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