Immersive Learning Research Network

State of XR & Immersive Learning

Outlook Report 2021

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State of XR & Immersive Learning 2021 Outlook Report

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Please cite as: Lee, M. J. W., Georgieva, M., Alexander, B., Craig, E., & Richter, J. (2021). *State of XR & Immersive Learning Outlook Report 2021*. Walnut, CA: Immersive Learning Research Network.

ISBN: 978-1-7348995-1-1

Additional resources and materials related to the State of XR & Immersive Learning project are available on our website:
https://www.immersivelrn.org/stateofxr

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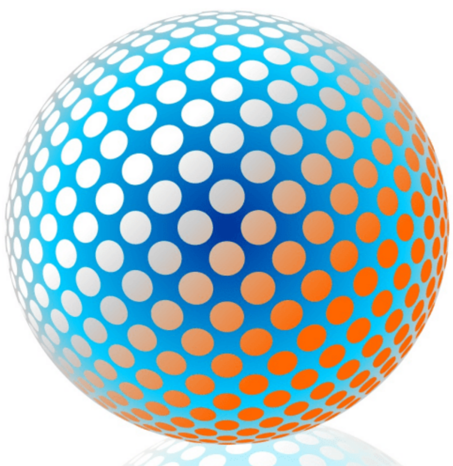


About iLRN

The mission of *iLRN is to cultivate communities of research, innovation, and evidence-based practice around "what works" in XR and immersive learning.*

The Immersive Learning Research Network (iLRN) is a 501(c)(3) nonprofit organization that connects educators, developers, and researchers to work together on realizing the scientific, technical, and applied potential of immersive learning.

New and emerging virtual reality (VR), augmented reality (AR), mixed reality (MR), and other related technologies (collectively known as "Extended Reality") present unique opportunities for fostering learning that address some of the world's most capacious societal, environmental, and economic problems. iLRN seeks to foster a global, interdisciplinary community of scholarship and practice, founded on the principles of open science and open design, aimed at leveraging those opportunities for the good of our planet and its inhabitants.

Central to iLRN's mission is developing, innovating, and showcasing a rigorous evidence base of "what works" for facilitating effective and engaging experiences using XR and immersive technologies across the full span of learning—from K-12 through higher education to work-based, informal, and lifelong learning contexts.

By offering resources, tools, and forums for experts to meet, share, and collaborate, as well as by undertaking its own strategically targeted research efforts, iLRN strives to assist and promote the development of knowledge, skills, principles, and practices of using XR-for-Learning.

iLRN's two flagship activities are:

- The **State of XR & Immersive Learning Project**, which combines an annual environmental-scanning and future-forecasting effort with the development of a crowdsourced empirical evidence and knowledge base on "what works" in XR and immersive learning; and

- The **iLRN Annual Conference**, featuring high-quality, original peer-reviewed research papers and presentations as well as practitioner contributions showcasing innovation and best practices at the leading edge of the XR and immersive learning field. Since 2014, the conference has rotated between North America and Europe, but with the pandemic, the 2020 and 2021 conferences were online.

Our other key strategic initiatives include**:**

- **Conferences and Events**: While the 7th Annual iLRN Conference takes place in Spring 2021, iLRN also hosts a variety of XR-for-learning meetups, seminars, and other programming throughout the year, including IEEE TALE, IEEE ISMAR, IEEE VR, and the National Center for Science and Civic Engagement's SENCER Summer Institute.

- **Innovation Gardens:** iLRN's Innovation Gardens are spaces for planting and cultivating seeds of robust design and testing of XR-for-learning experiences. The Innovation Gardens host game jams, hackathons, and design workshops, and generating tutorials, how-to manuals and instructions in addition to making virtual space available to qualifying project teams for ongoing inspiration, co-design, and skill-building supports.

- **Champions in Higher Education of XR (CHEX)**: The professional association for XR higher education that brings together campus leaders around the world to advocate for and accelerate the growth of XR and immersive technologies for learning across the higher education sector.

- **Grand Challenges**: iLRN seeks to help solve the world's most capacious problems through innovation and applied use of XR.

- **Building a Student Network:** Engaging students and emerging professionals in XR-for-learning design, innovation, and development, iLRN promotes opportunities such as game jams, business and design competitions, eSports, and mentor programs.

iLRN also provides supports for its members to network with colleagues, engage in activities, and advance their individual immersive learning goals through an emerging set of special interest groups: iLRN Houses and iLRN Chapters. **iLRN Houses** gather people of interest in XR and immersive learning in areas of application, such as Medical and Healthcare Education or Nature and Environmental Sciences. **iLRN Chapters** are geographical subdivisions of the Network that cater to the needs of members within a particular city, state/province, or country and that champion the mission and goals of iLRN within that region.

Introducing the State of XR & Immersive Learning Project

The State of XR & Immersive Learning Project is comprised of two parts: the annual *State of XR & Immersive Learning Outlook Report* and the iLRN Knowledge Tree. These two components work together to compile research, track developments, and promote evidence-based practices.

Annual Outlook Reports

The first component of the State of XR & Immersive Learning Project is the annual *State of XR & Immersive Learning Outlook Report*. This report is the culmination of an annual, Delphi-inspired environmental scanning and forecasting study similar to the well-known Horizon Report series previously published by the New Media Consortium.

For this inaugural *State of XR & Immersive Learning Outlook Report*, over 100 educators, education leaders, researchers, technologists, and others representing diverse learning sectors were selected to join a global panel of experts. Each was invited to contribute their perspectives on current and emerging trends in, as well as important developments and research on, the use of XR and immersive technologies for supporting learning.

Their open, asynchronous discussions and deliberations over the course of four months served as the springboard to produce this report, which showcases the findings of the study of XR and immersive learning in relation to:

- The most important needs and opportunities
- Barriers to adoption
- Catalyzing technologies and developments

In future annual iterations, iLRN Houses and Chapters will undertake environmental scanning and forecasting using a similar process but focusing specifically on particular regions (Chapters) and interest areas and application domains (Houses), culminating in the production of mini-reports that feed into the wider environmental scanning and forecasting effort. The plan is to gradually move toward a more open, crowdsourced model for identifying/scanning for and also vetting relevant research studies, projects, cases/exemplars, resources, etc. rather than relying on a single, centralized model.

The iLRN Knowledge Tree

The second component of the State of XR & Immersive Learning Project is the *iLRN Knowledge Tree,* a long-term, ongoing effort to create a robust and ever-growing evidence base cultivated by the iLRN community. In early 2021, a group of iLRN scholars began taking steps to outline how the network might pursue this interdisciplinary effort, with potentially far-reaching impact (Beck, et al.). The aims of this effort are to promote evidence-informed practice and to guide future research in the field.

The effort entails:

1. Performing a **scoping review of the literature** in order to distill from the extant body of scholarship the contours of the design problem space for creating high-quality, effective and engaging learning experiences using XR and immersive technologies.

2. Developing a **taxonomic framework and conceptual data model** for capturing empirical research findings on the relationships between the constructs identified in the scoping review. In addition to facilitating the collation, classification, and synthesis of findings from past studies, this will encourage the channeling of future research efforts and contributions across the field toward a shared overall framework and agenda.

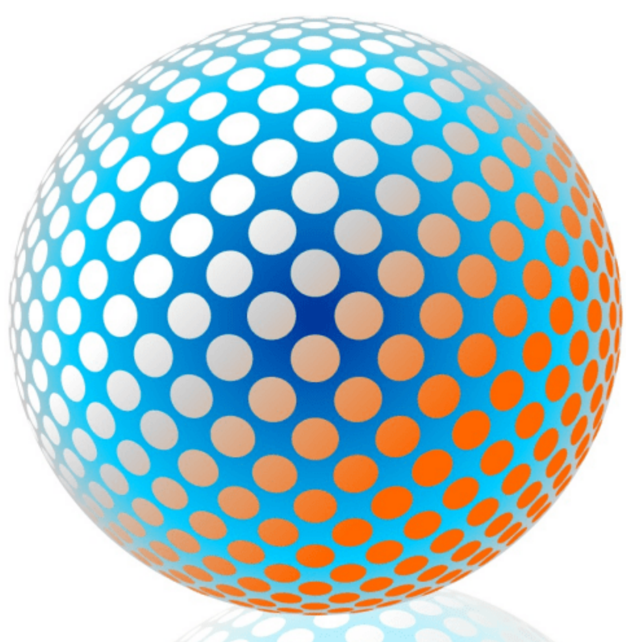
3. Building a **web-based evidence repository**, based on the taxonomic framework and conceptual data model, that will enable the derivation of evidence-based design principles, guidelines, and best practices encapsulating “what works” (and what does not) for creating effective and engaging XR and immersive learning experiences. The project team will populate the repository with information gleaned from a content analysis of a small set of seminal research articles, with the dual purpose of seeding the evidence base as well as iteratively developing, testing, and refining an analysis protocol that can be applied at scale to achieve a crowdsourced, dynamic systematic review process. We hope that the evidence base will continue to grow at the hands of the wider community through this process as well as through crowdsourcing of new original-research studies. There may also be the potential to employ big data analytics and machine learning techniques to continually mine contributed data sets for new insights and discoveries. Importantly, the principles, guidelines, and best practices housed in

the repository will be traceable to the sources of the underlying evidence that support them, which may be in the form of peer-reviewed research papers, empirical case studies, and analyses of open data sets.

4. Maintaining a community-curated **collection of exemplars** embodying and demonstrating the operationalization of the principles, guidelines, and best practices, complemented by a **library of resources** to assist educators and developers in their implementation.

As with the Annual Outlook Reports, the iLRN Houses and Chapters will play an active role in nurturing and growing the Knowledge Tree by taking ownership of a particular "branch" specific to their respective interests, application areas, and geographical regions.

In combination, the Annual Outlook Reports, with their future-oriented focus, along with the Knowledge Tree, with its focus on stocktaking and synthesis of extant research, will help illuminate emerging best teaching and instructional design practices as well as priority areas within the field of XR and immersive learning that need further exploration, investigation, and development.



The 2021 Outlook Report Authors

Mark J. W. Lee is Executive Vice President and Chief Research Officer of iLRN, and the Project Leader/Principal Investigator of iLRN's State of XR & Immersive Learning Project. An educational technologist and learning scientist who divides his time between Australia and the United States, he is known internationally for his scholarship and innovation in the virtual and immersive learning arena, as well as his interest in creative and playful pedagogies that transcend multiple spaces, temporalities, and/or modalities. In recent years, he has been exploring how wearable augmented reality, 3D volumetric video, haptic interfaces, and other emerging mixed-reality technologies can be harnessed to blend aspects of the real/physical and virtual worlds for learning and collaboration. In addition to his role with iLRN, Mark is President of the International Board of Standards for Training, Performance, and Instruction (IBSTPI); sits on the Board of Governors of the IEEE Education Society; and serves as Editor-in-Chief of IEEE's *Transactions on Learning Technologies*.

Maya Georgieva is a futurist, XR strategist, immersive storyteller, producer, and a sought-after keynote speaker on the future of immersive learning and innovation in creative industries. As the Director of Education Futures and the XR and HCI Innovation Labs at the New School, Maya provides strategic leadership in creating a culture and capacity for innovative design with emerging technologies, including XR and AI. Maya leads a team driving new media and innovation focused on immersive storytelling, spatial computing, future interfaces, and design. She regularly guest-teaches at The Parsons School of Design. Her work has been featured at SXSW, the MIT Media Lab, *The Atlantic*, *The Economist*, and the Fulbright Program, among others. She has authored white papers on the future of education and immersive learning in *EDUCAUSE Review*, *The Chronicle of Higher Education*, *EdSurge,* and other publications. She is also the co-founder of Digital Bodies, an award-winning website focusing on VR/AR/MR and their impact on media and society. Maya has spoken at United Nations forums and assisted the European Commission on policy recommendations for the future of learning and work.

Emory Craig is the Co-Founder and CEO of *Digital Bodies*, a global XR consulting group and popular website for news and analysis of immersive technologies. With broad experience in higher education and the creative industries, he works with nonprofits, universities, and international organizations, including the UN and OECD, to design, develop, and implement initiatives in XR, AI, and digital ethics. He is an Innovator in

Residence at Arizona State University for the ShapingEDU project on the future of learning in the digital age. As a futurist, writer, and speaker at global conferences, he explores how the convergence of XR and AI will transform how we learn, work, and interact with one another, opening creative possibilities and profound ethical challenges. His work explores the emerging norms of the Metaverse and the strategies we will need to live in a world where experiences are available on-demand and the boundaries between the real and the virtual disappear.

Bryan Alexander is a Senior Scholar at Georgetown University and founder of Bryan Alexander Consulting. He is the author of several books, including *Academia Next* (Johns Hopkins University Press) and *The New Digital Storytelling* (2nd edition, Praeger), as well as the creator of the Future Trends Forum and the *Future Trends in Technology and Education* report. An award-winning and internationally renowned futurist, he researches the transformation of higher education in the 21st century. His forthcoming book, *Universities on Fire*, explores how climate change might impact academia over the next 75 years.

Jonathon Richter is the Co-Founder, President, and Chief Executive Officer of iLRN and the Director of Tech4Good Programs at Salish Kootenai College on the Flathead Indian Reservation of the Selis, Qlispe, and Kutenai peoples in Montana. Prior to iLRN's founding in 2014, Jonathon was the founding President of the American Educational Research Association's Applied Research in Immersive Environments for Learning Special Interest Group (ARIEL SIG), a predecessor of iLRN. Jonathon's focus on technology adoption, collaboration in immersive environments, and design patterns for learner engagement in XR across the disciplines stems from design, research, and teaching for specific learner populations. He is responsible for cultivating the rigor and relationships across the research network and co-leads the iLRN House of Nature & Environmental Sciences.

Historical Overview and Recent Developments

To understand extended reality (XR), it is helpful to review the technological developments that underpin it: virtual reality (VR) and augmented reality (AR).

Virtual Reality

Born out of early experiments in the 1960s by Ivan Sutherland, Tom Furness, and others, VR refers to digitally simulated immersive environments in which users can look, move around, and/or interact with a virtual space or objects (Biocca, 1992). By the 1980s, researchers had developed early applications for flight simulation, industrial, and military use. Early achievements included David Em's navigable worlds for NASA's Jet Propulsion Lab, created while he was an artist-in-residence there; Eric Howlett's Large Expanse, Extra Perspective (LEEP) optical system, which became the basis for early VR imaging; and Jaron Lanier's invention of several groundbreaking devices at VPL Research (he also popularized the term "virtual reality").

The VR boom expanded in the 1990s, as the gaming and entertainment industries embraced the technology and popular culture took notice (notably in Brett Leonard's 1992 film, *Lawnmower Man*). However, cost, size, and usability issues limited early efforts to expand its use in education, the sciences, and entertainment. When Disney closed all but one of its massive DisneyQuest VR experiences in 2001, it seemed to mark the end of an era, and VR was largely seen as a technology unable to deliver on all of its promises.

The Resurgence of Virtual Reality

Virtual reality resurfaced at the beginning of the last decade with Palmer Luckey's Oculus Kickstarter project in 2012, which raised a remarkable $2.4 million or 974% of its original funding goal, and Google Cardboard, a DIY cardboard viewer that was initially distributed as conference swag. Facebook's purchase of Oculus VR for $2.3 billion would lead to the release of developer kits for the Oculus Rift (the DK1) in 2013 and commercial release in March 2016.

Paralleling these developments, the HTC Vive and Sony PlayStation VR head-mounted displays (HMDs) were released in the same year. The new, lighter weight headsets provided consumers with more affordable access to the technology even though they remained bulky and costly—a gaming computer being the primary requirement. The field continued to progress with devices such as HP (the Reverb) and Lenovo.

In 2019, Facebook's Oculus Quest, a standalone HMD, sharply lowered the barriers in terms of cost and ease of use. Improved headsets continue to launch, most notably Facebook's Oculus Quest 2 in October 2020.

Augmented Reality

In contrast to VR, AR is the opposite end of the spectrum of immersive technologies, linking digital information to specific activities or locations in the physical world.

An early forerunner of AR was the 2013 release of Google Glass, wearable glasses that positioned a miniature display in front of the user's eye. While generating considerable press, usability issues, cost, and privacy concerns limited its acceptance.

In 2016, The mobile game Pokémon GO (released by Niantic) and Snapchat filters popularized AR applications. They overlayed virtual content onto the user's view of the physical world as seen through their smartphone, superimposing that content on the live images captured by the phone's camera. Snap was also one of the first to sell low-cost AR glasses.

More advanced forms of AR employ sophisticated display and geolocation technologies in heads-up displays designed for construction, engineering, telemedicine, and military applications. Current devices are expensive and focus on specific use cases (e.g., the Vuzix line of smart glasses, Raptor's cycling glasses, and Epson's Moverio).

Use of AR by the public and in education is expanding rapidly but remains limited by the need to use a handheld device such as a smartphone or tablet. However, 2020 has seen the release of a new generation of lightweight consumer AR glasses (Nreal Light eyewear), the announcement of major AR projects (Facebook's Project Aria), and continuing rumors of AR glasses from Apple.

Mixed Reality

Mixed reality (MR) is considered a broader term that encompasses AR, though it has its own defining characteristics. Here, digital objects are not overlaid on the user's environment as in AR but coexist and interact with the real world.

While there were early university research and military experiments in the 1990s, commercial applications did not arise until Microsoft's HoloLens in 2016. Though the company did not invent the term "mixed reality," they are most closely associated with the concept. With the release of HoloLens 2 in 2019 Microsoft pivoted from the consumer and educational markets to focus on enterprise applications. The heavily funded and widely publicized 2010 startup Magic Leap also released their own MR device, the Magic Leap 1, in 2018. However, both devices are expensive and made only limited inroads in education. In early 2020, Magic Leap laid off nearly 50% of its staff and followed Microsoft's lead in focusing on the enterprise market.

The Growth of Immersive Content

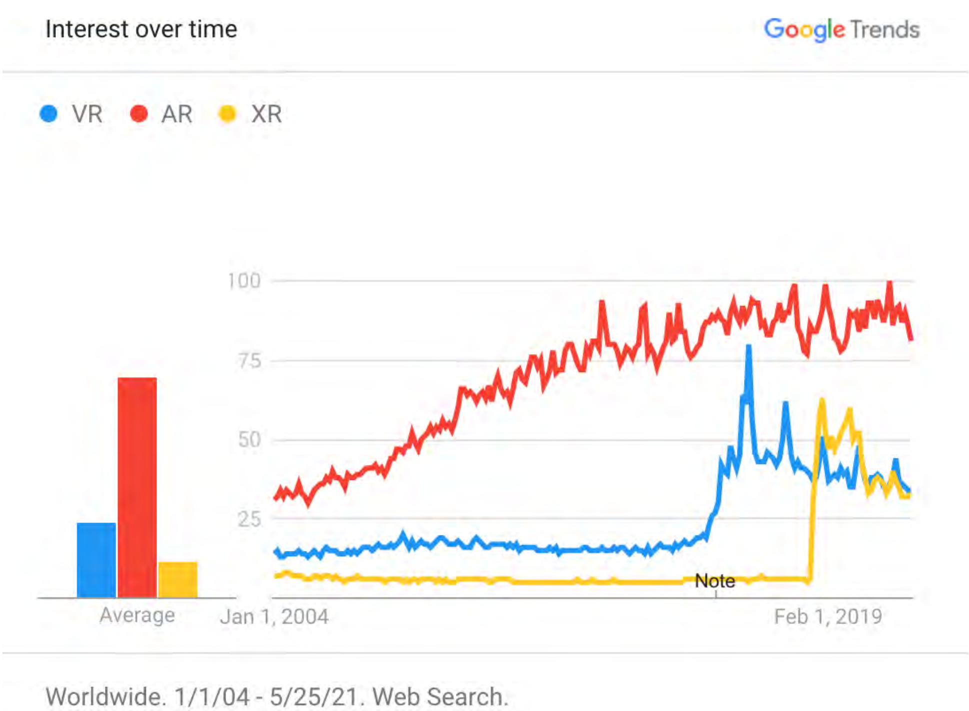
As the technology rapidly changed and creative tools arrived, filmmakers and artists such as Gabo Arora and Chris Milk created innovative 360-degree videos. Nonny de la Peña pioneered immersive journalism and developed full VR participatory experiences (Palmer Luckey was a former intern of hers at the University of Southern California); she was the first person to bring VR to the Sundance Film Festival.

Content for XR now covers a wide range, from immersive images and 360-degree video offering 3-DoF (or three degrees of freedom) experiences to 6-DoF fully immersive environments. At the most advanced level, virtual environments may include AI-driven avatars or content developed through motion-capture technologies. Directional audio is widely used, and there are increasing experiments with haptic feedback and virtual interfaces, which currently rely on voice commands or hand gestures.

Despite ongoing barriers of access, educational institutions, nonprofits, museums, and individual artists have created innovative XR projects that are transforming how we learn and our understanding of ourselves.

XR as an Overarching Concept

As immersive technologies have become more widely known and available to the general public, “XR” (or “extended reality”) has become an umbrella term encompassing augmented, mixed, and virtual realities in ways that can merge the physical and virtual worlds. XR does not refer to specific technologies but how this entire category of technological development extends and enhances human experience. Reviewing the data from *Google Trends,* the term languished in relative obscurity until September 2018, when it quickly gained popularity (Google, 2020). As a concept, XR embraces the broad spectrum of immersive experiences extending from basic AR data overlays to fully immersive high-end VR.



data source: Google Trends

XR and Education

Throughout these developments, educators have been drawn to the tremendous potential for XR and immersive learning in both K-12 and higher education.

XR is not merely another educational technology tool but a paradigm shift in our relationship to digital technologies. No longer are we viewing media within a rectangular frame on a wall or in our hands if we are using a mobile device; instead, we are stepping into the media.

As Jeremy Bailenson, Professor of Communication and founding director of the Virtual Human Interaction Lab at Stanford said, "Virtual reality is not a media experience. When it's done well, it's an actual experience."

Beyond its obvious use for simulations in STEM disciplines, XR offers a radical opportunity to more directly integrate human experience into formal and informal education and workforce training. In our research and implementation of immersive technologies, iLRN recognizes the potential of XR to transform learning and even the structure and relevance of our educational organizations.

XR and a Global Pandemic

As the Expert Panel wrapped up its work in 2020, the COVID-19 pandemic brought massive disruption to faculty and students in the XR community, and K-12 and higher education in general.

The human cost of the pandemic remains incalculable, and it is challenging to assess its ultimate impact on the XR ecosystem. Manufacturing and supply chains remain unstable, collaboration and design work must be done virtually, and most university and XR research labs are closed.

However, the pandemic has also been a catalyst for new XR developments, especially social VR platforms like AltspaceVR. Such platforms previously had limited appeal due to their design and lack of a sound business model; AltspaceVR only survived through a last-minute reprieve by Microsoft in 2017. Others, such as VRChat, generated controversy as spaces that fostered potentially offensive activities and abusive behavior. Even though some platforms resolved most of these issues, they were not widely used by XR practitioners in the academic community until the pandemic.

In March 2020, these online XR platforms suddenly found themselves in the spotlight when quarantine restrictions shut down educational organizations. As educators scrambled to find tools to support virtual presence, social and collaborative spaces became a new place to learn, work, and connect with others. Some, like Nanome, were used by scientists to collaborate on researching the virus. Others, like Virbela, hosted online courses and served as virtual conference sites, including iLRN's own summer 2020 international conference. The momentum in this space will likely continue over the next few years as education and businesses leverage XR to go beyond the screen-based presence of traditional video conferencing.

XR Technology continues to develop even amidst a global health crisis. The recent Facebook Connect 2020 conference brought the release of a significantly improved Oculus Quest 2 headset, the news that Project Aria is slated to research and deliver AR glasses by next year, and Facebook's "Infinite Office," a project to merge virtual and real elements (including a physical keyboard) is expected to leverage the benefits of XR for productivity in the Quest ecosystem.

What the Future Holds

In writing this State of XR Outlook Report, we recognize that the Expert Panel's insightful work was undertaken amid the disruption of a global pandemic and significant developments in the XR space.

When the panel began in 2019, the Oculus Quest had just arrived, the Valve Index appeared in June, and by December, Facebook had implemented controllerless hand tracking on the Quest. In 2020, we saw the end of Google's once-promising Daydream VR platform (widely used in K-12), the retirement of Facebook's popular Oculus Go, and Magic Leap's retrenchment. Monitoring and analyzing these developments while simultaneously responding to their own organizations' needs was a testament to the depth of expertise and commitment of the panel's members.

The pace of change of XR in education and elsewhere is due to the remarkable work of researchers, faculty, students, artists, and filmmakers. Even during the production and distribution of this report, new XR developments are on the way, bringing new opportunities and challenges for how we will learn in the future. Above all, we have poignantly felt the need to listen to our students, who are eager to expand the creative potential of technologies that will profoundly shape their world in the future. What follows is the collective wisdom of educators and XR industry leaders who are at the forefront of the research and implementation of XR within the educational community. This report represents the collective voice and opinions of the iLRN State of XR Expert Panel and authors.

Research Method and Questions

The Delphi-inspired study, whose outcomes are the basis of this report, center around three major questions:

1. What are the greatest needs and the most promising opportunities in learning that XR and immersive technologies can help fulfill?
2. What are the most salient barriers facing institutions and organizations seeking to adopt XR and immersive learning technologies?
3. Which XR, immersive, or other related/complementary technologies, tools, and digital developments have the potential to help transform learning and teaching/training practices?

By tackling these questions, iLRN endeavors to contribute insights and inspiration that will inspire practicing educators and other learning professionals, as well as provide helpful information and examples for organizational decision-makers weighing the introduction of XR and immersive learning innovations against a variety of demands and challenges. Pursuing answers to the above questions will hopefully also open potential avenues for new research and raise awareness among policymakers regarding the need for new incentives and governance structures that best accommodate these innovations and their opportunities.

The Expert Panel activities consisted of several phases, beginning with an orientation or “Setting the Tone” phase in which panelists read introductory papers, reports, media articles, and other resources curated by the Project Leadership team. They supplemented those resources with other seminal content and responded to additional content suggested by other panelists.

The “Setting the Tone” phase was followed by three successive rounds in which the panelists first responded to different prompts linked to the project’s research questions, and then engaged in a dedicated interactive period in which they were tasked with specifically responding to one another’s ideas to build a conversation.

In the final phase, the panelists voted to determine the topics and issues that informed the development of the sections of this report describing:

- Opportunities for XR and immersive learning
- Barriers to XR and immersive learning
- and Catalysts of XR and immersive learning.

The timeline for the Expert Panel activities was as follows:

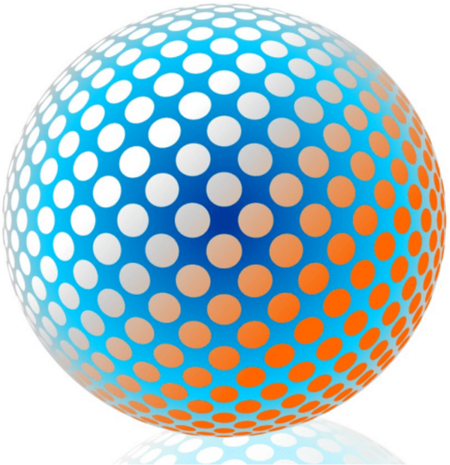
- **Week 1:** Expert Panel orientation via participation in “Setting the Tone” resources
- **Weeks 2 & 3:** Expert Panel asked to respond to Research Question 1 (RQ1)
- **Week 4:** Expert Panel RQ1 dedicated interactive period
- **Weeks 5 & 6:** Expert Panel asked to respond to Research Question 2 (RQ2)
- **Week 7:** Expert Panel RQ2 dedicated interactive period
- **Weeks 8 & 9:** Expert Panel asked to respond to Research Question 3 (RQ3)
- **Week 10:** Expert Panel RQ3 dedicated interactive period
- **Weeks 11 & 12:** Project Leadership conducted content analysis of Expert Panel discourse to identify candidate report topics
- **Weeks 13 & 14:** Expert Panel voted on report topics
- **Week 15:** Project Leadership analyzed voting results and developed the report categories (Opportunities, Barriers, Catalysts) based on the results

Throughout the 4-month period, the Expert Panel was also invited to suggest and review research that they believed was indicative of “what works” for creating effective and engaging XR and immersive learning experiences. They were encouraged to continually be on the lookout for relevant research to share with others on the Panel, and to assist in distilling from the findings of that research evidence-based principles and guidelines that will lay a foundation for the iLRN Knowledge Tree.

Notes on audience and intent

Note that this report is a blend of the work of the iLRN Expert Panel and the views of the report authors themselves. It also constitutes an attempt to simultaneously address multiple audiences. iLRN’s Outlook Report is intended for teachers, designers, community leaders, industry, researchers, and more. Of course, there is a real and present risk in attempting to fulfill so many purposes, something each of our respective writing teachers long ago warned us not to do. Nevertheless, we will make the attempt, so compelling is our wish to bring together these previously disparate groups of professionals and creators from this moment, going forward. While we are indeed a research network interested in high quality evidence upon which to stake claims and there are notable attempts to base our observations and positions in what evidence we can find throughout, this product cannot legitimately be called “research,” per se.

The iLRN State of XR and Immersive Learning Report is the product of a future-focused activity: scanning for and discussing the perceived importance of emerging immersive technologies and innovations applied to teaching and learning in the broadest sense. The authors repeatedly returned to the volume of work created by the Expert Panel for this project to best represent their perspectives and ideas, using direct quotes when possible. Our authors too, at times, make declarative statements about what trends indicate when they feel it's appropriate. Thus, it is intended to be a noteworthy companion to research and a pathway to possibilities for discovering new methods to achieve meaningful teaching and learning.



Research Question 1: Opportunities

What are the greatest needs and the most promising opportunities in learning that XR and immersive technologies can help fulfill over the next 3 years?

The current wave of extended reality (XR) represents the continuation of a decades-long journey toward understanding the technology and its impact on education, the workforce, and society at large.

By the end of this decade, the use of 360-degree videos and of virtual, augmented, and mixed reality under the umbrella term of “XR” may well permeate our daily lives in ways “mobile” does today. Headsets like the Oculus Quest 2 are becoming lighter, more flexible, more powerful, and more affordable. At the same time, Gartner (2021) predicts that Silicon Valley will deliver augmented reality (AR) glasses targeting mainstream consumers sometime between 2021 and 2023.

In the years ahead, the convergence of emerging XR technologies with artificial intelligence (AI) will lead to novel applications and solutions that transport us into multisensory virtual worlds and that seamlessly integrate digital content into the real world. As learning institutions continue their exploration of immersive learning, there is little doubt that XR will profoundly reshape learning and, ultimately, the human experience. The future is human, and the future of learning is immersive. In the future, learning will take the shape of a story, a play, a game; involving multiple platforms and players; driven by dialogue and augmented with technology, an interplay of immersive experiences, data, and highly social virtual worlds.

The examples in this section present a window of insight into what we see today shaping our tomorrow.

In response to the first research question, the Project Leadership and Expert Panel identified six key Opportunity areas in learning that XR may help fulfill over the next 3 years:

- Facilitating Authentic Learning Experiences
- Empowering Learners as Creative Designers and Makers
- Integrating Immersive Storytelling in Learning
- Integrating Immersive Learning in STEM
- Fostering Collaboration with Social VR and Other XR Technologies
- Cultivating Immersive and Blended-Reality Learning Spaces and Laboratories
- Developing the Capabilities of the Future Workforce

This section of the report focuses on the creativity and innovation needed to move beyond traditional pedagogical models and practices, laying out some of the possibilities for supporting and enhancing learning and teaching with XR. The barriers to XR adoption, addressed by the second research question, will then be covered in the next section of the report.

For educators and other learning professionals, XR is not simply another set of technology tools for accomplishing specific tasks in the learning environment, but rather represents a paradigm shift in how learners interact with content, with instructors, and with their peers. Framed in this way, the concept of needs is not about the access, challenges, and barriers with emerging and immersive technology, but about the potential to reinvent our educational practices to meet the demands of learners and organizations in the 21st century. It is about the vision of what is possible and critical in learning and how the rapid development of XR technologies will spur this transformation.

Opportunity 1: Facilitating Authentic Learning Experiences

Authentic learning activities are embedded in real-world contexts and have both personal and cultural relevance. Personal relevance means that learners can connect what they are learning to their own lives, while cultural relevance refers to the applicability of that learning to the values, goals, and norms of the social and professional communities of which they are a part. Most importantly, engagement with authentic tasks and situations presents learners with opportunities to perceive the world more like expert members of their field of study.

XR expands the foundation of authentic learning experiences through their rich capabilities, enabling the creation of on-demand opportunities for learners to immerse themselves in particular contexts. They are embodied either as themselves or as characters, embarking on a learning journey to create, design, act, analyze, evaluate, make decisions, and live through the consequences.

In Chapter 6 of *Learning in Virtual Worlds* (Gregory et al., 2016), Helen Farley shares the research of Herrington, Reeves, and Oliver, who identified 10 characteristics that capture the essence of authentic learning (pp. 130–131):

1. Authentic activities have real-world relevance . . .
2. Authentic activities are ill-defined, requiring students to define the tasks and subtasks needed to complete the activity . . .
3. Authentic activities comprise complex tasks to be investigated by students over a sustained period of time . . .
4. Authentic activities provide the opportunity for students to examine the task from different perspectives, using a variety of resources . . .
5. Authentic activities provide the opportunity to collaborate . . .
6. Authentic activities provide the opportunity to reflect . . .
7. Authentic activities can be integrated and applied across different subject areas and lead beyond domain-specific outcomes . . .
8. Authentic activities are seamlessly integrated with assessment . . .
9. Authentic activities create polished products valuable in their own right rather than as preparation for something else . . .
10. Authentic activities allow competing solutions and a diversity of outcomes

Throughout history, it's been challenging for most teachers or trainers to provide every learner with experiences that meet well the hallmarks of authentic learning as described by Herrington, et al. Within XR technologies and immersive learning experiences, we find new and accessible levers for providing these kinds of meaningful experiences for more learners.

As XR-for-learning use cases and applications expand across disciplines, researchers continue to zero in on the design elements and features that facilitate authentic learning experiences in immersive environments with greater efficacy. Companies like STRIVR focus on designing immersive learning that include features such as embodiment, perceptual and emotional fidelity, real-time feedback, and experiences that may be repeated on-demand. STRIVR's Ultimate Guide to Immersive Learning highlights that we experience perceptual fidelity when interactions in the virtual worlds mirror those in the physical world. Emotional fidelity gives us a sense of presence within a virtual world or with a virtual being. Being able to experience challenges, make decisions, and ultimately understand their impact is critical to knowledge transfer and retention; experiencing responses like surprise and anxiety creates memories and learning that stick.

Further, the opportunity to repeat and improve performance in virtual experiences can lead to real behavior changes. Data-driven analytics in XR are rapidly developing, and in the near future will be able to provide insights and actionable results. The data-driven science of creating authentic immersive learning experiences that anchor to real-world learning transfer will go far beyond the video capture or rendering of a faithful simulation. Authentic learning with XR will also include bio and sensory data that can reveal attention, performance, and sentiment. As we capture these data points, we will be able to apply predictive analytics, create authentic personalized experiences, and ultimately accelerate and transform learning.

For schools and universities, the path to creating authentic learning experiences lies in reshaping the traditional models of instructor-led classrooms, encouraging educators to move away from rigid curricula and embrace new experiences and active learning models where teachers take on the roles of mentors and coaches. Immersive experiences enable students to step into the shoes of explorers, scientists, and designers — in other words become active "players."

Some of the projects demonstrating this work today focus on developing XR experiences for students that include:

- Experiencing science phenomena in both sensory and dimensional ways:

- Understanding complex subjects and concepts through experiencing of real-life scenarios and interactions;
- Living or embodying characters in new forms of narratives;
- Building and creating virtual worlds to explore new constructive and creative art forms;
- Virtually visiting sites that may be remote, dangerous or expensive to access;
- Increase student motivation by incorporating problem-solving and challenge-based dynamics as well as immediate feedback;
- Connecting and fostering social, creative and learning collaborations regardless of physical location and allowing students and participants to feel present;
- Creating opportunities for campus and other virtual tours and events;
- Enabling networking opportunities for students to engage with experts and alumni.

XR also creates new learning opportunities by transcending the traditional barriers of space and time. The University of Illinois at Urbana-Champaign is using XR to teach archaeology and address the challenges of students finding time and funding for fieldwork, an essential requirement of that discipline. The VR laboratory, VRchaeology, is one such project, funded by a National Science Foundation grant and designed by anthropology professor Laura Shackelford; Educational policy, organization, and leadership professor David Huang; and computer science graduate student Cameron Merrill. The virtual experience is based on an actual North American cave site excavated in the 1930s and includes over 110 virtual artifacts, many of which are based on objects in the University's own collection.

These immersive experiences cover complex activities that comprise the work of a professional archaeologist, from initially mapping a site to creating an excavation grid and using ground-penetrating radar. Students learn how to dig for artifacts, record data, collaborate with each other, and reach scientific conclusions. Importantly, students have the agency to manage their own learning journey. In addition, their possible miscalculations and missteps do not impact the value of the historical artifacts, nor alter the significance of an actual site; instead, they help them develop and apply a deeper understanding to students learning to become expert archaeologists in their own right. With the virtual cave lowering the barriers to the fieldwork requirement, it also opens up the discipline to lower income students who may be unable to travel to an actual site.

Figure 1: VRchaeology gives students at the University of Illinois a chance to learn the skills normally acquired at a remote archaeology field school site.

As important as these developments are, they only hint at the many ways XR promises to revolutionize learning to be more authentic and powerful in both formal and informal settings. XR is also becoming a platform for understanding ourselves in rich and meaningful ways not possible before, probing deeper into the human condition. Tom Furness, one of the early pioneers of VR and founder of the Virtual World Society (VWS), has argued that he wants to see the VWS do the opposite of the National Geographic Society (NGS). Whereas the NGS sent teams of researchers and people into society and nature to understand the world, Furness sees the goal of the VWS to turn inward, to use XR to better understand ourselves.

In the coming decade, XR will become the foundation for many new kinds of authentic learning experiences that not only connect students to tangible aspects of the real world as we know it, but also to connect them to its most abstract components as well as worlds beyond. Today, we can see a plausible future with XR for learning that offers an unprecedented opportunity to do what previous educational innovators such as John Dewey could only have dreamed of: to bring every facet of human experience into the learning environment. How we inspire, manage, and leverage those virtual experiences for authentic learning will be the fundamental challenge for educators working in XR over the next decade.

Opportunity 2: Empowering Learners as Creative Designers and Makers

One of the most exciting areas in recent XR developments is the the empowerment of students as creative designers and makers.

Like authentic learning, the act of engaging directly with a phenomenon to create it leads to a deeper understanding for how that thing works and builds on the theory of Constructionism developed by AI pioneer and educator Seymour Papert. Constructionism advocates student-centered, discovery, and project-based learning. A follower of Piaget, Papert believed that including computer applications in learning activities encouraged exploration and critical thinking and should be used to empower students with the opportunity to create microworlds where they learn through exploration and discovery. With XR, we are introducing our students to a powerful new set of 3D and XR creative tools. These tools give students "superpowers" to create, collaborate, share, and prototype at a much faster rate as well as the ability to not just visualize but build scenarios and worlds where they can embody and test hypotheses. We are seeing Papert's ideals more fully realized through these XR and immersive learning applications.

One thought-provoking example is "Spatiality," a VR experience developed by Akshansh Chaudhary, a Parsons School of Design at The New School student. Akshansh created "Spatiality" as part of his participation in the VR/AR Association Global Summit Student Competition, which he won in June 2020. In a world of a global pandemic and increasing uncertainty about the use of our personal data, "Spatiality" reflects on the Internet, privacy, and safety. The architectural landscape he designed is stylistically organic and redefines the notion of visiting social media sites within a virtual reality world setting. The design in Google's Tilt Brush is transformed inside Unity into an interactive experience. The floor and external shapes are not solid forms but overlapping layers of text that include personal information used to exploit our privacy. This virtual space is a gallery of the major tech companies including Google, Facebook, Instagram, and Twitter — a "technological landscape" that demonstrates his impressions of how they manage users' private information and their roles in society.

Walking through “Spatiality" gives you a visceral experience of the impact of our decisions when we engage with social media, prompting critical questions and reconsideration of our online behavior. This designed experience demonstrates the ability for students like Akshansh to make abstract ideas and connections more tangible and visible. This enhances the ability to convey complex concepts and previously invisible relationships in a shareable, visceral fashion. Having this capability through XR technologies at a learner’s disposal will lead to the co-creation of many more meaningful learning opportunities.

Figure 2: “Spatiality,” a VR experience on Data Privacy by Akshansh Chaudhary, a student at the Parsons School of Design at The New School.

Already, we’re beginning to see the proliferation of learners as creative designers and makers through XR and immersive learning. The [Carolina AR/VR Student Group (CARVR)] at UNC-Chapel Hill is another example of a highly active organization that supports student XR projects and works with real-world clients. For example, students and faculty collaborated on the cutting-edge Brain VR project, which uses electroencephalogram (EEG) data with XR headsets to allow users to move around a virtual landscape using only their thoughts. Similar work engaging student groups has been developing at Yale’s Center for Collaborative Arts and Media, Carnegie Mellon’s Entertainment Technology Center, and an increasing number of XR labs, research centers, and makerspaces across campuses globally.

Empowering learners as creators also takes place outside our formal educational organizations, as seen in the work of the nonprofit [Digital Promise] Global’s 360° Story Lab, an organization that supports the use of emerging and interactive technologies that expand the frame of traditional media and journalism. Recognizing XR's storytelling potential, Digital Promise, the United Nations Sustainable Development Goals (SDG) Action Campaign, and Oculus have created the global MY World 360° campaign to further the UN SDG goals. MY World 360° invites creators of all ages to use a variety of media, including XR, to express the multi-dimensionality of their local communities and create a vision for a better world that reduces inequities, promotes good health, and increases access to clean energy.

As immersive applications and headsets evolve, we also see new construction tools for teachers and students emerging. The Zoe VR App (Beta) is a standalone application where students can build their 3D environments directly in the headset. The application is geared to middle and high school students and enables them to tell stories, create games, and explain processes. Students may apply an infinite number of actions or sequence of actions to their 3D models and trigger animations, sounds, and behaviors based on a dozen different conditions made for VR/AR. Zoe VR offers support to teachers in various curriculum topics such as physics, science, art, social impact, and language.

Figure 3: The Zoe VR app

Expanding the toolset available to educators and opening XR labs and initiatives in K-12 and higher education to support both curricular and extracurricular projects are critical in advancing the opportunities XR presents for learning. A growing number of applications and providers within universities, not-for-profit organizations and business communities are developing a vital ecosystem essential to bringing awareness about the potential of immersive technologies as well as making them accessible to students. Developing the next generation of a diverse body of XR makers, scientists, designers, and immersive storytellers to create content for students is one of the most significant responsibilities that educators, designers, technologists, and practitioners are charged with today.

Opportunity 3: Integrating Immersive Storytelling in Learning

A number of projects in both K-12 and higher education cut across the disciplines and challenge the definition of distinct programs within the institution. While there is proven potential in the application of XR for precise simulations across the sciences, the full potential of XR will be realized in an interdisciplinary approach that draws upon the human need for narrative and storytelling. Some of the early experiments in 360 video and XR were undertaken by journalists, filmmakers, and media producers who created compelling immersive storytelling experiences. Filmmaker and WITHIN cofounder, Chris Milk, sees XR and immersive learning as the "foundations for a medium that could be more powerful than cinema, than theatre, than literature, than any other medium we've had before to connect one human being to another" (2015). The potential of immersive experiences to foster empathy and connection in human beings presents one of the unique opportunities for XR.

A team at the University of Birmingham developed a fascinating project to mark the 400-year anniversary of the Mayflower sailing vessel's departure for the Americas. The Virtual Mayflower project leveraged a wide range of XR technologies including tethered and stand-alone VR headsets, wearable motion capture systems (MOCAP), and head-worn AR displays to capture the complexity of the historical setting. The goal was not simply to accurately convey a past event, but to leverage the sense of immersion in XR to support motivational and educational interactions with the avatars of the Mayflower crew and passengers. For users, it became a "journey of discovery" that incorporated interdisciplinary topics to generate new narratives and cultural exchanges. The historical event would profoundly shape the narratives of multiple cultures in the centuries that followed. Paralleling this, the goal of the project was to foster an ongoing dialogue among the participants beyond the XR experience itself.

Figure 4: The [Virtual Mayflower project](#) developed by the University of Birmingham

Fall 2020 saw the conclusion of a two-and-a-half year project on immersive storytelling in Canada, "[Immersed in Youths' Stories of Toronto: The Power of VR Storytelling](#)." Developed by Artscape and Centennial College, the initiative transformed the stories of inner-city youth into immersive experiences that highlighted their voices. The participants were connected to design teams and technical help from Centennial, drawing upon faculty and students in the Game Art program, the Broadcasting program, and Applied Research, Innovation and Entrepreneurship Services (ARIES). The project culminated in a webinar and a series of hands-on toolkits designed by artists and organizations to ensure that the stories of marginalized communities are represented in the expanding range of XR content.

Those who accessed the XR installations felt they had bridged challenging social boundaries. "Everywhere I looked, I was part of the story" one participant commented, while another added, "It allowed me to be in the voice's shoes. I could see and experience it as if I was really there." (Few, 2020). Projects like this highlight the power of immersive storytelling to foster diversity, equity, and inclusion in XR and learning.

Finally, immersive projects enabled by AR allow viewers to travel in time and appreciate world-renowned art and architecture masterpieces. University of Cambridge art historian Donal Cooper, Fabrizio Nevola from the University of Exeter, and a team of researchers, curators and software developers have resurrected a cornerstone of Florentine life with a geo-located app. [Hidden Florence 3D: San Pier Maggiore](#) enables iPhone or iPad users to enter a 3D visualization of the church from any location, offering a new sense of scale and context.

Opportunity 4: Integrating Immersive Learning in STEM

One of the reasons why XR has been quickly embraced by the science, engineering, and medical fields is their already long-held traditions of using simulations for learning. But the current XR trend marks what we see as a paradigm shift where we may transition from physical or flat screen simulations to immersive and embodied scenarios and environments. STEM simulations in XR can be gamified, incorporating adaptive learning and allowing students to learn through failure.

The United States Bureau of Labor Statistics predicts that STEM jobs will grow by nearly 11% between 2016 and 2026. This prediction, coupled with the urgent need for qualified medical professionals throughout the global community, means that XR simulations will likely play a critical role in educating a new generation of healthcare professionals. Simulations grounded in scientific principles and anchored to expert-based skills and practice will, in all probability, provide humankind with a great number of future discoveries and inventions.

In K-12 education, too, several companies are offering full suites of XR science simulations that include analytics and reporting functionality. For example, Veative offers more than 550 immersive STEM modules, which can be used on VR headsets, laptops, desktops, and Chromebooks, that guide students through interactive activities and provide formative and summative feedback for students.

In another example, zSpace provides unique simulation solutions for STEM learning in over 800 school districts with an all-in-one AR/VR display with glasses and stylus that transforms science and medical content into interactive virtual objects. With the zSpace glasses, students can participate in individual or collaborative learning experiences.

Finally, Alchemy Immersive (formerly Alchemy VR) takes yet a different approach to K-12 STEM learning by incorporating immersive educational stories of well-known contemporary and historical figures in the sciences. Students can follow Charles Darwin across the Galapagos Islands or dive underwater to the Great Barrier Reef with David Attenborough. Setting a high bar for the quality of their XR experiences, an Alchemy Immersive story won a BAFTA award (the British equivalent to the Academy Awards).

In higher education, with the spread of the COVID-19 across the global community, Professor Mina Johnson-Glenberg, a research scientist in the Arizona State University (ASU) and director of the Embodied Games Lab, has led the development of a web-based and AR COVID-19 modeling simulation by creating an engaging way to teach people how the virus spreads as well as ways to reduce transmission. The simulation works as an interactive public service announcement and focuses on two simple behavioral changes: social distancing and wearing a mask. In the simulation, the user defines the physical spacing and whether or not the game's character is wearing a mask and observes the direct consequences in a 2D or 3D scenario. Johnson-Glenberg's project provides an intuitive and embodied way that helps people better internalize these important messages.

We find it worthwhile to provide a few more examples of how XR technologies have a powerful impact when situated well into the learner's experience in understanding STEM domains and their importance to meaningful living today:

At the University of Michigan, the Center for Academic Innovation seeded six new XR projects in spring 2020 as part of an ongoing effort to fully embrace immersive education. One upcoming project explores the challenges of working within nuclear reactors. The school's Ford Nuclear Reactor in Michigan permanently shut down in 2003 and was decommissioned in the years following, leaving the top-ranked university program without a research reactor. This XR project will develop an Extended Reality Nuclear Reactor Laboratory simulation where students can virtually walk around the reactor, look into the core, and interact with the control panel. As Brendan Kochunas, project manager and assistant professor in the Department of Nuclear Engineering and Radiological Sciences described it (2020):

> *In reality, one does not simply walk up next to an operating nuclear reactor core, but in virtual reality one can. We can also overlay simulation results on the virtualized physical systems allowing students to experience neutron fields or temperature fields visually, where in reality this is not possible.*

A recently announced partnership between the location-based VR company Dreamscape Immersive and ASU will explore the power of immersive storytelling in a variety of disciplines. The new project will include XR experiences for both campus-based and online courses, starting with introductory biology and eventually expanding to other STEM disciplines and beyond. It will include the establishment of immersive Dreamscape Learn Lab facilities on the ASU campuses, where students will work with science, arts, and engineering faculty to discover, observe, and experience hands-on problem-solving tasks in—as ASU's President Michael Crow phrased it—"emotionally driven learning experiences."

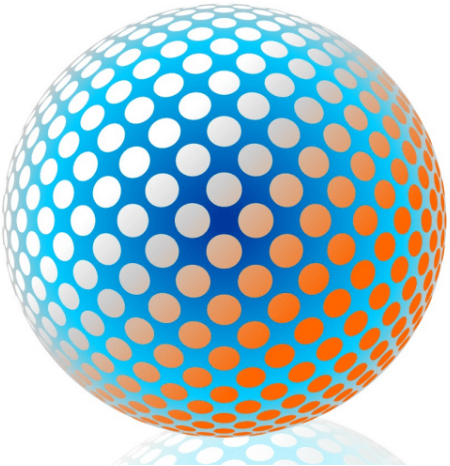
> *For Dreamscape Learn, the Alien Zoo will become an immense VR "laboratory" that allows students to explore, observe and collect digital specimens and solve problems that reflect the key concepts taught in introductory biology. Working independently or in teams, students will confront issues arising in real wildlife refuges on Earth, such as treating infectious diseases, managing genetic diversity and balancing food webs. In doing so, they will complete the requisite coursework for introductory biology in an entirely new, experiential way. (Harth, et al., 2020)*

Students will be able to access the initial XR experiences in Dreamscape Learn in 2021, with an expanded rollout in 2022.

Figure 5: A Virtual Forest Walk developed by Penn State University

Meanwhile, at Penn State University, researchers combined information on forest composition and ecology to create a virtual forest similar to those found in the State of Wisconsin in the United States (Huang, 2020). The causes and effects of climate change can be difficult to grasp, but in a virtual reality forest, users can walk through a simulated forest and see the impact of various developments over time. The virtual reality experience incorporates climate change models, sophisticated vegetation models, and ecological models to demonstrate how multiple systems interact with each other and are affected by external forces. The objective is to create concrete experiences of forests under climate change that can facilitate communication among experts, policymakers, and the general public.

As iLRN advisor and co-founder Chris Dede summarized over a decade ago on the impactful learning gains realized by immersive technologies: “Studies show that immersion in a digital environment can enhance education in at least three ways: multiple perspectives, situated learning, and transfer” (2009). The examples selected for this STEM learning category and others throughout the report demonstrate those very ways of enhanced learning. We expect to continue to see STEM-related educational opportunities expand substantially across the disciplines and in many domains in the near future.



Opportunity 5: Fostering Collaboration with Social VR and Other XR technologies

From the moment Ivan Sutherland created the first VR headset until the advent of the Oculus Rift in 2012, XR has largely been a single-user experience. While there have been so-called "immersive" environments since the days of Second Life, these platforms were still based on flat screens, not true virtual XR experiences. Early Social VR platforms such as vTime, Rec Room, and AltSpaceVR appeared in 2015-2016 and were very much works in progress, with limited functionality and spartan environments. Today, their roles have changed dramatically. We have a wide range of immersive social XR platforms that serve a variety of needs from social networking (VRChat) to science research (Nanome) and academic needs. XR as a social and collaborative enterprise thus holds enormous promise for learning of all kinds, providing capabilities to connect people to one another so that they may learn together.

Despite the rapid expansion of social XR platforms due to COVID-19, the landscape remains highly fluid. Project Sansar, which Linden Labs began developing in 2014 as the much-hyped XR successor to *Second Life*, closed and sold off its assets in 2020. Reacting to the pandemic, collaborative platform Spaces quickly pivoted from providing VR experiences at theme parks and retail locations to video conferencing through XR. And just recently, was acquired by Apple for possible use with their own XR project. Platforms like the fully immersive Engage, AltSpace, and Spatial as well as 3D worlds (accessible on desktop and headsets) like Virbela, FrameVR, and open-source Mozilla Hubs, have become pathways for universities to implement virtual environments in teaching, learning, and social activities.

Facebook's massive OASIS-style Horizon project, an evolution of its work on multiple platforms (Rooms, Spaces, and Venues) remains in invite-only beta status. However, Horizon marks a breakthrough in that everything users encounter in the platform is built using Horizon's own tools, opening new creative possibilities. In addition to Horizon, Facebook announced their Infinite Office project at the recent 2020 Facebook Connect conference. The project's goal is to create a seamless environment where users can simultaneously work in both real and virtual spaces, even using real-world digital hardware such as keyboards that will be recognized by the Oculus Quest 2 headset.

In a year marked by lack of access to VR labs, Mozilla Hubs gave opportunities for students to use collaborative tools and explore creating together in social worlds. At Parsons School of Design in Fall 2020, over 100 students enrolled in the Immersive Storytelling course met weekly in Mozilla Hubs to co-create virtual narratives, play, and build worlds.

Inspired by the work at the [XR and HCI Innovation Labs] at The New School, faculty and students from across the Parsons Art Media, Technology, and Fashion schools exhibited their 3D models and presented projects in virtual galleries using audio, video, and an abundance of student creativity. While students acknowledge the limitations of the Mozilla Hub interface, most reported that they enjoyed the opportunity to be in a shared space. One of the students summed it up: “I think it is very fun to be in a virtual world, for me it is a place where I can explore my ideas that may not be possible to create in the real world.”

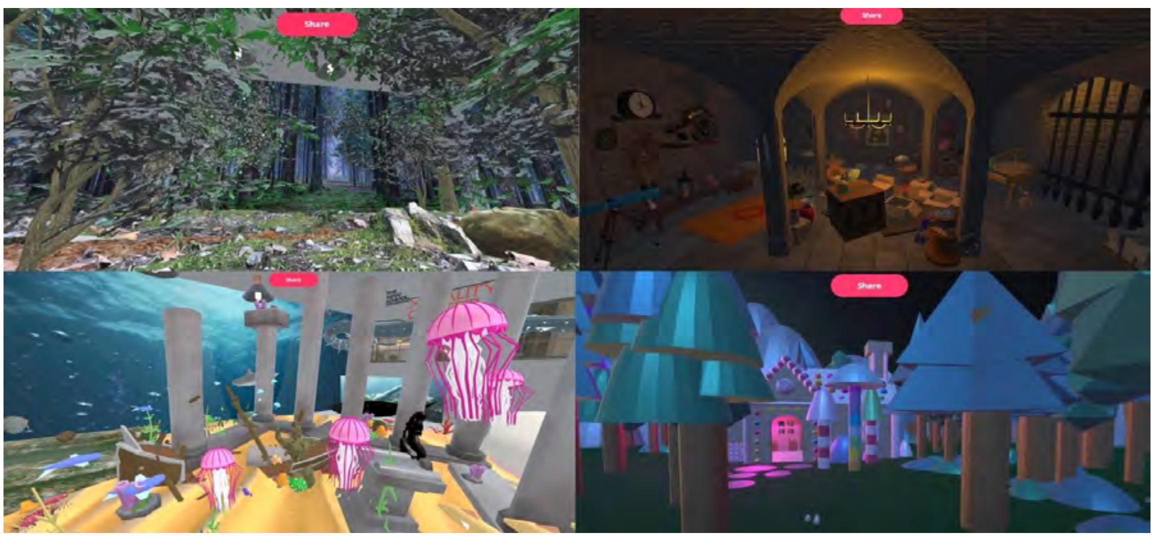


Figure 6: Student-created worlds from the Immersive Storytelling course at The New School’s Parsons School of Design.

Today we view the development of social VR platforms as a new, distinct category in XR, but this distinction will likely fade in the coming years as the opportunities to connect and be present in virtual spaces become a common part of our lives. As the catalyzing technologies such as AI, haptic feedback, and complex avatars analyzed in Research Question 3 mature, mixed reality environments will become integral parts of our students’ learning and working experience—a world where we learn and work alongside virtual humans, digital avatars, and personal assistants. Immersive platforms in the future will become the basis for interactions with both real and virtual beings in our work and learning experiences, raising a slew of ethical challenges as we blur the lines between the virtual and physical worlds.

Opportunity 6: Cultivating Immersive and Blended Reality Learning Spaces and Laboratories

Over the past few years, we have seen the rapid development of blended reality learning spaces and XR labs in K-12 and higher education. While some universities have embarked on building dedicated VR and AR labs, others have incorporated them into existing makerspaces, libraries, and open areas. The role of these facilities has taken a new direction as the global pandemic limited or entirely curtailed in-person visits. Instead of serving as experimental areas for specific courses or programs, many have shifted the scope of their activities to support the urgent and widespread need for remote learning. While some disciplines can be taught remotely through traditional digital tools and course management platforms, others require hands-on experience or interaction between students that XR is ideally positioned to support. The global pandemic has accelerated universities' interest and pace in exploring virtual and augmented environments for learning and social activities.

This new focus has included exploring social VR platforms and providing access to 3D creativity tools, ranging from computer science and engineering fields to art, media, and design schools. However, XR labs face funding challenges and many of the barriers discussed in the second Research Question, including students lacking hardware and high bandwidth for in-depth XR learning experiences. New strategies for accessing XR tools and platforms are being developed in this highly fluid situation, with some labs planning to reopen with limited access in spring 2021, while other institutions are shipping VR devices to students for remote use.

There are, however, several notable examples of large-scale projects or XR labs that are transforming student learning experiences. A collaboration between IBM Research and Rensselaer Polytechnic Institute (RPI) addresses the challenge for many students who do not have the time or financial resources to spend a year abroad. It offers students studying Chinese another option: a [360-degree virtual environment]() that teleports them to the busy streets of Beijing or inside a crowded restaurant. The virtual learning space relies on digital projections of street scenes in China and an array of cameras and sensors that register and respond to students' locations, words, and hand gestures. Specially designed speech recognition algorithms pick up the complexity of the language and the virtual agents as street vendors bargain and respond to the students. The project took inspiration from two faculty members who leveraged role-playing games to help their students learn a foreign language (Hao, 2020).

Figure 7: Cameras and sensors track the students' gestures so they can freely point at objects in a scene to engage. Developed by the Rensselaer Polytechnic Institute.

The Virtual Reality Lab at Deakin University hosts a variety of activities, from students taking part in the School of Engineering outreach activities, including visualizing final project designs and capturing environmental information through 360-degree photos and videos, to research opportunities with corporate partners. The facility has a reconfigurable CAVE/CAD environment that offers large-scale immersive interfaces that can accommodate many individuals at a time or large groups of people. The space includes ambisonic (i.e., full-sphere) surround sound, 3D wall and floor projections, and haptic devices for sensory feedback. Students can manipulate and feel the weight of medical tools, creating a deep sense of realism during their learning activities.

Figure 8: Virtual Reality Lab at Deakin University

The F. Edward Hébert School of Medicine at the Uniformed Services University of the Health Sciences houses the 30,000-square-foot Val G. Hemmings Medical Simulation Facility to train both military and U.S. Public Health Service physicians. Preparing armed forces medical personnel calls for a far more expansive and high-intensity simulation than what most XR labs can provide. Their WAVE (wide area virtual environment) is an 8,000 sq. ft. immersive virtual reality theater that includes live actors and high-quality digital imaging to recreate medical emergencies and mass-casualty events under the most challenging environments.

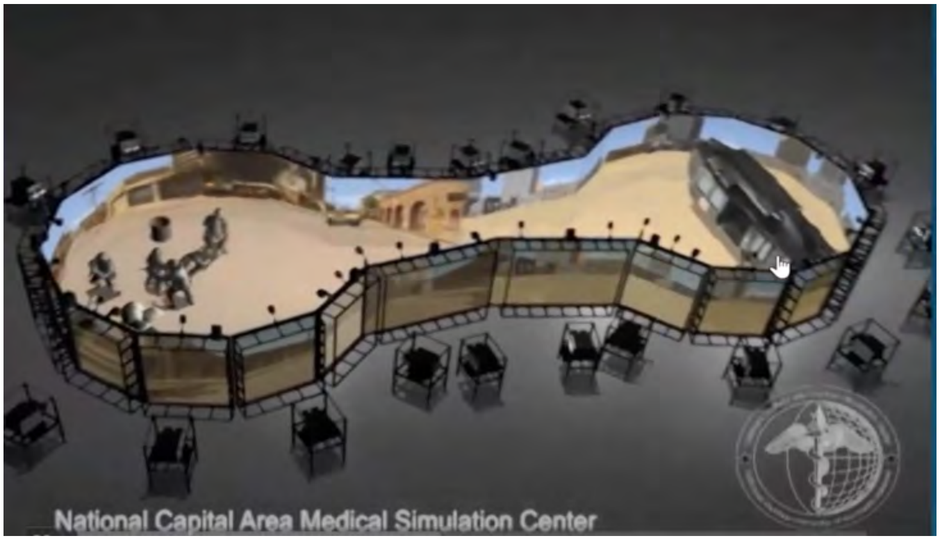


Figure 9: Val G. Hemmings Medical Simulation Facility at the Uniformed Services University of the Health Sciences.

Research and Industry XR labs increasingly play critical roles in developing more efficient and user-friendly manufacturing centers, building designs, and infrastructure planning. One of the largest of these facilities is the massive Elbedome at The Fraunhofer Institute for Factory Operation and Automation IFF in Magdeburg, Germany. Covering 16 meters in diameter and 6.5 meters high with a projection area of 450m², this mixed reality laboratory is particularly suited for the display of large-scale virtual machines and systems for interactive visualizations. In 2019, it was used to test a life-size 3D visualization of the shipping port in Magdeburg.

Figure 10: Elbedone at The Fraunhofer Institute for Factory Operation and Automation IFF in Magdeburg, Germany.

XR labs also play an essential role in the technology sector, serving as research centers for new XR hardware developments. Microsoft Mixed Reality & AI Lab - Zurich has a broad portfolio, working on building the future of mixed reality with computer vision that maps out and understands our environment and develops hardware and software to recognize and track objects. At the same time, Facebook Reality Labs (FRL) Research continues its groundbreaking work in developing highly realistic avatars, a catalyzing technology for deeply immersive XR experiences in the future (see Research Question 3). FRL Labs is also at the center of Facebook's efforts to develop AR glasses and future wearable devices as part of Project Aria.

Finally, Intel's volumetric film studio, referred to as the "world's largest immersive media hub," was a 10,000-square-foot-tall geodesic dome outfitted with 96 high-resolution 5K cameras for *volumetric-capture* (vol-cap) filmmaking. The recently closed studio offered filmmakers and creators a new way of recording that will influence the future of moviemaking. The cameras captured scenes that were converted through algorithms into full, 360-degree virtual environments. The result was "three-dimensional stories" in which the audience stepped into the environment and experienced it firsthand instead of passively viewing it. While the studio is no longer in operation, the development of volumetric capture and 3D scanning applications will continue to evolve and mature with modular and flexible XR studios that open up new frontiers for storytelling and the creative arts more broadly. As XR technologies have matured and as distributed lab teams and needs have grown, we expect to see a proliferation of immersive and mixed reality labs over the next several years in both the workplace and education.

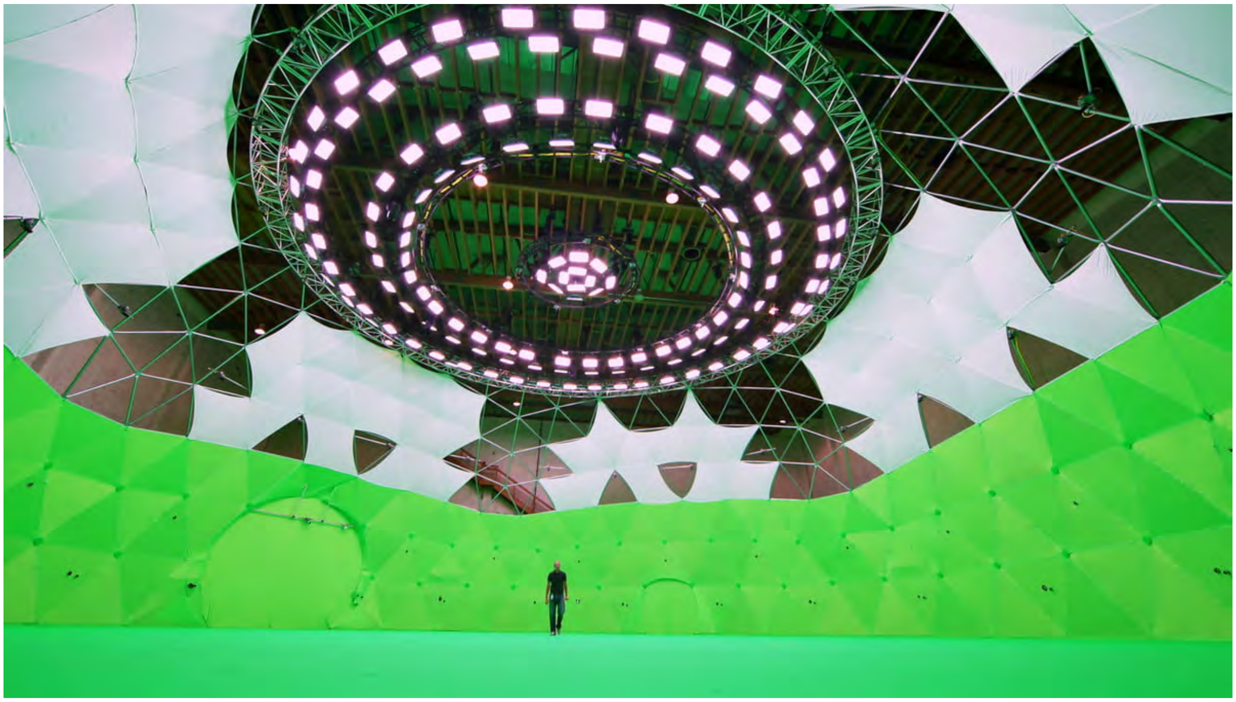


Figure 11: Intel's volumetric film studio.

Opportunity 7: Developing the Capabilities of the Future Workforce

Both K-12 and higher education are under tremendous pressure to reinvent themselves to meet the growing need for an innovative and agile future workforce. As the World Economic Forum wrote in its report entitled *The Future of Jobs* (Leopold et al., 2018):

New categories of jobs will emerge, partly or wholly displacing others. The skill sets required in both old and new occupations will change in most industries and transform how and where people work.

The FUTURE Time Traveller is a project developed and co-funded by the European Union's Erasmus+ programme and coordinated by Bulgaria's Business Foundation for Education in partnership with seven national organizations. The project's goal is to transform career guidance for the next generation of learners through an innovative, games-based approach. Participants are invited to complete seven unique missions as they hone their critical thinking, entrepreneurial, and creative skills while preparing them to make sound decisions about their future professional development and career pathways.

Figure 12: FUTURE Time Traveler initiative is funded by the European Commission and involves 7 recognized organizations from all parts of Europe: the Business Foundation for Education in Bulgaria, the Computer Technology Institute and Press "Diophantus" in Greece, the Italian permanent learning center CIAPE, the European Board for Certified Counselors based in Portugal, the University of Lodz in Poland, the Innovation in Learning Institute in Germany, and the Aspire-Igen group in the UK.

The primary objective of the project is to “foster innovation thinking and future-oriented mindset of young people—through an innovative game-based virtual reality that will help them explore the future world, understand the trends that shape the future world of work, the emerging jobs, the skills they will require.”

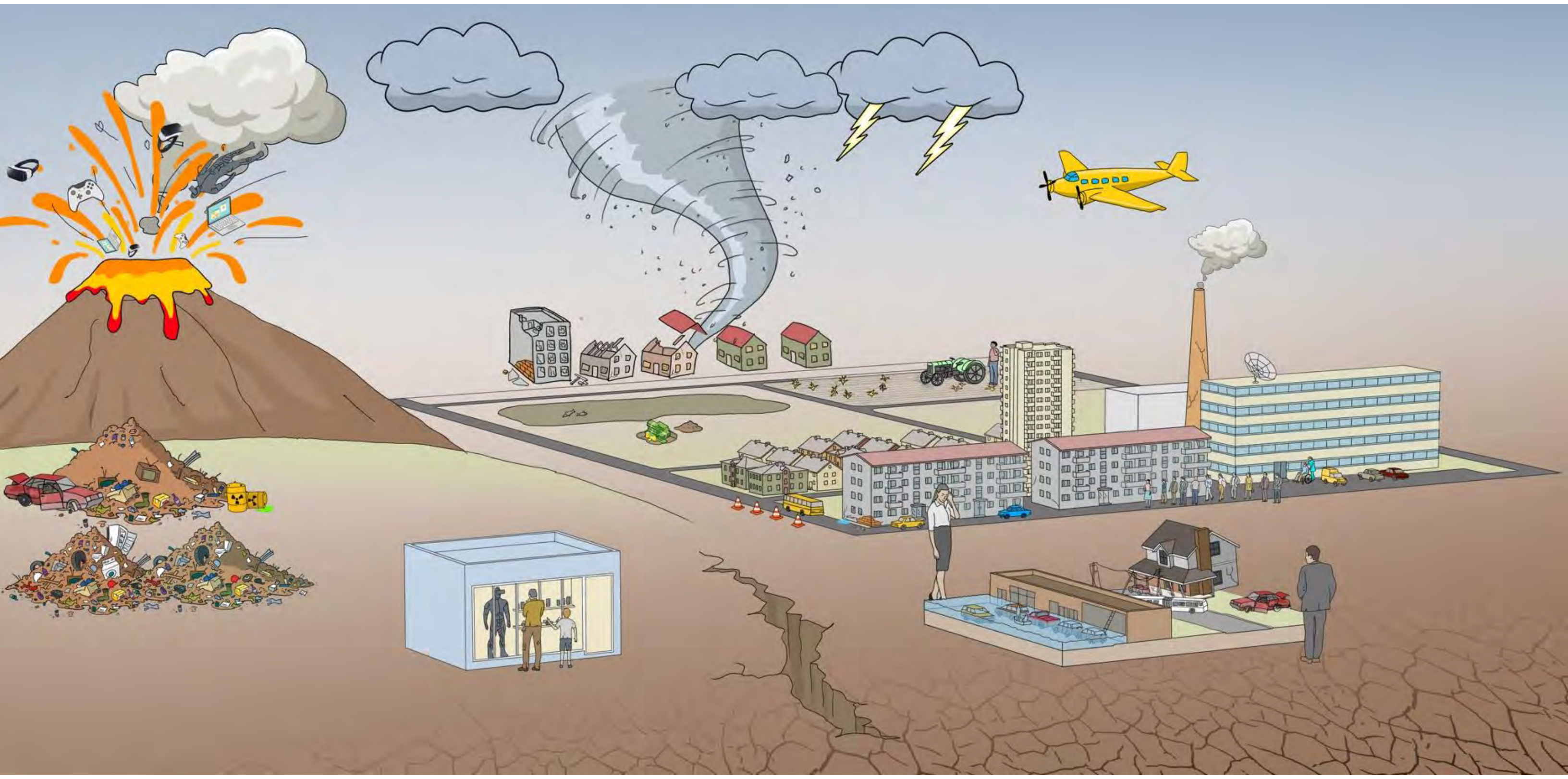
To address the need for on-demand training, XR is already seeing rapid adoption in the workplace. Companies such as the Stanford startup STRIVR quickly evolved from sports to workforce training. They leverage immersive experiences and behavioral science to improve employee engagement, retention, and safety in manufacturing, logistics, retail, and financial services. One of the more creative implementations is with Verizon, which uses STRIVR to train their 22,000 employees in 1,600 retail stores to handle the challenging situation of armed robberies.

Another company, Talespin, uses XR for what it terms the “new OS for work,” training employees in leadership, empathy, teamwork, and decision-making skills. The agile workforce of the future will develop through interactions with lifelike digital avatars that adapt to employees’ learning modalities.

Interpersonal skill training is also being addressed in the healthcare sector, which has historically focused on learning proper procedures instead of human interactions. Companies like MPathic are using virtual beings to help medical professionals and trainees learn how to interpret verbal and nonverbal cues when delivering care and when discussing life-changing news with patients and their families.

As XR continues its rapid evolution, we will see the development of deeply realistic simulations created through catalyzing technologies such as haptic devices and artificial intelligence analyzed in the third Research Question. The workforce of the future will find it difficult to imagine how employees functioned in our era without extensive opportunities to improve their skills through immersive and mixed reality environments.

Research Question 2: **Barriers to Adoption**



What are the greatest barriers for institutions and organizations adopting XR and immersive learning technologies?

While XR enjoys many opportunities and can address various pedagogical needs, it also faces significant barriers to adoption. In this section we'll explore the obstacles our respondents deemed most important to overcome.

Barrier 1: Access

Connecting users to technology in ways that they can apply it is the essential challenge of technology adoption. This barrier is often the result of legal and/or corporate supply chain challenges. For example, some of the major headsets and XR software continue to be out of reach for students and faculty in different parts of the world. The Oculus Quest 2 is not available in China and several Chinese vendors offer XR technology not available in the US and Europe. In addition, as an emerging technology, it is often challenging to anticipate the demand of XR products, and many consumers and organizations in the US are faced with regular delays in acquiring new XR headsets and supporting hardware. Both the Microsoft HoloLens and Oculus Quest headsets have been in short supply because demand exceeded expectations.

Once available, configuring technology to maximize usability for all is one of diffusion's major hurdles. Many types of XR hardware and software remain inaccessible to people with various forms of disability. Specifically, he medium today is predominantly visual, and hence largely unavailable to the visually impaired. While innovative projects are underway (such as Microsoft's Holocane experiment and Samsung's Relúmĭno app), there is no widely available translation method as there is for digital images and 2D websites: no alt-tags, for example, as there are on the web with JAWS-style screen readers. Similarly, XR audio breaks for those with hearing impairments, especially when transcription practices are not in play. Accessibility technologies that allow the modification of the presentation for differently abled users have been extremely complex to engineer with immersive technologies thus far.

The 2020 release of Grzegorz Bednarski's WalkinVR on Valve's Steam distribution platform marks the first major app that allows for adjustments in XR experiences based on users' height and various disabilities. However, additional research and new applications are critically needed for potential users with mobility impairments. As immersive applications and XR content for learning expand, the imperative to address these issues will grow commensurately. Further research and development involving both academia and industry is paramount.

Barrier 2: Affordability

Related to questions of physical access is the problem of economic availability. Much VR technology, especially products that win media and popular attention, is expensive. Most headsets cost several hundred US dollars, and some cost thousands. Moreover, as Jorge Bacca-Acosta of the Expert Panel observed, there are international dimensions to the problem: He observes that in some developing countries the costs associated with VR headsets or AR glasses are very high and some institutions do not have enough budget to buy them. Consequently, students do not have many opportunities for using these technologies as part of their learning process. In some cases, only few universities can afford those devices and then mainly for research purposes. This might restrict the use of these technologies in schools and might increase the digital divide between developed and developing countries.

The well-known exception to this rule is Google Cardboard, a VR frame that costs roughly $10 to purchase or even less to print. However, using the technology requires access to a smartphone—which, while popular, is neither ubiquitous nor generally low cost. Moreover, as Bacca-Acosta notes, "the interaction and the experience is not the same," as with the higher-end devices and ecosystems. Google has also recently ceased to support Google Cardboard (2021) and users are turning to such applications as Thinklink and web VR solutions as viable alternatives.

Other infrastructure costs are barriers to educational uses of XR. Additional computer hardware is necessary for some platforms, such as PCs with the right combination of sufficient graphics, CPU, and memory capacity, all of which can exceed teacher and student access. Downloading or streaming XR content also requires significant bandwidth, which is not necessarily available in all schools, homes, or other needed locations.

This is, on the face of it, a basic challenge to equity and inclusion, and one that becomes more salient when we consider the current educational emphasis on meeting the needs of marginalized learners, many of whom face economic hardships on top of other marginalizing dynamics. These hardships have been further exacerbated in countries suffering a COVID-19-driven recession, where many families have lost spending power and schools have faced funding cuts.

Barrier 3: Inadequate XR Teacher Training Programs

At many educational institutions, support structures for faculty, staff, and students in the use of XR support is either nonexistent or in their infancy. Since the technology still has a way to go in terms of its ease of setup and overall user friendliness, those support structures are even more crucial to growing adoption.

A 2018 EDUCAUSE report noted the following: “Some early adopters on campus will teach themselves to use 3D [i.e., XR] technology, but many campus users will need support to learn to use this technology. The development of training sessions and workshops on 3D technology–related topics is critical for these technologies to gain traction on campus beyond the rarefied circles of early adopters.” Almost three years later, this remains a challenge.

In addition to technical support, educators also need pedagogical and instructional design support to assist them in successfully integrating XR into their teaching practice. There is a budding world of online peer support in this regard, especially accessible through social media networks and other online forums. Online events can also help educators, like Educators in VR. In addition, iLRN (the publisher of this report) hosts virtual world meetings on XR educational topics on its iLRN Virtual Campus, powered by Virbela. Commercial providers are also starting to offer online resources, such as Lenovo VR Classroom. Some also offer support for a fee, such as ThingLink. Mobile phones also have a number of apps and capabilities that make AR fairly affordable (LiDAR, etc.).

Postsecondary educators are starting to offer graduate programs in XR support, notably California State University Northridge, which has developed an MA in Instructional Design with a focus on XR and immersive games and simulations. We should expect more of this, especially as the novel coronavirus drives up demand for instructional designers for online learning. There are precedents from the virtual worlds community, where we saw colleges and universities offer specialized courses and even programs (e.g., MA Education in Virtual Worlds offered by the University of the West of England). On another level, teacher XR certification may be desirable, but there are no examples of it at the time of writing this report.

Barrier 4: Interoperability

As XR rises, it enters a digital world split by two competing organizational paradigms. On the one hand, we can find content and services based on interoperability and shared standards, from basic web pages and APIs to the pdf, html5, and mp3 standards. On the other, we see closed ecosystems that reduce or bar movement of data and access to various degrees for a range of reasons, including security, lack of standards, and maintaining business models. XR so far has proceeded down the latter path, as most of its content is locked to certain hardware, software, and commercial structures. For educators, this presents a range of challenges, including increased training time (on multiple platforms), difficulty aligning particular technology capabilities to good pedagogies, and forcing organizational priorities and standardization.

For instance, many learning institutions are selecting and using VR headsets for teaching and learning. The gear they ultimately choose sets up a trajectory of subsequent decisions dependent on the implications of that headset selection. The user requirements, software catalog, user training support and community ecosystems particular to each of these VR headsets create an effective ”walled garden” for these educators, within which they are then constrained, even while the same headset can afford many benefits for teaching and learning. Such choices thus combine pedagogical advantages and operational constraints due to this lack of interoperability.

To be fair, the jump to 3D from 2D technologies is a large one. A great deal of innovation, experimentation, and discovery may precede the development of standards and interoperability, especially insofar as they require agreement amongst designers and manufacturers. We can find a useful comparison in the rise of the World Wide Web. Sir Tim Berners-Lee's creation grew and scaled rapidly by relying on metaphors and infrastructure from many preexisting human innovations, especially our reliance on text and basic images, during the Web's early days. In contrast, the media demands needed to enable digital embodied movement through 3D immersive spaces are far more intense. Further, XR has fewer ubiquitous media to piggyback.

However, here have been some efforts towards greater XR interoperability. In 2019, the XR Association published a developers' starter guide calling on content creators to adhere to standards. The IEEE 1589-2020 - IEEE Standard for Augmented Reality Learning Experience Model (ARLEM) working group is learning-specific, led by Fridolin Wild to support the implementation of AR training systems in the work environment. The ARLEM standard, which is sponsored by the IEEE Learning Technologies Standards Committee, is one of over a dozen other standards that have been developed or are in development under the auspices of their VR/AR Standards Committee. We expect the demand and efforts to achieve XR technologies interoperability to intensify.

Barrier 5: Lack of Content

As with any emerging technology, educators face the problem of finding educational content for XR, or content capable of being repurposed for educational use. While some educational content exists and the amount is growing, we have yet to see XR materials available across the curriculum. One reason for this shortfall is the quantity of resources required to develop XR content. As with creating any educational materials, a publisher requires time to create them and staff with the right expertise required to proceed: technical skills, subject matter expertise, assessment knowledge, and an understanding of the audience. Educators may hold the latter three, but not necessarily the technical aspect, and are certainly challenged for time to learn. Indeed, as Expert Panelist Jason Jerald put it in the project workspace,

> *I suspect commercial training is going to move faster in regard to XR than educational institutions due to cultural, structural, administrative, and political challenges.*

That said, we can point to areas of study where XR educational content is appearing. In the lead is the medical field, which has a centuries-long tradition of developing simulation materials for learning. Some other STEM fields are also leading the way in XR development, partly because they are more likely to have access to technical expertise, and because content visualization is a major issue for many of their classes.

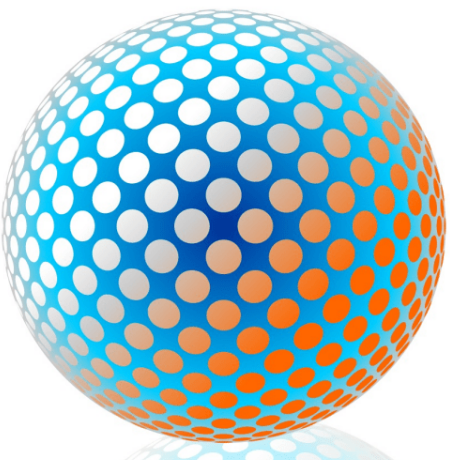
Cyntia Franco offered a fine example of this in the project workspace:

> *In 2017 I was engaged with the School of Physics, University of Sydney. My job was to coordinate the transfer of all School of Physics unit content from Blackboard to Canvas LMS. On my way of transfer all content from all 4 years of Physics and Astrophysics, I saw an opportunity to engage with the use of Virtual Reality on basic content of Astrophysics, "Stellar Evolution." With some skills in VR Development, I create an engaging*

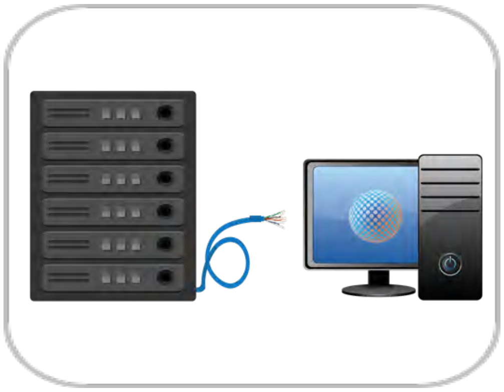
project designed to teach students about Stellar Evolution, using real simulation of star evolution. Students were building stars and analyzing the evolution of the stars during the simulation timeline. Students were using critical thinking and creating their hypothesis about the relationship of the star mass and their evolution lifetime.

There is XR creation in the arts, but often outside the education ecosystem. Filmmakers have been exploring new forms of storytelling, with VR films debuting in the Tribeca and Sundance film festivals. Museums have also been mounting XR presentations, including the Museum of the University of St. Andrews.

Meanwhile, new tools have been appearing that might prove useful for educators who wish to create XR content. Trivantis and CenarioVR have released VR e-learning authoring tools, while LearnBrite offers VR functionality in its suite of instructional design tools. Other applications have recently appeared which, while not aimed solely at learning and teaching, can be used for that purpose: Zappar, BlippAR, and Adobe Aero. The call for greater diversity and scope of high quality XR-for-Learning content for learner populations of all kinds will continue to grow for the foreseeable future.



Barrier 6: Lack of Infrastructure and Tech Support



As with any technology, educational deployment requires a baseline of infrastructure. Institutions and organizations must be able to provide the right mix of hardware, software, and networks to handle XR. Equally as critical is human infrastructure, including technical support, which requires hiring or training people who can not only use the technology fluently but to also deploy it in educational settings. As Cynthia Franco observed in the project workspace:

> *We need well-trained personnel to push the barriers to adoption, these personnel are expensive technologists, as they acquire their skills independently and most of the time under their own expenses. XR companies are the catalysts of these special technologists, by being innovative, these companies attract technology pioneers.*

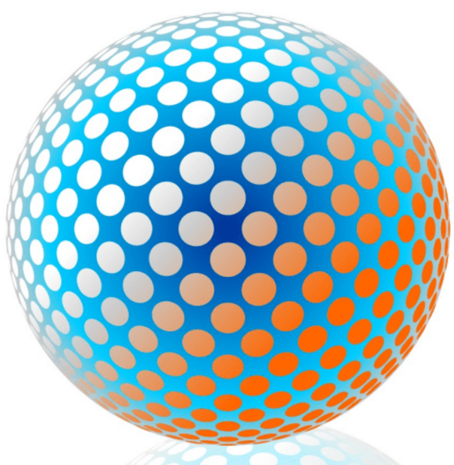
Also in the workspace, Erica Southgate linked infrastructure to access issues:

> *I work with schools from low socioeconomic and rural communities doing research on VR and learning. Access is an issue in terms of affordability (and immense confusion) concerning hardware, bandwidth with streamed applications, issues with the range and quality of student mobile devices esp. smartphones in BYOD contexts, a lack of smart devices that the schools own as class kits, and school system networks which block access to game stores or applications meaning teachers have to take equipment home to update it on their own data and this too can be an issue in rural areas with limited connectivity.*

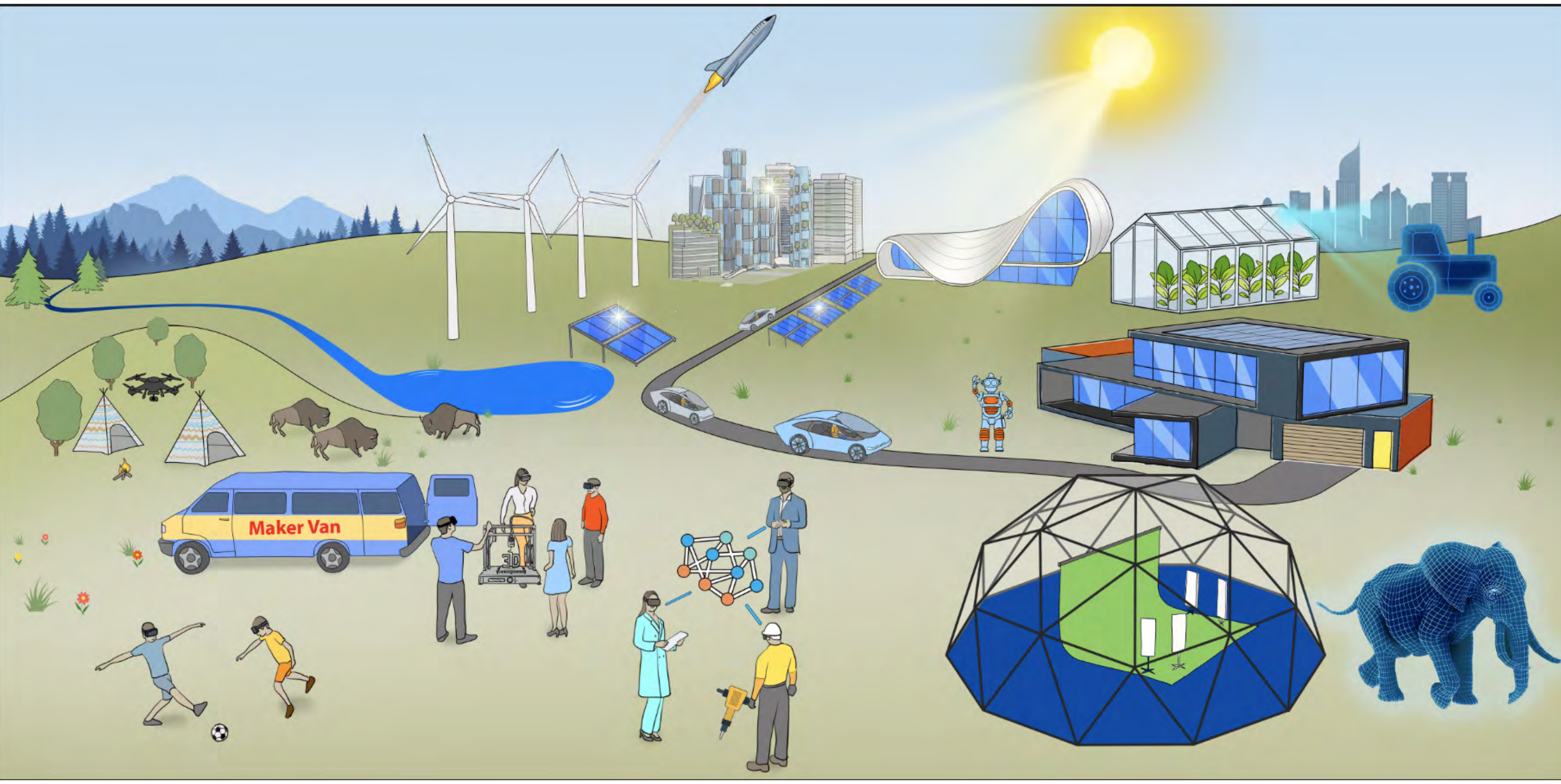
Additionally, for those faculty and support staff who wish to learn about XR or to keep current, professional development lags. Moreover, XR use remains on the small scale of pilot or class projects; enterprise-level (campus-wide) uses are rare. In other words, XR remains at the early adopter stage and requires technical and human scaffolding to grow.

The support picture is not entirely bleak; the tools do become easier to use over time. as Jason Jerald observed in the Expert Panel project workspace, “Fortunately easy-to-use systems such as Oculus Quest are making this less of a problem.”.

We believe that the growing community of experts interested in deploying these XR-for-Learning and other immersive technologies will address the barriers outlined in this report and more, as the application potential becomes clearer to all and as the community becomes better organized.



Research Question 3: Catalysts



What XR and immersive or other related/complementary technologies, tools, and digital developments have the potential to help transform learning and teaching/training practices?

As Research Question 1 examined the needs and opportunities of XR and Research Question 2 explored the barriers to adoption for organizations and end-users, in Research Question 3, the Expert Panel turned toward catalyzing developments in the future. The panel explored XR and its broader ecosystem of converging and related technologies to understand its potential to transform teaching and learning.

Catalyst 1: Flexible and Open XR Resources

Understood as a catalyzing development, the (in)ability to access open XR content through learning object repositories (LORs) remains a fundamental challenge for education and training.

Currently, there are no collections of full XR environments, and repositories of XR assets face their own unique challenges. As a nascent field of practice, developing high-quality content in XR is generally a costly and labor-intensive undertaking. Unlike many traditional open educational resources (OERs) such as lecture notes, syllabi, assignments, readings, and assessments, which can be the product of individual faculty or staff members, developing a complete XR experience often requires a sizable team that may include not only content specialists but also software engineers, user-experience (UX) specialists, scene modelers, 2D and 3D artists, sound designers, and producers.

Existing LORs were designed to cater to individual learning objects, not full-blown virtual experiences and environments. Widely used metadata standards (IEEE LOM, Dublin Core, etc.) were originally intended for a world of electronic document publishing as opposed to complex XR environments that are ambient, three-dimensional, and user centered. The field will need new data-tagging and interoperability standards to ensure that assets are modular, reusable, and scalable. In addition, LORs housing XR resources will face challenges in infrastructure capacity and delivery, especially if they are designed to host remotely accessible experiences.

Despite these challenges, open XR resources are emerging in several areas, including open repositories, collections developed by commercial vendors and other non-academic organizations, and more focused educational projects.

- The **OER Commons** website holds a limited number of XR resources. A majority of the current content focuses on teaching resources (such as how to teach with XR), not actual simulations.

- **Sketchfab** has quickly grown into one of the largest existing XR repositories in terms of users and content. Technically, only a percentage of the content is open, as many XR developers utilize the site to sell their work (though much of it is priced at nominal cost). The vast majority of the content listed is not comprised of complete virtual scenes or simulations but rather individual assets that creators use for their own projects. Sketchfab incorporates many of the essential features for an XR-focused LOR, including platform compatibility information, licensing models, tagging, user reviews, and comment sections.

- **Non-academic organizations**. Several focused collections of XR content have been created by established news organizations and nonprofits, including the BBC, Guardian News, and *National Geographic*. The numerous AR/VR experiences by *The New York Times* are available on the Web, their mobile app, and in the Oculus Store. It includes groundbreaking projects in immersive journalism and storytelling such as The Displaced, Remembering Emmett Til, and David Bowie in Three Dimensions.

- **Published lists of resources**. With little organization of the XR content that is freely available, organizations such as ISTE have published lists of XR resources. These guides are generally designed for K-12 teachers, though many are useful for higher education faculty exploring the potential of XR in the curriculum. Some of the resources in ISTE's list are under a subscription model but most are free, including 360Cities (which hosts 360 videos of urban areas, natural scenes, and historical sites), CoSpaces EDU (a platform for students to create and animate their own 3D scenes), and the freely-available 360 video content on YouTube 360.

- **Industry vendors.** Several companies offer free educational XR resources through repositories designed to support their products and platforms. For example, the Lenovo Classroom VR platform includes free content from other vendors, including 360 videos from *The Wild Immersion* project and access to the interactive, curriculum-aligned, XR modules from Veative. However, only 40 of the 500 STEM, ELL, and virtual tour modules are free, with the others available at additional cost. In addition, Lenovo offers K-12 lesson plans and assessment examples as part of their VR classroom package.

As the XR community addresses the need for open repositories, the Expert Panel noted the work of individual practitioners and the need to be forward thinking when developing new models. One notable example is the work of David Towey and others at the University of Nottingham Ningbo China (UNNC), summarized in the TALE paper, “Developing Virtual Reality Open Educational Resources in a Sino-Foreign Higher Education Institution: Challenges and Strategies” (2018). In addition, the SAMR Model for selecting, using, and evaluating technology developed by Dr. Ruben Puentedura might serve as a model for the future. By categorizing immersive learning technologies on four levels that move from simple substitution to augmentation, modification, and ultimately redefinition, Puentedura’s work may provide a foundation for understanding the impact of XR on learning environments.

Catalyst 2: Haptic Feedback and Sensory Interfaces

The catalyzing developments in the area of haptic feedback and sensory interfaces hold the potential to reshape the use of XR in education and workforce training.

While the early research in XR focused on visual and auditory input, haptic feedback and sensory interfaces will deepen the sense of presence and the real-life feel of immersive experiences.

Haptics can be divided into passive and active modalities. The former involves positioning low-fidelity real world objects such as doors and walls to correspond with their high-fidelity virtual counterparts in XR. Passive modalities help resolve one of the most unsettling aspects of virtual environments — that virtual objects do not behave like their counterparts in real life (where you are unable to walk through walls or windows). However, the more groundbreaking research is in the area of active haptics, which strives to integrate all of the human senses into XR experiences.

Several innovative haptic feedback developments incorporating touch and non-touch (ultrasonic) technologies were identified by the Expert Panel and the SOXR team:

- **Haptic suits and vests**. Full-body suits such as the Tactsuit (from bHaptics) and the Teslasuit provide a deeply immersive solution to haptic feedback in XR experiences. The Teslasuit is a complete full-body interface designed to provide thermal and haptic feedback (enabled by 80 electro-stimulation channels), motion capture, and a biometric system (through embedded ECG and EDA sensors). Gathering real-time data from users, including their emotional state, stress level, and key health indicators, it supports interactive and personalized XR training content. Haptic vests offer more limited feedback but present challenges in terms of cost and sizing issues. They are popular in the gaming community and increasingly found in XR labs.

Figure 13: TactSuit is a line of wireless haptic accessories.

- **Haptic gloves**. Haptic gloves are an easier-to-use solution that may cover a significant portion of our interaction with virtual environments. The Tesla Glove (which can be optionally paired with the Teslasuit) includes haptic and force feedback features designed for entertainment, workforce training, and learning activities. An array of nine electrodes on each finger produce the sensation of touching a virtual surface, while a plastic exoskeleton creates resistance that simulates the grasping of solid objects. Other companies (HaptX and VRgluv are two examples) have also developed haptic gloves and research continues in miniaturizing the technology so that the devices do not interfere with the sense of immersion in XR experiences.

- **XR body devices**: Innovative haptic solutions are also coming to the market, including the crowd-funded Feelbelt, a wearable haptic belt, and Droplabs EP 01 audio-enabled footwear that can connect via Bluetooth with gaming and XR headsets. While these devices lack the full range of sensory feedback found in haptic vests, they are low-cost alternatives that could be leveraged by university XR labs and public exhibitions. They also hold the potential to serve as assistive devices for people with hearing loss or those who are hard of hearing.

- **Haptic clothing and digital skins.** Researchers at Northwestern University are developing the soft silicon wireless patches (Yu et al., 2019) from vibrating silicon wafers that may eventually be incorporated into haptic clothing without the bulk of full-body suits. The early seeds of this work can be found in the Google ATAP

(Advanced Technology and Projects) Lab's Project Jacquard, which focuses on standards and designs for wearable fabrics that interact with our digital devices.

- **Multisensory devices**. Several companies have developed supplemental devices that can be attached to standard XR headsets. Feelreal is a multisensory mask device utilizing a "scent generator" that utilizes replaceable cartridges with aroma capsules. The crowd-funded device generates warm and cool wind, water mist, and vibrations next to the user's face. The project is currently on hold due to the need for FDA certification as it uses the same technology as vaping devices. OVR Technology's Architecture of Scent project offers haptic applications that include a library of over 200 scents "which are grouped into aromas associated with camping, cooking, garden, baking, and trauma (such as gunfire, burning rubber, blood)." They have partnerships with several XR projects, including the University of Southern California's Bravemind Exposure Therapy program for returning veterans with post-traumatic stress disorder. Computer scientist Jas Brooks and colleagues from the University of Chicago (Ackerman, 2020) are researching digital synesthesia, which uses odorless chemicals to access the trigeminal nerve in the nose to trigger sensations of hot and cold in XR experiences.

Several research projects and initiatives are focusing on the development of nonphysical interfaces for XR experiences. At the furthest reach of this frontier is the work on brain-computer interfaces, which could profoundly transform the implementation of haptic feedback and, ultimately, our relationship to technology.

- **Eye-tracking technologies**. Eye tracking is critical for XR developments in several ways. Companies such as Tobii provide an eye-computer interface with hardware for eSports, games, and XR experiences. It provides users with limited ability to manipulate virtual objects with their eyes. The Magic Leap 1 uses eye-tracking technology to render virtual objects at the appropriate distance, integrating them into the user's surrounding environment. Oculus has been researching eye-tracking for foveated rendering in headset displays, concentrating high-definition renderings directly in front of the user's gaze. This would lead to more realistic XR displays while simultaneously saving on processor and battery use. HMDs with eye-tracking capabilities hold tremendous potential in the learning environment. As Craig Vezina, Executive Director at Z School, stated:

  > *What I find very exciting is that because we can measure how people move, because we can measure where they're looking, what they're*

paying attention to, things that before we were collected in a subjective and analog way, we now are able to collect in a reproducible & objective fashion. This offers tremendous new tools for research, but also new tools for assessment.

- **Hand-tracking technologies**. A major goal of XR headset designers has been the implementation of hand-tracking solutions that would alleviate the need for hand-controllers and open the door to innovative XR interfaces. Since XR hand controllers are primarily modeled on video game controllers, it would resolve a common tech barrier for older adults who did not come of age in the modern digital gaming era. Oculus has been at the forefront of these developments (implementing hand-tracking on the relatively low-powered Quest), along with Magic Leap and Microsoft (with its innovative gesture-based commands on the new HoloLens 2). In August 2020, Qualcomm announced an agreement with UltraLeap to create a wide range of XR headsets based on their new Snapdragon XR2 chipset. Hand-tracking is likely to be one of the first catalyzing technologies that we will see fully implemented in the next 2-3 years.

- **Nonphysical haptic solutions**. UltraLeap (formerly Ultrahaptics) is using ultrasound to project tactile sensations onto users' hands. Users 'feel' and interact with virtual objects and controls in mid-air, without controllers, wearables, or touching physical objects. UltraLeap currently partners with automotive, location-based entertainment, industrial training, medical, and gaming companies. Their 2019 acquisition of Leap Motion, which made hand-tracking systems for XR headsets, raised considerable anticipation in the XR community on the future potential of nonphysical haptic and sensory interfaces.

- **Brain-computer interfaces**. Neurable provides easy-to-use hardware and software tools that "read" electrical brain signals using non-invasive electroencephalography (EEG) techniques. While current experiments have demonstrated only limited brain–computer controls, the field has seen considerable progress over the past decade. The goal of Elon Musk's much-hyped Neuralink project is to achieve a direct integration between humans and technology through a brain–machine interface (BMI). The project is developing a procedure for robotic surgical implantation of up to 96 flexible "threads" incorporating up to 3,072 electrodes. While Musk's purported goal is ultimately to find a solution that helps us keep up with the rapid development of AI, which he has called humanity's "biggest existential threat" (Piper, 2018), BMI applications would revolutionize XR interface design and have far-reaching implications for the treatment of neurological disorders.

Catalyst 3: Volumetric Capture and Motion Sensing

With rapid improvements in technology over the past decade, motion capture has moved from high-end digital studios to the “prosumer” level, affordable to startups and higher education XR labs. Declining costs and new scanning devices will eventually shift the technology to the consumer level with mobile or home motion-capture systems.

Several motion-capture solutions are already in use in media studios and universities. XSens is a motion capture solution for 3D character animation using Xsens’ motion-capture (“mo-cap”) equipment and proprietary mo-cap software, MVN Animate. The mo-cap platform by OptiTrack was used in the first AR surgery, the development of the VR game *Call of Duty: Modern Warfare*, and the making of *The Lion King* 360-degree-video experience. The company provides a variety of build-your-own systems for low-latency, wide-area tracking for CAVEs and HMDs. Finally, Vicon hardware and applications are used in the life sciences, engineering, and entertainment sectors to create XR experiences.

Future developments in this group of catalyzing technologies include advanced research on avatars, creative projects that use real-time body tracking, and experimental projects to create larger multiuser virtual spaces. The following are representative examples that push the boundaries of our current XR experiences and environments.

- **Advanced avatars**. From Facebook’s early experiments with XR avatars in 2016, the company has made remarkable progress by incorporating hand gestures and facial expressions. Their groundbreaking work at the renamed FRL in Pittsburgh focuses on developing lifelike avatars that replicate human motion, facial expressions, and eye movements. Their Codec Avatars are currently created through large-scale 3D capture installations and AI systems that will eventually shrink in size and cost. In the future, these developments will become accessible to XR labs in higher education and other organizations, expanding the use of virtual avatars in the workplace and learning environments.

- **Experiments in embodiment**: With limited funding sources, XR developers across the globe have found a welcome home for creative work at film festivals. Tribeca, Sundance, and the Venice film festivals (to name just a few) provide financial support and recognition for a growing number of groundbreaking XR projects. For example, Maria Guta's *Interlooped* XR experience at the 2018 Sundance Festival incorporated a virtual environment, real-world objects, and digital avatars created through live motion-capture. Combined into a single XR project, the motion-capture technology was no longer a development tool but a live virtual production platform (a long-term goal of many media artists and developers), an essential feature of the virtual experience itself.

- **Expanding virtual space**: From Vive's introduction of its room-scale positional tracking system (creating a 5-meter diagonal area) in 2017, XR spaces continue to evolve in size and sophistication. Facebook's experimental *Dead and Buried Arena* demo at the Oculus Connect 5 conference offered a massive 4,000 sq ft virtual play area, which they referred to as "arena-scale VR." More recently, the XR studio Inner space created a "poetic virtual garden" project covering an area of 15 meters by 30 meters, with the ability to include eight people simultaneously using the Oculus Quest. Immersive domes are also evolving from their initial iteration as static, resource-intensive installations in universities and research centers to portable, modular kits. These developments will bring new flexibility and the option of developing large-scale multi-user virtual spaces in our institutions of learning.

Catalyst 4: XR and Games

Not surprisingly, the gaming industry is one of the main drivers of XR innovation. This is partly due to the marketing focus for two of the most popular XR platforms, PlayStation VR and Oculus Quest. The current global pandemic has also had an unanticipated impact of driving the need for new forms of contactless entertainment. There are several catalyzing developments in this area including sophisticated XR games, the integration of game mechanics in XR, and scenario-based learning in XR.

Spring 2020 saw the release of several deeply realistic XR games with complex virtual environments. In both Stress Level Zero's *Boneworks* and Valve's long-awaited *Half-Life: Alyx,* almost every object can be manipulated and responds differently based on that object's real-life size and weight. *Half-Life: Alyx* also incorporates a variety of game mechanics in the first chapter, providing the user with the opportunity to become familiar with the environment and tools.

But as content creators have long recognized, the power of games lies less in their realism than in their dynamics to encourage users to focus, engage, and persist on critical tasks. As Jesse Schell has argued in *The Art of Game Design: A Book of Lenses*, "the same basic principles of psychology that work for board games, card games and athletic games also are the keys to making top-quality video games" (2020).

While traditional learning games offer players a sense of autonomy, identity, and interactivity (Gee, 2004), agency is radicalized in XR. Players are no longer bound by an external board or screen, but fully immersed in the environment. User agency can be an obstacle or an opportunity depending on the game design (both *Grand Theft Auto 5* and *Red Dead Redemption* are well known for the non-game activities that users pursue). With Valve releasing a set of modding tools for *Half-Life: Alyx* that allow users to build new environments and levels in the game, it will be fascinating to see how game dynamics are implemented in user-created experiences.

Figure 14: Half-Life: Alyx is a 2020 virtual reality first-person shooter game developed by Valve.

Several XR projects are leveraging scenario-based learning. Role-playing is a common technique in face-to-face training in the workforce, but users often struggle with the believability of the actors—especially when they are coworkers—and settings that may be out of context. Scenario-based learning in XR fully immerses learners in real-world situations where they face challenges and solve problems in virtual environments that closely mirror their actual experience. The experiences can be repeated at low cost, serve as safe places to fail, and ultimately deepen practice and aiding retention and recall. Virtual actors and patients can be programmed to challenge students based on their abilities.

Here are two examples that use game dynamics in scenario-based learning:

- **Labster** is a Copenhagen-based startup that offers virtual science labs designed around gaming and scenario-based learning. Their fully interactive lab simulations support open-ended investigation based on mathematical algorithms, virtual learning assistants, and gamification elements to engage students in the learning process. With the global pandemic, use of the simulation has expanded rapidly as schools and universities look for alternatives to video-conference-based learning environments in STEM disciplines.

- **The Virtual Trauma Center at Children's Hospital in Los Angeles** is an interactive, programmable, AI-based simulation designed to help students learn how to save an infant in anaphylactic shock or a child who has suffered a seizure. Students work with a virtual patient in a complete recreation of a trauma center, including hospital staff, parents, and other virtual actors**.** Similar to the way airline pilots are trained in flight simulators, elements of the simulation can be adjusted to meet students' skill levels and learning needs.

Catalyst 5: Artificial Intelligence and Machine Learning in XR

As with all paradigm-shifting technology developments, the most significant impact of XR will arise from its convergence with other technologies, especially AI. This will profoundly influence how virtual environments are generated, the use of avatars in XR simulations, and data gathering and analysis of user experience. The latter is particularly important both for the development of adaptive and personalized learning experiences and for the privacy implications it raises.

AI-generated environments. Research is underway on how AI can be used in the creation and delivery of XR environments. Facebook is experimenting with future XR display technologies, demoed at Oculus Connect 6, that incorporate foveated rendering. The headsets will reconstruct the peripheral details of our vision in XR experiences through machine learning algorithms to compress the display data streams. The HMDs utilizing this technology will likely require eye-tracking capabilities, as in the Vive Pro Eye).

- The XR developments here parallel the broader emerging media landscape where AI is used to resolve high-resolution rendering challenges (see the forthcoming version of Unreal 5). Overcoming the hardware limitations of current XR displays will open exciting opportunities in creating new immersive environments while at the same time raising ethical concerns about the authenticity of the content we experience.

AI-driven avatars (embodied AI) and virtual assistants. One of the most striking uses of AI is in the development of virtual avatars. Encountering Magic Leap's MR avatar, Mica, is a deeply compelling experience as she responds to users' gestures and eye movements. As a holographic instead of robotic entity, her movements and interactions are much more fluid and natural. While not designed directly for XR environments, Soul Machines' avatars demonstrate the growing sophistication and power of AI-driven avatars that can remember faces and base their responses on a history of previous interactions. In July 2020, Soul Machines partnered with the World Health Organization to share life-saving information and combat misinformation during the COVID-19 pandemic.

Figure 15: Mica, a humanlike artificial intelligence avatar that can be viewed with Magic Leap headset.

- **Personal AI avatars**. The past few years have seen the release of consumer AR and mixed reality apps that support virtual companions. With the coming release of AR glasses, these virtual avatars could become everyday companions in our lived experience. The current mobile app avatars are primitive instances of AI companions, but reveal the potential of this catalyzing technology to impact learning in higher education, workforce training, and personal entertainment. How they will be used in the learning environment remains a speculative exercise, but one could envision students in the future working with university-provided avatars that serve as 24/7 coaches and guides through their educational journey. Ultimately, AI-based avatars might become part of student orientation programs and extend beyond graduation through alumni relations.

  As the following two examples reveal, AI avatars are moving beyond the limitations of the now ubiquitous chatbots that are part of our digital lives.

  - **Replika** is an app-based AI avatar that resides on a smartphone (with free and paid subscriptions) and serves as a virtual companion. Despite its rudimentary form, the user reactions on the Replica Facebook group are a fascinating window into some of the complexities of how we will relate to avatars in the future.
  - **Gatebox** is Alexa-type assistant that “lives” in a capsule as a virtual figure. Originally developed as a home companion in Japan, the expensive

device ($1,392 plus $14 a month) was in the process of transitioning to a customer assistance model before the pandemic struck.

- **Analyzing data intensive XR environments**. XR simulations and virtual environments will generate massive amounts of data on user experience. This will not only raise fundamental privacy issues, but infrastructure challenges related to how this data is stored, managed, and accessed. An Internet Engineering Task Force (IETF) Draft Memo, entitled “In Network Computing Enablers for Extended Reality” (Montpetit, 2019), proposes the use of dynamic network programmability that enables joint learning algorithms across data centers, edge computers, and HMDs. This would lead to the creation of semi-permanent data sets and analytics distributed across a variety of environments and devices instead of a single location. The data generated through XR environments will be essential for developing adaptive and personalized learning experiences in the future.

Some members of the Expert Panel felt that the data generated through XR experiences would revolutionize learning since teachers would have access to a vast array of analytics on students’ attention, and even their physical and emotional states in interacting with learning resources. Others expressed deep concerns about how this data will be collected, stored, and analyzed, especially with the convergence of XR and AI, which could allow data collection without users’ knowledge and informed consent. One Expert Panelist, Erica Southgate of the University of Newcastle, Australia, forcefully noted the ethical dilemmas we will confront in the ambient collection and use of student data in the future:

> *“I have serious concerns about machine learning automating/adapting dynamics of XR applications especially with black box decision-making re: transparency, potential for bias and accountability. Ambient use of AI in applications makes it almost impossible for people to detect its use and therefore consent to it. The harvesting of biometric data (especially tracking data) for AI applications should require explicit consent and opt-out/in or we will not even know it is happening. The issue of vulnerable populations needs to be addressed. Policymakers in education systems, and teachers need educating and empowering so that they do not simply bring AI-infused apps into classrooms without understanding the legal, ethical issues this entails. Students and their parents need education and empowerment regarding their digital rights in this area. Regulatory frameworks need developing—but most of all ordinary people should have basic digital rights and understand how to enact these.”*

Catalyst 6: Evidence-based XR Learning and Program Design

In the final section of catalyzing technologies and developments, the Expert Panel considered the critical need for evidence-based learning and program design.

Given the paradigm shift that XR brings to the user–technology relationship, traditional instructional design will not seamlessly translate into the virtual domain. As XR finds progressively wider application, research from cognitive psychology and neuroscience developments will need to be more extensively applied in our learning environments. At the same time, XR developments will raise profound challenges as the converging technologies discussed above (especially AI, haptics, and eye-tracking) will require educators to balance the need for evidence collection and personal data with student and faculty privacy concerns.

One model to explore may be found in the initiatives underway in healthcare to develop evidence-based design. The Center for Health Design's Evidence-Based Design Accreditation and Certification (EDAC) program works to ensure that healthcare environments are created by professionals certified in evidence-based design. With the rapidly expanding use of XR in medicine and STEM disciplines, we will likely see evidence-based XR learning design emerge in this area first. XR learning design will benefit from the more formal problem-solving approach already used in healthcare, which could be broadly reformulated as follows:

- Cultivate a spirit of inquiry
- Frame the appropriate questions
- Search for the best evidence
- Critically appraise the evidence
- Integrate the evidence with learning expertise
- Monitor and evaluate the outcomes
- Disseminate the results

There are several higher education XR design initiatives underway, including the University of Washington, Department of Human Centered Design & Engineering's annual XR Day, which focuses on the hurdles to broader adoption, understanding user needs, and applications to design a better future.

A body of research has been undertaken that investigates how we might measure the effectiveness of gestures in XR environments to support embodied learning (see, for example, Johnson-Glenberg, 2018). The constructs of sensorimotor engagement, the congruence of gestures to the content to be learned, and the degree of immersion experienced by users may serve as an initial framework for evaluating XR learning projects.

Moving forward, it will become increasingly critical for XR learning designers to shift from a “2D” mindset to an immersive and 3D spatial one, utilizing virtual tools as part of the design process. In cutting-edge projects, engineers are already using XR to interact with and evaluate product design, not via traditional displays but within virtual spaces. A notable example is the partnership between the car manufacturer Volvo and the advanced VR / MR headset developer Varjo. Varjo’s VR-1 Developer Edition is a MR HMD with integrated eye-tracking, ultra-low latency, and photorealistic visual fidelity that seamlessly blends real and virtual environments. Volvo engineers and observers wear the headsets driving in real-world conditions that can be manipulated (road obstacles, falling trees, etc.) to assess driver responses. Their responses lead to the improved redesign of instrument panels.

Extrapolating from these developments, we foresee a moment when we no longer design XR learning experiences from our screens but use XR to design and assess the immersive learning experiences of students. Google Blocks, Mozilla Hubs, and other platforms are already basic implementations of this approach. Our virtual spaces could become our design environments in the same way that everything encountered in Facebook Horizon, including the central Plaza and individual worlds, is built using the tools in Horizon. The potential of XR extends far beyond workforce training, and far beyond the shape and content of students' educational process. It will also transform how we conduct scientific research as well as how we design and build evidence-based learning environments that address society's needs in the future.

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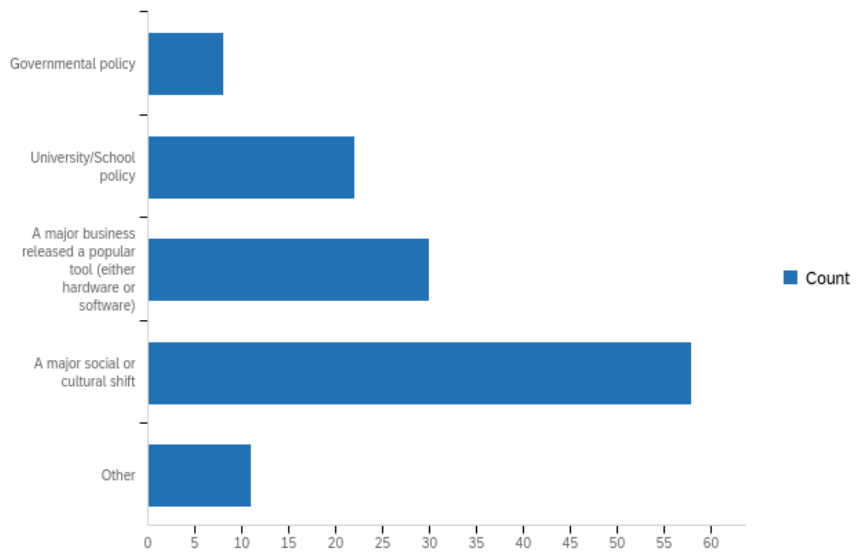
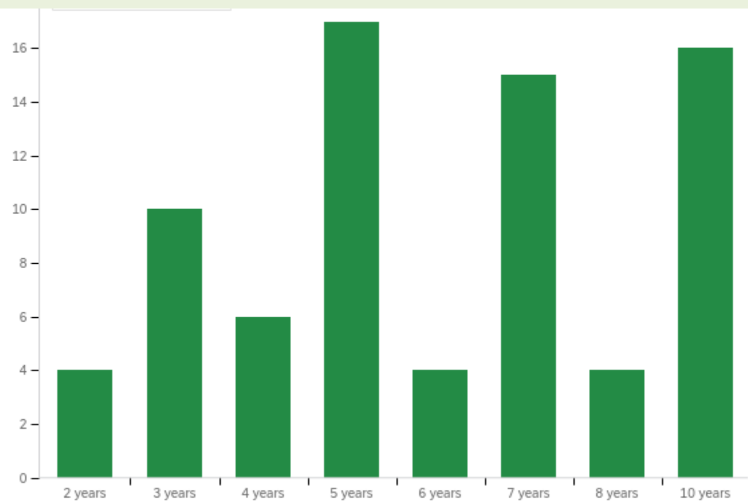
Expert Survey Results

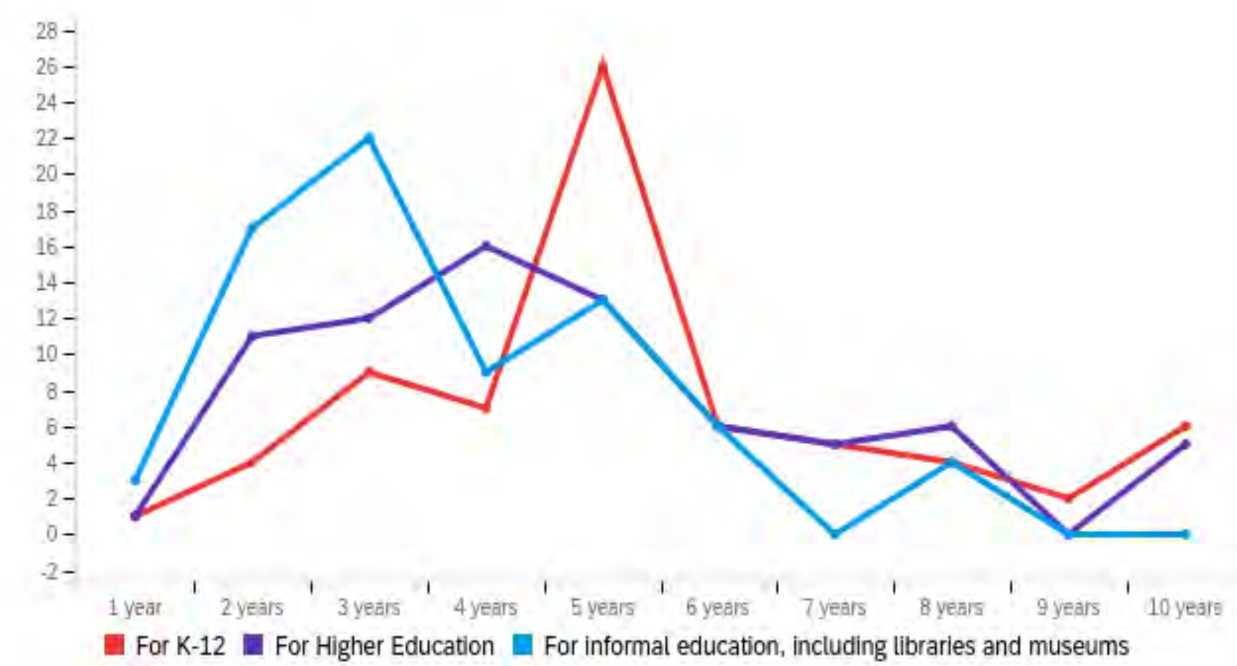
What event do you see as most likely to dramatically propel XR forward in education?



When do you envision a time when at least half of instructors will have taught with XR at least once?



When do you see XR passing a tipping point, so that at least half of educators, staff, and students have had some hands-on experience in formal and/or informal educational contexts? (1 - 10 years)



Next Steps and Call to Action

This inaugural Outlook Report represents one big step forward in iLRN's State of XR & Immersive Learning Project, the product of several years' work engaging experts within our iLRN Community. Now that the public has the fruits of this collaborative effort, this document outlining the State of XR & Immersive Learning at this moment in time, we now seek to validate our findings and see where the world takes us next. For the findings and trends indicated by the 19 Opportunities, Barriers, and Catalysts in the 2020 report, iLRN will continue to seek new evidence and innovations in those areas. We invite XR-for-learning professionals to make use of these trend categories and the associated Creative Commons-licensed icons to tag, discuss, collaborate, and creatively morph on these themes. We hope that this report and its parts will proliferate out on the open web via social media, learning forums and our partner organizations, as well as in university seminars, futures salons, museums, libraries, non-profits, organizational board rooms, and creative ventures.

In addition to this Outlook Report, the other major component of iLRN's State of XR & Immersive Learning Project is the iLRN Knowledge Tree. As described in the Introduction of this report, the development of the iLRN Knowledge Tree will be underpinned by a scoping review of the literature, which will lead to the creation of a taxonomic and conceptual data model along with a web-based repository based on that model. Those elements are designed to facilitate the systematic identification of evidence-based principles, guidelines, and best practices in XR for learning, instantiated within a collection of exemplars and complemented by a library of resources for educators and developers. We plan to actively engage the iLRN Houses and Chapters in nurturing and growing various branches of the Tree.

With the release of this inaugural Outlook Report, iLRN is also now prepared to embark with their partners and friends on a second round. The XR-for-learning space continues to evolve rapidly with technologies, innovations, partnerships, evidence across myriad disciplines, and new learning opportunities so diverse and varied as to be astounding. Persevering to collaborate with experts across this emerging ecosystem in order to identify and showcase the changing landscape will hopefully provide better clarity for educational leaders to make informed decisions, and for educators to better adapt, reach, and cater to their students.

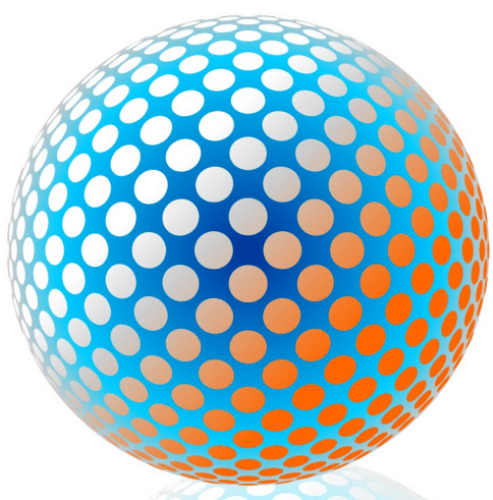
iLRN seeks new talented members to join our Expert Panel for the second annual iteration of the State of XR & Immersive Learning Project. This will include improvements to our environmental scanning, analyses, community-building, and reporting processes. We invite you to nominate yourself and/or a colleague for the

Panel, as well as to get involved in the Project at the House, Chapter, or Initiative level. During this next round, each iLRN House, Chapter, and Initiative will have two complementary tool sets with which to organize and conduct persistent environmental scanning and analyses:

(1) T**he iLRN website.** iLRN's website for 2021 will incorporate a daughter of the Expert Panel's State of XR & Immersive Learning Workspace, an Evidence Builder to gather journal articles, video, and other tools for both building and co-designing their respective iLRN community capacity and contributing to the Expert Panel's set of resources for finding what's emerging and "what works" in XR and immersive learnig.

(2) **The iLRN Virtual Campus, powered by Virbela. This space** is set up for putting an ongoing Weekly Spotlight on the emerging trends and technologies in XR. Each week in the iLRN Campus Lighthouse, these new scans will be aggregated using the #iLRNscan and #(topic) tags. iLRN members are encouraged to discuss and collaborate on emerging XR and Learning Trends during "Pie & Coffee" on the iLRN Virtual Campus. Houses, Chapters, and other iLRN Initiatives are encouraged to make use of Virbela's situated space and collaborative document sharing combined to develop community and collectively contribute to the 2022 State of XR Outlook Report.

By situating our diverse community of experts into dialogue and practice, collaborating on a shared framework of evidence and identifying emerging new technologies, challenges, and opportunities, we strive to lower the barriers, showcase dependable evidence-based use cases, and create capacity for everyone to participate in identifying, showcasing, and innovating on the amazing power of XR for learning.



The 2019 – 2020 Expert Panel Members

Sun Joo (Grace) Ahn University of Georgia, USA
Karen Alexander XRconnectED, USA
Dan Ayoub Microsoft, USA
Jorge Bacca Konrad Lorenz University Foundation, Colombia
Cindy Ball Oculus / Facebook, USA
Steven Bambury Independent Consultant, UAE
Justin Berry Yale University, USA
Ayora Berry PTC, USA
Lucia Binotti The University of North Carolina at Chapel Hill, USA
James Birt Bond University, Australia
Lucas Blair RTI International, USA
Elizabeth Boyle University of the West of Scotland, UK
Aileen Chai Ministry of Education, Singapore
Emory Craig Digital Bodies – Immersive Learning, USA
Jesse Damiani Southern New Hampshire University, USA
Linda Daniela University of Latvia, Latvia
Drew Davidson Carnegie Mellon University, USA Lisa Dawley University of San Diego, USA
Koos de Beer University of Pretoria, South Africa Sara de Freitas, Birkbeck, University of London, UK
Chris Dede Harvard University, USA
Johannes DeYoung Carnegie Mellon University, USA
Heather Dodds Independent Scholar, USA
Jaime Donally ARVRinEDU, USA
Lana Franceska Dreimane Ministry of Education and Science, Latvia
Asha Easton ImmerseUK, UK
Sana Farid Munfarid Consulting, UAE
Helen Farley Department of Corrections, New Zealand
Sarah Fielding University of Southampton, UK
Cyntia Franco The University of Sydney, Australia
Michael Fricano II Iolani School, USA
Maya Georgieva The New School, USA
Alex Haber Magic Leap, USA
Stella Hadjistassou University of Cyprus, Cyprus Rhonya Hamada Google, USA
Sean Hauze San Diego State University, USA
Eric Hawkinson Kyoto University of Foreign Studies, Japan
Debbie Holley Bournemouth University, UK
Toshi Hoo Institute for the Future, USA
María Blanca Ibáñez Universidad Carlos III de Madrid, Spain
Sheila Jagannathan The World Bank, USA
Jason Jerald NextGen Interactions, USA
Mina Johnson-Glenberg Arizona State University, USA
Amy Kaufman University of California San Diego, USA
Fengfeng Ke Florida State University, USA
Roland Klemke Technical University of Cologne, Germany
Alexander Klippel The Pennsylvania State University, USA
Eric Klopfer Massachusetts Institute of Technology, USA
Richard Lamb East Carolina University, USA
Fabrizio Lamberti Politecnico di Torino, Italy
Becky Lane Ithaca College, USA
Belinda Lange Flinders University, Australia
Chad Lewis Tampa Preparatory School, USA
Daniel Livingstone The Glasgow School of Art, UK
Maja Manojlovic University of California, Los Angeles, USA
Sergio Martin National Distance Education University (UNED),
Spain Kevin Merges Rutgers Preparatory School, USA
Diane Michaud Victoria College within the University of Toronto, Canada
Shailey Minocha The Open University, UK
Barbara Mones University of Washington, USA
Jacki Morie All These Worlds, LLC, USA

Brooke Morrill Schell Games, USA
Anna Carolina Muller Queiroz Stanford University, USA
Susanna Nocchi Dublin Institute of Technology, Ireland
Carlos J. Ochoa Fernandez ONE Digital Consulting, Spain
Jessica Ochoa Hendrix Killer Snails, USA
Amy Peck HTC, USA
Andrew Phelps American University and University of Canterbury, USA and New Zealand
Johanna Pirker Graz University of Technology, Austria
Jan Plass New York University, USA
Lance Powell VR First, Turkey
Ekaterina Prasolova-Førland Norwegian University of Science and Technology, Norway
Iulian Radu Harvard University, USA
Matthew Ramirez Jisc, UK
Deborah Richards Macquarie University, Australia Nicola Rosa Accenture, USA
Dan Roy Massachusetts Institute of Technology, USA
Donna Russell Walden University, USA
Norma Patricia Salinas Martínez Tecnológico de Monterrey, Mexico
Steven Sato Rolling Hills Country Day School, USA
Philippos Savvides Arizona State University, USA
Kathy Schrock Wilkes University, USA
Claire Seldon NSW Department of Educaion, Australia
Carl Smith Ravensbourne University London, United Kingdom
Erica Southgate University of Newcastle, Australia
Marcus Specht Delft University of Technology, Netherlands
Bryne Stothard Frankfurt International School, Germany
Simon Su U.S. Army – Combat Capabilities Development Command Army Research Laboratory, United States
Kenji Tanaka Sony Electronics, United States Heather Thomson University of Toronto, Canada
Romero Tori Polytechnic School of the University of São Paulo, Brazil
Jolanda Tromp Duy Tan University, Vietnam
Barbara Truman University of Central Florida, USA
Jordan Tynes Wellesley College, USA
David Varela The Manufacturing Technology Centre, UK
Craig Vezina Z School, France
Fridolin Wild Oxford Brookes University, UK
Hla Hla Win 360ed, Myanmar
Michał Wróblewski Learn Teach Explore, Poland
Nabil Zary Mohamed Bin Rashid University of Medicine and Health Sciences, UAE
Cindy Ziker SRI International, USA

Project Leadership Team

Project Leader/ Principal Investigator:	Mark J. W. Lee *Executive Vice President and Chief Research Officer, Immersive Learning Research Network*
Co-Investigator:	Jonathon Richter *President and Chief Executive Officer, Immersive Learning Research Network*
Chief XR Strategist	Maya Georgieva *Director, Education Futures / XR and HCI Innovation Labs The New School*
Project Architect (2019):	Samantha Becker *President, SAB Creative & Consulting*
Project Consultant and Community Manager (2019):	Paul Signorelli *President, Paul Signorelli & Associates*
Research Fellow:	Rachael Afolabi Royes *CEO, Paradigm Global Innovations*
Research Associate:	Noah Glaser *Postdoctoral Research Fellow at the Neag School of Education at University of Connecticut*
Research Assistant and Project Librarian:	Allison Hatch *Master's student in Library and Information Science, University of Denver*
Technical Consultant:	Gordon Jackson *President, Gordon Jackson Consulting, LLC*
Report Artists	Mirko Andric – Cover Illustration and Report Category Sections Karina Branson – Executive Summary Report Alex – Category Icons

Partner Representatives

Malcolm Brown, EDUCAUSE, USA

Norton Gusky (CoSN Representative), NLG Consulting, USA

Jeffrey Pomerantz (EDUCAUSE Representative), Simmons University, USA

David Kelly, The Learning Guild, USA

Jane Bozarth, The Learning Guild, USA

Sponsor Representatives

Ellen Flaherty, *Unity Technologies*, USA

Craig Frehlich (*SpringboardVR* Representative), Stamford American International School, Singapore

Jessica Lindl, *Unity Technologies,* USA

Paul Martin, *HP, Inc.,* USA

Joseph Parlier, *zSpace,* US

Michael (“Gus”) *Schmedlen, HP, Inc*., USA

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Leonel Morgado, *Universidade Aberta & INESC TEC*, Portugal

Patrick O’Shea, *Appalachian State University*, USA

Jonathon Richter, *Salish Kootenai College,* USA

Anasol Peña Rios, *British Telecom Research Labs*, UK

Minjuan Wang, *San Diego State University*, USA

Immersive Learning Research Network

340 S. Lemon Ave. #6262
Walnut, CA 91789, USA
Website: www.immersivelrn.org
Email: info@immersivelrn.org Twitter: @immersiveLRN
Facebook: www.facebook.com/immersiveLRN/

iLRN's mission is to cultivate communities of research, innovation, and evidence-based practice around "what works" in XR and immersive learning.

Visit us on the iLRN Virtual Campus, powered by Virbela and join our Discord server