Learning in Three Dimensions:

Report on the EDUCAUSE/HP Campus of the Future Project

EDUCAUSE

Contents

Learn More

Access additional materials, including a blog series on the campus case studies, on the EDUCAUSE/HP project research hub at https://www.educause.edu/hp-xr.

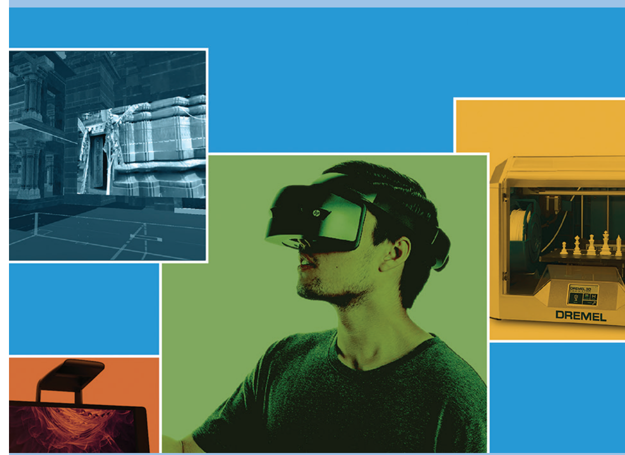
Author

Jeffrey Pomerantz, Associate Professor of Practice, School of Library and Information Science, Simmons College

Citation

Pomerantz, Jeffrey. *Learning in Three Dimensions: Report on the EDUCAUSE/HP Campus of the Future Project.* ECAR research report. Louisville, CO: EDUCAUSE, August 2018.

©2018 EDUCAUSE. Creative Commons BY-NC-ND 4.0.



EDUCAUSE is a nonprofit association and the foremost community of IT leaders and professionals committed to advancing higher education. EDUCAUSE programs and services are focused on analysis, advocacy, community building, professional development, and knowledge creation because IT plays a transformative role in higher education. EDUCAUSE supports those who lead, manage, and use information technology through a comprehensive range of resources and activities. For more information, visit http://www.educause.edu.

HP Inc. creates technology that makes life better for everyone, everywhere—every person, every organization, and every community around the globe. For higher education, HP combines instructional innovation, applied research, 3D technologies, and advanced information security to empower the Campus of the Future. Learn more at http://www.hp.com.

Executive Summary

Extended reality (XR)—a wide range of technologies along a continuum, with the real world at one end and fully immersive simulations at the other—is having a dramatic impact on pedagogy in higher education. To explore the potential of XR technologies in higher education, EDUCAUSE and HP collaborated on the Campus of the Future: 3D Technologies in Academe project, focusing on those XR technologies encompassing 3D simulations, modeling, and production. This project sought to identify current innovative uses of these 3D technologies, how these uses are currently impacting teaching and learning, and what this information can tell us about possible future uses for these technologies in higher education.

This report describes a wide range of pedagogical uses of 3D tech in higher education, from augmenting experiences in the physical world to creating simulations of things that are inaccessible in the physical world, and from designing virtual things that may be made into physical things to repeating experiences virtually that cannot be repeated in the physical world. The report also discusses hurdles in implementing 3D technology and the possible future of 3D technology in higher education, and it makes recommendations—in terms of technical requirements, support needs, and organizational policies—for institutions wishing to deploy 3D technology on campus.

The Campus of the Future project sought to identify interesting and novel uses of 3D technology at the institutions participating in this project, and, more broadly, to identify types of uses of 3D technologies that hold the greatest potential for learning and research outcomes. Two findings of this exploratory evaluation are that 3D technologies enable active and experiential learning, and they promote shared experiences and collaboration. Furthermore, 3D technologies support a wide range of learning goals across a wide range of disciplines; this report articulates some of these learning goals and the 3D technologies that effectively support them.

Key Findings

- **3D technologies give users virtual superpowers.** In a virtual reality (VR) simulation, a user can fly like Iron Man, have superstrength like Wonder Woman, and walk through walls like Kitty Pryde. VR and augmented reality (AR) give users X-ray vision like Superman's. VR and 3D printing give users the ability to manipulate very small objects, like Ant-Man and the Wasp; to manipulate energy, like Magneto; and to create objects from empty space, like Doctor Manhattan and Elsa of Arendelle.
- **VR is like being there.** A well-constructed simulation is visceral: One's intellectual and physiological reactions to objects and events in VR are similar—and sometimes identical—to one's reactions in the physical world.
- **VR and AR are multisensory experiences.** Much VR and AR development focuses on the visual functionality of those technologies, but they are capable of more. The auditory functionality of VR and the haptic functionality of both VR and AR are critical for creating a realistic simulation.
- **3D technologies enable active and experiential learning.** Virtual reality simulations enable users to interact in a space or around an object in ways beyond what is possible in the real world. Augmented reality enables users to interact with an object while possessing "superpowers," such as the ability to see through surfaces or to see data overlying objects. With 3D printing, users can quickly create physical objects that might otherwise exist only in simulations. These functionalities enable users to gain hands-on experience with objects that might otherwise be inaccessible in teaching and learning contexts.
- **Simulations enable individual practice and skill-building.** In the medical professions, for example, VR enables students to repeat hands-on experiences that might not otherwise be possible (e.g., repeating a dissection multiple times) and to experience events that they might not otherwise be able to (e.g., diagnosing a rare condition, testing specific types of emergency medicine). Through repeated practice, students emerge more skilled.
- **Simulations enable high-touch, high-cost learning experiences to be scaled up.** While developing a simulated lab may be expensive, it is far less expensive than building and maintaining a physical lab. Furthermore, a simulated lab can be made available to individuals who are not co-located. VR and 3D printing therefore make it possible to provide lab experiences to a far greater number of users, perhaps even simultaneously.

- **3D technologies foster and sometimes require collaboration between campus units.** The deployment of new technologies often fosters new collaborations across campus. Supporting users of 3D technology on campus requires a range of expertise, which encourages (if not requires) collaboration between campus IT units and instructional designers. The use of 3D technology has also fostered collaborations involving students and faculty across academic disciplines.
- **Training is critical.** Some early adopters on campus will teach themselves to use 3D 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.
- **It takes time for the benefits of 3D technology to be realized on campus.** While 3D technology is getting easier to use, it must still be set up and configured; software must be installed and possibly updated. Furthermore, users need time to learn to use the technology, and instructors need time to figure out how to use the technology in their teaching. Courses take months to be redesigned. The first year of deployment of 3D technology may be largely devoted to learning to use and integrate it into teaching and support practices; it may take until year two for the full benefits of using 3D technology on campus to be realized.

Introduction

Institutions of higher education are hotbeds of innovation. Several institutions no doubt leap to the reader's mind as being on the cutting edge of technology innovation. But innovation is not confined to technology development: Innovations in pedagogy are equally if not more important to institutions of higher education.

Extended reality (XR) technologies, which encompass virtual reality (VR) and augmented reality (AR), are already having a dramatic impact on pedagogy in higher education. XR is a general term that covers a wide range of technologies along a continuum, with the real world at one end and fully immersive simulations at the other. Within the past few years, a variety of technologies along this continuum have become increasingly widespread, as their cost has decreased and their ease of use increased. While high-end VR and AR headsets are still relatively expensive, inexpensive smartphone-based versions of both have made these technologies readily accessible. Of course, as with any computer hardware, what is today a high-end headset will be inexpensive tomorrow. This pressure from both above and below has driven the widespread adoption of many technologies, from the personal computer to the smartphone. And it is when technologies become widespread that they really begin to have a broad impact and their full potential can be realized.

To explore the potential of XR technologies in higher education, EDUCAUSE and HP collaborated on the Campus of the Future: 3D Technologies in Academe project. This project focused on a subset of XR technologies concerned with 3D simulations, modeling, and production: VR, AR, 3D scanning, and 3D printing. This project sought to identify current innovative uses of these 3D technologies in higher education, discover how these uses are currently impacting teaching and learning, and determine what this information can tell us about possible future uses for these technologies.

Project Description

The Campus of the Future project was an exploratory evaluation of 3D technologies for instruction and research in higher education: VR, AR, 3D scanning, and 3D printing. The project sought to identify interesting and novel uses of 3D technology at the institutions participating in this project, and, more broadly, to identify uses of 3D technologies that hold the greatest potential for learning and research outcomes. The evaluation questions motivating this project were twofold:

- What educational activities lend themselves to the use of 3D technologies?
- What are the most effective 3D technologies for various learning goals?

This project is not the first effort to integrate VR, AR, or 3D printing and scanning technologies into educational experiences. Prior work exists in both K–12[1] and higher education.[2] For the most part, however, this prior work reports on the integration of 3D technologies into individual courses, though the range of courses is quite broad: from the sorts of technical courses one might expect, such as programming, game and app development, and other computer science courses, to perhaps less obvious subjects such as courses on visual arts, biodiversity, and cultural studies.[3] The Campus of the Future project is, however, the broadest project to study the integration of 3D technologies into education that we are aware of, spanning a larger and more diverse sample of institutions and learning environments and reaching a larger number of users.

HP approached EDUCAUSE in early 2017 about conducting this evaluation, and the following parameters were established: HP would provide the hardware, and EDUCAUSE would provide the methodological expertise to conduct an evaluation research project investigating the potential uses of 3D technologies in higher education learning and research. HP, keenly aware of the risk of sponsorship bias[4] (even the perception of bias), gave EDUCAUSE maximum latitude in carrying out this project. While most of the technology provided for this project was HP-branded, and HP provided technical support to participating institutions, EDUCAUSE distributed this technology to participating institutions and was their primary point of contact. More importantly, EDUCAUSE developed the methodology for this evaluation and conducted all data collection and analysis entirely independently.

The institutions that participated in the Campus of the Future project were selected because they were already on the cutting edge of integrating 3D technology into pedagogy. These institutions were therefore not representative, nor were they intended to be representative, of the state of higher education in the United States. These institutions were selected precisely because they already had a set of use cases for 3D technology available for study (though naturally additional uses emerged at nearly all institutions over the course of this project). The reason for selecting a nonrepresentative sample such as this was to identify the leading edge of the use of this technology in higher education and to thereby attempt to project the future of 3D technology in higher education.

Participating institutions were expected to use the provided technology to conduct an active exploration of 3D technologies in the classroom, as a component of research projects, or both. These explorations naturally involved both faculty and staff at each institution, as it is faculty who develop course syllabi and assignments, while staff in IT units and campus centers for teaching and learning provide technology support to those faculty. Participating institutions were also expected to include graduate and/or undergraduate students in these explorations, either to address a component of their coursework or as research assistants.

HP has a longstanding Education Solutions division, which routinely partners with educational institutions on innovative projects. HP has also been developing 3D technology for several years. The Campus of the Future project is in fact not HP's first project in this space: A collaboration between HP and Yale University predates this project by a year and was, in a way, a pilot for this project. At the start of the 2016–17 academic year, HP provided Yale with 5 Sprout Pro G2 computers and 20 Dremel Idea Builder 3D printers (the same pieces of equipment received by participants in this project), and student- and faculty-led project teams were selected to participate. The projects were selected by a faculty steering committee with one major criterion in mind: Could the experiences—and, in some instances, the results of these endeavors—point to new ways of thinking and creating for artists, designers, researchers, scholars, and scientists? The results, experiences, and lessons learned from the Yale project were detailed in the report *A Year in the Blender: Practical Applications of 3D in Virtual, Mixed and Printed Forms from Yale University's Blended Reality Applied Research Project*, as well as on a project blog. Many of the lessons learned by Yale during the Blended Reality project, both the good and the bad, played out over the course of this project.

Participating Institutions

Eleven US institutions of higher education participated in the 2017–18 Campus of the Future project:

- Case Western Reserve University
- Dartmouth College
- Florida International University, College of Communication, Architecture + The Arts (CARTA)
- Gallaudet University
- Hamilton College
- Harvard University, Graduate School of Education
- Lehigh University, The Wilbur Powerhouse
- MIT, Scheller Teacher Education Program
- Syracuse University, Newhouse School of Communications
- University of San Diego
- Yale University

The makeup of these participating institutions was as follows:[5]

- All were four-year institutions.
- Most were doctoral universities, except for one master's institution (Gallaudet) and one baccalaureate institution (Hamilton).
- About two-thirds were majority or exclusively undergraduate institutions; about one-third were majority graduate institutions.
- Most institutions have high research activity, except for one liberal arts–focused institution (Hamilton).
- Most were private nonprofit institutions, except for Florida International University (FIU), which is a large public land-grant institution.

At some institutions, the group participating in the project was an academic unit (e.g., the Newhouse School of Communications at Syracuse University; the Graduate School of Education at Harvard University). At these institutions, the 3D technology provided by HP was deployed for use more or less exclusively by students and faculty affiliated with the particular academic unit. At other institutions, the participating group was an administrative unit (e.g., Information Technology Services at Yale University; the Research & Instructional Design team within the Library & Information Technology Services unit at Hamilton

College). Such units serve the entire institution and therefore made their 3D technology kit available for use by all students and faculty affiliated with the entire institution.[6]

At still other institutions, the participating group was a semi-autonomous campus unit (e.g., The Wilbur Powerhouse at Lehigh University; the Miami Beach Urban Studios [MBUS] within the College of Communication, Architecture + The Arts [CARTA] at FIU). These facilities are shared spaces containing computers and other technology and are accessible to all in their respective campus communities. They might better be called *makerspaces*, and given that there is no widely agreed-on definition of what makerspace means, that is a legitimate generic term for them. However, these facilities go well beyond what one generally thinks of as a makerspace: The Wilbur Powerhouse occupies an entire 17,000-square-foot building and contains, among other hardware, laser cutters and a woodshop. The MBUS is an anchor institution in Miami-Dade County and, like other types of anchor institutions[7] (such as museums), offers workshops and other programs that integrate into local K–12 education in the STEAM (science, technology, engineering, art, and mathematics) disciplines.

As mentioned earlier, the institutions that participated in the Campus of the Future project were not representative of the state of higher education in the United States or globally. The service models under which 3D technology was made available for use to the campus communities, however, spanned the range of approaches to technology deployment that are currently common in US higher education.

Definitions

3D technologies are not new. Development of technology recognizable as virtual reality (VR) dates back to the Sword of Damocles head-mounted display system, developed by Ivan Sutherland in 1968,[8] though non–computer scientists may be more familiar with Jaron Lanier and colleagues' work at VPL Research in the mid-1980s.[9] Augmented reality (AR) technology arguably dates back even further, to the military's development of heads-up displays for fighter jet pilots in the 1950s.[10] 3D printing technology began in the 1980s with the development of rapid prototyping and stereolithography technology;[11] the earliest 3D scanning dates back to the invention of LIDAR in the 1960s, although the close-range photogrammetry that we now think of as 3D scanning dates to the 1980s. These technologies are likely to be at least somewhat familiar to readers, even if they have seen only limited adoption in educational settings.

That said, however, there is not universal agreement on the definitions of these terms or on the scope of these technologies. Also, all of these technologies currently exist in an active marketplace and, as in many rapidly changing markets, there is a tendency for companies to invent neologisms around 3D technology. This section briefly defines the 3D technology terms used throughout this report. See the appendix for detailed descriptions of the equipment supplied by HP and deployed by institutions participating in the Campus of the Future project.

A *3D scanner* is not a single device but rather a combination of hardware and software. There are generally two pieces of hardware: a laser scanner and a digital camera. The laser scanner bounces laser beams off the surface of an object to determine its shape and contours. This is similar to aircraft- and drone-based LIDAR platforms that are used to map features on the ground and which are increasingly being used in archaeology to discover sites hidden by tree cover[12]—the difference being, of course, that 3D scanning is done at much closer range. The digital camera takes more traditional photographs of the object; software then uses photogrammetry functionality to "wrap" these photos around the 3D model of the shape of the object.[13] The size of the object being scanned may determine the hardware that can be used: A small object can be scanned by a desktop-sized rig (figure 1), while a large object (such as a statue or an assembled dinosaur skeleton in a museum) may require a rig mounted on a tripod or drone.

Figure 1. A 3D desktop scanner for small objects
Image courtesy of HP Inc.

Several types of *3D printers* are available,[14] but the Dremel Idea Builder printers provided to participants in the Campus of the Future project were of one type only: fused deposition modeling (FDM). FDM printers have a printhead that melts and extrudes plastic filament (which often comes in rolls); this melted plastic is printed on an *x-y* plane just as desktop printers layer ink on paper, but with the additional feature that plastic is printed in layers in the *z*-axis to create 3D objects. The thickness of the filament and the speed of printing affect the level of detail of the printed object: The finer the filament, the finer the level of detail that can be achieved.

Although multiple types of 3D scanners and 3D printers are on the market, these technologies are mature enough that the terminology around them has largely stabilized. This is unfortunately not yet the case with VR and AR, which are, furthermore, increasingly being considered merely as points along a "virtuality continuum" of extended reality (XR).[15]

Virtual reality means that the wearer is completely immersed in a computer simulation. Several types of VR headsets are currently available, but all involve a lightweight helmet with a display in front of the eyes (see figure 2). In some cases, this display may simply be a smartphone (e.g., Google Cardboard); in other cases, two displays—one for each eye—are integrated into the headset (e.g., HTC Vive). Most commercially available VR rigs also include handheld controllers that enable the user to interact with the simulation by moving the controllers in space and clicking on finger triggers or buttons. VR is an active area of game development; readers may even have played such games as *Star Trek: Bridge Crew* or *Fallout*.

Figure 2. A virtual reality headset
Image courtesy of HP Inc.

Augmented reality provides an "overlay" of some type over the real world through the use of a headset or even a smartphone. Readers may also have had personal experience with AR, through enhanced exhibits in museums, such as the Skin & Bones exhibit at the Smithsonian National Museum of Natural History, or through virtual tours of cities, such as CHICAGO 00. Pokémon GO, a popular AR game, is also likely to be familiar to the reader. AR can be implemented in two primary ways: on a smartphone or other mobile device (e.g., Pokémon GO) or via a heads-up display (HUD), widely used in aircraft and increasingly in cars.

In an active technology marketplace, there is a tendency for new terms to be invented rapidly and for existing terms to be used loosely. This is currently happening in the VR and AR market space. The HP VR rig and the HTC Vive unit are marketed as being *immersive*, meaning that the user is fully immersed in a simulation—virtual reality. Many currently available AR headsets, however, are marketed not as AR but rather as MR (mixed reality). These MR headsets have a display in front of the eyes as well as a pair of front-mounted cameras; they are therefore capable of supporting both VR and AR functionality.

Hurdles in Implementing 3D Technology in Higher Education

It is inevitable that technical issues will arise with any rapidly developing or complex technology, and 3D technologies are both. Furthermore, institutions of higher education are often slow to adopt innovations, particularly innovations in pedagogy.[16] This combination of technical and cultural factors made it inevitable that there would be hurdles for the institutions participating in the Campus of the Future project. These hurdles fell into two broad categories: technical and pedagogical.

Technical Difficulties

Technical problems seem to simply be a fact of modern life. Many of us can probably set up a desktop or laptop computer straight out of the box, since these devices have become widely familiar and are manufactured to be relatively easy to use. However, it often takes someone from the IT department to configure a network printer or scanner or other peripheral device, despite their being equally familiar and ostensibly easy to use. The 3D technology provided by HP for this project consisted of comparatively new types of devices that are less familiar, less easy to use, and therefore that much more difficult to set up.

Technical issues can generally be divided into two broad categories: hardware problems and software problems. There is, of course, a common third category: human error. But human error cuts across both hardware and software, so we will maintain these two basic categories.

A hardware problem that some institutions encountered was the need for a particular hardware adaptor. This was especially an issue for the headsets, which required an HDMI-to-DisplayPort adaptor. Institutions that did not happen to have this adaptor had to purchase one. While such adaptors are not expensive, diagnosing this problem and ordering an adaptor slowed some institutions down in getting the headsets set up.

A software problem encountered by some institutions was the need to update software drivers. VR and AR are extremely graphics intensive and generally function best when the graphics drivers are up to date. Some participating institutions found that they needed to update multiple drivers to get the VR/AR headsets to operate, which, although not difficult, is time-consuming and may require rebooting the computer multiple times.

Both hardware and software problems were experienced with 3D scanning as well. On the hardware side, 3D scanning does not work very well on highly reflective objects or surfaces. Many 3D scanners illuminate the object being scanned with lasers; highly reflective surfaces can cause scans to be pixelated or distorted. A simple fix for this problem is a product called 3D Scan Spray, which is simply a spray-on matte finish (which is then easily wiped off). Again, however, while not expensive, diagnosing the problem and purchasing a product slows down the process of making 3D scans.

On the software side, a 3D scan is actually a set of images "stitched" together into a 3D model by software. This process is computationally intensive and requires a powerful computer (see the appendix for descriptions of the computers provided to participating institutions). An older or slower computer, a computer with inadequate RAM, or even an adequate computer that is simultaneously running other software may be unable to process a scanned object. The solution here too is simple: Use a computer configured to support high-end graphics, reboot it before using it to perform a 3D scan, and ensure that the 3D scanning software is the only application running. This is easier said than done, however; surely all of us have had the experience of knowing that we should reboot our computer for one reason or another but decide not to because it would insert a small amount of friction into our workflow.

The Technology Learning Curve

When setting up any technology, configuring the hardware and software to work correctly is of course a necessary prerequisite. But it is only the first step: Next comes the learning curve for figuring out how to use it.

The well-known diffusion of innovations theoretical framework articulates five adopter categories: innovators, early adopters, early majority, late majority, and laggards.[17] These categories are of course broad generalizations, but individuals and organizations within each category share certain characteristics that make them more or less amenable to adopting a particular innovation. Innovators and early adopters tend to enjoy experimentation and have the resources to expend on doing so. In the context of higher education, this often means faculty members who are comfortable with technology and are willing to devote time to learning to use it.

It behooves new campus technology initiatives to seek out innovator and early adopter faculty, since such individuals are the most likely to be advocates for new technology initiatives and to be opinion leaders among their peers. These faculty members are likely to be able to teach themselves to use the new technology, or at least to require fairly minimal training. It is also likely that staff in the campus IT unit or center for teaching and learning already know who (at least some of) these individuals are, since such faculty members are likely to already have had contact with these campus units.

Students may of course also be innovators and early adopters, and in fact several participating institutions found that some of the most creative uses of

3D technology arose from student projects. This was particularly the case at institutions where students were free to experiment with and even hack the 3D technology, rather than where that equipment was under lock and key. Indeed, at several participating institutions there was so much interest among the students in using this technology that there was simply not enough of it to go around. In campus technology labs where hardware must be reserved, the 3D technology was often reserved well in advance. Furthermore, at some institutions students were interested in working on projects with faculty who were using the 3D technology, but there were not enough projects and not enough available student positions on projects to accommodate the number interested. As a result, many students conceived their own individual or small-group projects to use the available 3D technology.

Not all faculty or students are innovators and early adopters, however. Indeed, most are not: Diffusion of innovations theory shows that the early and late majority are far larger categories. It is of course usually not necessary to have 100% of institutional affiliates using any specific campus technology (except perhaps email and the learning management system). But on the other hand, one does not want to simply preach to the converted: A campus technology initiative should not serve only those who self-select into it. The duration of the Campus of the Future project was only one academic year, however, and therefore not long enough for institutions to dramatically expand their local communities of interest. Consequently, involving a wider set of faculty and students in the use of 3D technology was a challenge for all participating institutions.

One of the most common mechanisms for doing this, and the seemingly most effective, was for the campus units participating in the project to run training sessions. Some of these were offered as workshops open to any and all comers from across campus, like workshops offered by IT units on other technologies or by centers for teaching and learning on pedagogical practices. Some of these were offered as sessions provided to individual courses, at the request of the instructor, or to individual working groups, often at the request of students. At some participating institutions, these training sessions and workshops have proven so popular that the institutions have begun developing curricula for those that they anticipate will see repeat demand. Hamilton College, for example, has developed a curriculum for an introductory workshop on creating virtual objects. FIU has developed curricula for workshops on narrower topics, such as the 3D scanning of found objects on either the DAVID scanner or the Sprout, and the use of the VR headset rig.

Workshops are useful not only for training users on specific hardware and practices, but also for fostering outreach to new users and user groups. FIU, for example, has developed workshops for new users both within and outside of the university: One workshop on using the Unreal Engine to develop VR environments was developed specifically for architecture students at FIU, while another on the Steam games distribution platform was developed specifically for K–12 students in the Miami-Dade County public schools. In both cases, workshop attendees may not know how to use 3D technology, and in fact a K–12 field trip to FIU might be many of these students' first exposure to these technologies.

Every institution has faculty and students who have the motivation to be innovators and early adopters. Even some of these individuals, however, came to their projects not knowing how to use 3D technology. Some faculty and students, having attended a workshop or encountered a peer's use of this technology, were motivated to learn how to use the technology for their own projects. However, such individuals often need a great deal of support as they work through the process of teaching themselves and, in the case of faculty, figuring out how to integrate it into their teaching. Faculty in particular may require "high-touch" service, and as prior EDUCAUSE research has found, faculty predominantly seek technology support from their institution's help desk.[18] Students may as well, but students—and particularly undergraduates—are more likely than faculty to have the flexibility to spend their evenings and weekends on a self-directed pursuit. Consistent with that, EDUCAUSE research has found that students predominantly prefer to figure out solutions to their technical problems on their own.[19] In both cases, users need support and resources, and they need a way to get questions answered. Faculty are likely to have complex questions, often requiring a face-to-face consultation. Students, particularly undergraduates, are likely to need support at odd hours: late at night, on weekends, and other times when campus offices and facilities are often not staffed. Supporting innovative uses of 3D technology may therefore require changes to the staffing model of the designated campus unit.

The On-Ramp to Sound Pedagogy

Setting up and configuring the hardware and software to work correctly is the first step, and learning to use it is the second step. But both of these, in the context of this project, and in higher education more broadly, are in the service of using technology for teaching and learning.

A faculty member may be an early adopter and need very little assistance in learning to use new technology, or a laggard needing a great deal of hand-holding. In either case, learning how to use new technology is one thing; figuring out whether that technology is appropriate for one's teaching, and if so how to integrate it into one's courses, is something else entirely. Students want their instructors to use more technology in their courses, but that technology must provide clear benefits.[20] And of course it is critical that technology be implemented in the service of a pedagogical goal; technology for technology's sake is not only bad teaching practice, but students find it unhelpful as well.

Institutions of higher education are increasingly investing in hiring instructional designers; these individuals often are located in a center for teaching and learning, or some campus unit with a more or less equivalent name and function. The campus IT unit, the library, or other units that support teaching and learning may also play this role. Whatever unit they are associated with on campus, however, instructional designers work with instructors who want to integrate a new technology or practice into their teaching. Instructional designers help faculty think through what the learning objectives of a course are and how best to meet those objectives, as well as how (and, indeed, whether) to use something new, such as 3D technology. Instructional design consulting with staff is generally time-consuming: Sometimes it may be a single meeting, and sometimes it may be a longer-term, ongoing consultation over the course of months or an entire semester. A workshop to train users on a new technology may be considered high touch, but that's nothing compared with providing instructional design support services to a faculty member redesigning a course.

This high-touch service model, however, is both necessary and effective when working with faculty. Faculty who are innovators and early adopters may self-select into new technology initiatives on campus, needing little assistance with the learning curve. Being able to figure out how to use a new technology is not, however, the same as figuring out how to use it in the classroom. Even early adopter faculty, therefore, will benefit from working with instructional designers. Still, faculty are busy people, and some may not have the time to devote to learning to use new technology and figuring out how to integrate it into their teaching, even if they are interested in doing so.

Institutions participating in the Campus of the Future project received their packages of 3D technology around the start of the fall semester of the 2017–18 academic year. Some institutions then found that even some faculty who were interested in using this technology were unwilling to commit to participating until the end of the fall 2017 semester, or even the summer of 2018, given the time commitment required to learn how to use the technology and integrate it into their teaching. Yale's *A Year in the Blender* report makes it clear that the first year of their institution's use of 3D technology was in large part a learning experience and that the full benefits of this technology on campus will be realized in year two and beyond. It seems likely that this will be true at other institutions as well.

The academic calendar is uneven, with some times of the year busier than others—a fact that campus teaching and learning staff know well. Just as other forms of faculty support must be scheduled with an eye to the academic calendar, so too must support for and outreach regarding 3D technology be scheduled for times of the year when faculty are likely to be at least slightly less busy: summer and between the bursts of activity at the start and the end of the semester or quarter. Obviously, these (relative) downtimes will vary by institution and by department.

It is even more important, perhaps, to provide adequate time for instructors to learn to use and to integrate 3D technology. A full-blown course redesign may take an entire semester—or longer if multiple instructors are involved. Even planning to integrate new technology, short of a full redesign, should commence a full semester in advance. And it's likely that the greater the level of support being offered to faculty, the longer the time required for this process. Again, supporting the campus deployment of 3D technology may therefore require changes to staffing models of the campus IT unit and the center for teaching and learning.

Pedagogical Uses of 3D Tech

Nearly a century ago, John Dewey told us that the most effective education is experiential: Learning is achieved through personal experience and doing.[21] Almost a century of subsequent educational research has shown that Dewey was correct and that active learning and experiential learning are highly effective. Some disciplines have always been able to engage in experiential education (not that they always *have* done so, just that they *could*). Disciplines such as environmental science, electrical engineering, studio art, and others that are inherently hands-on lend themselves to this type of teaching and learning. In other disciplines it is more difficult to engage in experiential education: In some it is a practical challenge to get hands-on experience (e.g., construction engineering, medicine, and law); in others the objects of study are inaccessible except by proxies and models (e.g., molecular biology, urban planning, and theoretical physics). One of the most important features of 3D technology is that it enables experiential teaching and learning in many disciplines where it would otherwise be challenging or impossible. 3D technology can make the invisible visible, the inaccessible accessible.

Modeling the Real

Perhaps the most straightforward use of 3D technology is to re-create objects and spaces that exist in the real world, but do so in virtual environments.[22] There is, however, not much point to simply re-creating the real in the virtual; for this type of use case to be worth the effort, there must be more to it.

One use case of this type is re-creating historical sites. Some of the earliest work in AR and VR in educational settings was done at the Institute for Advanced Technology in the Humanities at the University of Virginia in the mid-2000s. In particular, the Digital Roman Forum and Rome Reborn projects were efforts to re-create locations in ancient Rome as accurately as possible from historical records and to enable users to "walk through" VR-like digital models.[23] The Sacred Centers in India project at Hamilton College is in this vein.[24] This project examines the multiple layers of the history of 55 important shrines within the Hindu pilgrimage city of Gaya through textual, archaeological, and art-historical remains. Along with other work, this project has developed a VR walkthrough of the Vishnupada Temple (figure 3), complete with integrated photographs and videos. While these projects re-created the real in the virtual, they re-created real spaces that are inaccessible, either because they are distant or because they no longer exist. In either case, these projects enable historical research and archaeology that would not otherwise be possible.[25]

Figure 3. 3D model of the Vishnupada Temple, with a reconstruction layer
Image courtesy of Digital Humanities Initiative at Hamilton College

Another use case of this type is modeling spaces that exist in the real world and then manipulating those spaces in ways that are difficult or impossible outside of VR. A project at Gallaudet University is exploring this type of modeling in a unique context. Gallaudet is a school primarily for deaf and hard-of-hearing students. While one generally thinks of VR as simulating *visual* environments, a project at Gallaudet is using VR to simulate *auditory* environments. The audiology department at Gallaudet is experimenting with modeling complex auditory environments such as a noisy restaurant, a traffic intersection, and a corn maze. Hard-of-hearing individuals with hearing aids must work with an audiologist to tune and program new hearing aids, and often this involves multiple appointments: The individual must go out into the world and experience different auditory environments, come back to the audiologist, and tune the hearing aids iteratively. Modeling different auditory environments in VR would potentially enable an audiologist to tune an individual's hearing aids in a single appointment. This project at Gallaudet is similar in concept to a virtual walkthrough, though it might be more accurate to call it a virtual "hear-through." Such a use case re-creates the real in the virtual, but in such a way as to speed up a task and make it more convenient.

X-Ray Vision

The Sacred Centers in India project, in addition to a virtual walkthrough, has developed functionality to enable the VR user to peel away surfaces of the Vishnupada Temple to observe the layers constructed over the course of its history. Again, while this project re-creates the real in the virtual, it re-creates the real in a way that adds value, enabling a form of historical investigation that would not be possible in the real world.

Another example of virtual spaces enabling the manipulation of objects in ways beyond what is possible in the real world comes from medicine. A human anatomy lab course at Hamilton College uses commercially available VR simulations of organs within the body (figure 4), as well as functions and diseases of those organs. While these applications (Organon and YOU) enable the manipulation of generic anatomy, the Immersive Tools for Learning Basic Anatomy project at Yale goes a step further. This project enables the simulation in VR of individualized anatomy by converting the outputs of medical imaging devices such as MIR and CT scan images into 3D objects and environments.

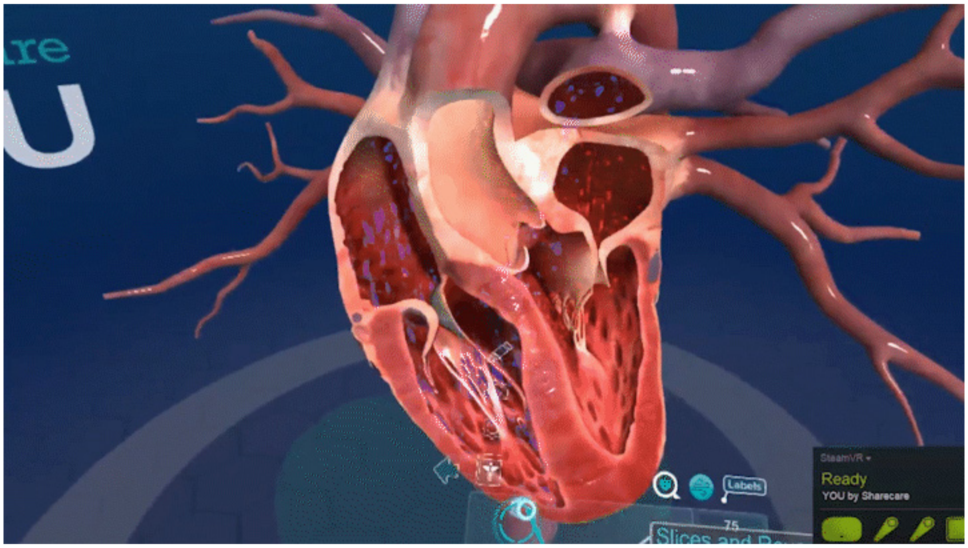


Figure 4. Simulation of blood flow inside a heart
Image courtesy of Benjamin Salzman, Hamilton College Library & Information Tech Services

Anatomy simulations also re-create the real in the virtual and by doing so enable teaching, learning, and experimentation with objects in ways not feasible in the real world. Medical students conduct dissections, for example, but cadavers are expensive, relatively rare, and, importantly, can only be used once; a virtual dissection enables a student to practice the same technique multiple times. Furthermore, some diseases and conditions are quite rare, and a medical student

> VR can give you experiences that are too rare, too expensive, too dangerous, or too remote.
>
> *—Elizabeth Evans, Duke University*

may never have the opportunity to see an organ with a specific condition; a virtual organ enables every student to see and treat even the rarest diseases.

All the Light We Cannot See

In addition to developing a VR dissection simulation, Yale's Immersive Tools for Learning Basic Anatomy project plans to develop AR overlays that can be used during real dissections. A dissection, like any surgery, is a challenging learning environment: There is usually only one lead surgeon, so not everyone may get to have an active hand in the dissection, and the organs being dissected are not labeled. A VR simulation provides everyone with the experience of dissection, and an AR overlay makes clear what everyone is looking at, leading to better use of a rare and expensive learning engagement.

Similarly, researchers at Harvard are developing AR overlays for building electronics. Generally, when building a circuit board, for example, one has to use a tester, which is a separate device from the object being built. Harvard researchers are developing an AR electronics tester that allows one to see sensor values and diagnostics overlying the object being built. This is but one set of AR functionality enabling the user to see overlays of segments of the electromagnetic spectrum outside the visible range. Figure 5 is a screenshot from a video of a Hololens AR project, which shows magnetic fields and electricity from audio speakers.

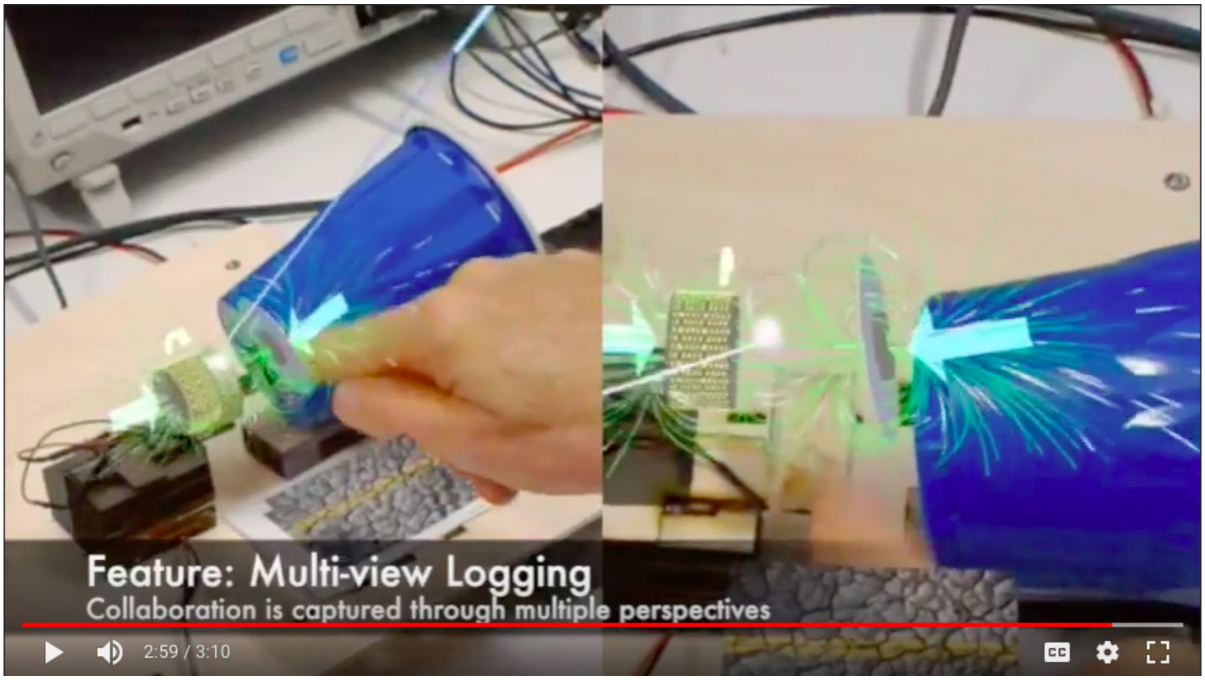


Figure 5. AR overlays of the user's line of sight with magnetic fields and electricity from audio speakers
Image courtesy of Bertrand Schneider, Iulian Radu, and the Harvard Graduate School of Education

The Very Small and the Very Large

The range of sizes of objects with which humans come into regular contact spans only about five orders of magnitude (a grain of rice is about 1 cm in length; even very large buildings are less than a kilometer in length). The range of sizes of objects that humans can comfortably manipulate with their hands is even smaller.[26] An important use of 3D technology, therefore, is to enable interaction with objects that are very small or very large.

To work at the very small end of the scale, a materials science student at Lehigh University built a VR model to enable the visualization and manipulation of atoms, cells, and enzymes. This VR model replicates an actual lab on campus in which, among other things, research is ongoing on synthesizing modular biomaterials for tissue engineering and regenerative medicine (for example, growing an organ on a scaffold with architectures and spatially organized functionality that resemble native biological tissues, which could then be transplanted into a human). This model enables atoms, cells, and enzymes to be expanded to a size large enough to be manipulated, like a virtual version of the ball-and-stick chemistry sets in high school science classes. The user can virtually walk through a scaffold and manipulate individual atoms or enzymes to see their effect on cell growth. These scaffolds can then be 3D printed and used in the offline world.

Scale of course is not binary: Something small enough to benefit from using VR to simulate manipulating it could have constituent parts with a wide range of sizes. A project at the MIT Scheller Teacher Education Program is developing a VR walkthrough of a cell in which the objects within the cell are represented appropriately scaled: Organelles are a fraction the size of the cell, enzymes and proteins are a fraction the size of organelles, etc. This type of scale-accurate visualization is very difficult to convey in other media, such as print or even video,[27] but it's perfectly feasible in VR, because it is possible to zoom in and out to better see and manipulate these subcellular objects.

At the other end of the scale, the very large—buildings such as the Vishnupada Temple and cities such as ancient Rome—are far too large for an individual to manipulate. But just as atoms and cells can be expanded to a manipulable size, so too can buildings and cities be reduced. 3D scanning and modeling is becoming increasingly common in the cultural heritage sector, particularly in museums and digital libraries, for both documentation and preservation. A notable example is the partnership between the Google Cultural Institute and CyArk, working to create a collection of 3D scans of archaeological sites.[28]

Beyond even cities, VR enables users to interact with and manipulate entire environments. At Lehigh, a project is under way to develop VR simulations that allow users to explore the Lehigh River watershed and its unique geological formations. At FIU, a project called Community was developed for a first-year experience course in the College of Communication, Architecture + The Arts. This project requires an interdisciplinary array of students to manipulate, in VR, a plot of land that is under 18 inches of water—a hypothetical site in the Everglades where industrial damage has occurred. This project involves multiple small-scale construction tasks for students across the many disciplines in the college and requires the manipulation of an entire environment containing many objects with various properties. Such manipulation would be well beyond what would be possible in the physical world, and certainly within the span of a semester. The VR project invites students to discuss and explore personal values while they think about their role in the collective. During the course of the semester, in which they build in VR on their own lots and in the community space, they are asked to address questions about the environment, ethics, morality, the origins of government and politics, and what it means to learn and grow together within a university community.

Design

For projects such as the Sacred Centers in India, the object being studied must be as realistic as possible in order to be useful as an object of research. Other projects, however, benefit from the ability to change objects and to manipulate them in ways that may be difficult or impossible in the real world.

VR is used extensively for the visual arts. Students at FIU have designed jewelry in VR, creating shapes and using materials that might be difficult or prohibitively expensive to work with in the physical world. Similarly, arts faculty have experimented with VR sculpture, which then can be 3D printed. At FIU, one arts faculty member is experimenting with 3D scanning and printing as a "creolization" of sculpture.[29] At Hamilton, students in a literature course created an AR book as a "hybrid object" by 3D scanning book art objects and using those scans as AR overlay images in a book that the class wrote and designed.

In the biomaterials lab at Lehigh, an important use of VR is to enable interaction with objects of varying sizes. Also at Lehigh, as well as at Hamilton College, theater departments are using VR to design models of stage sets and lighting schemes. At Lehigh, students in a course on digital rendering build VR models that the actors and director can walk through prior to those sets' being built. This allows them to diagnose how the sets and lighting will work in the offline space of the stage—just as in any architectural design work.

Architectural design relies on the use of space, its properties, and the objects it contains. Not only can VR enable interaction with objects of varying sizes, it can also enable the properties of objects to be changed in ways that would be impossible in the physical world. At FIU, for example, architecture students use found objects to inform their design. Students have been known to simply go outside and pick up natural objects, scan them using a 3D scanner, and manipulate the resulting digital model as a component of a larger design project. At Yale, architects have employed VR as a tool to aid in the design of a multi-unit, all-gender bathroom, enabling the experience of the visual and acoustic qualities of the space.

Also at FIU, VR and 3D printing are being used more systematically in a course on e-commerce offered by the architecture department. In that course, students design a product and 3D print the prototype to explore how VR experiences might enhance the consumer experience of product design in e-commerce. In a service economy in which value is co-created between the provider and the customer,[30] this approach to product design has the potential to dramatically change the nature of customization.

Similarly, two instructors, one at Hamilton and one at Harvard, have developed assignments for their courses that require students to design toys in VR and then 3D print them. At Hamilton College, students design and create toys in a psychology course on lifespan development. At Harvard, students interview children and then design and create a "dream toy" in a course on digital fabrication and making in education. Both projects involve designing an object in VR, either by using "canned" 3D models of shapes or by scanning 3D objects, which are then manipulated. The designed object is then 3D printed.

Collaboration

Virtual spaces enable the manipulation of objects in ways beyond what an individual user can do in the real world. Virtual spaces also enable a degree of collaboration beyond real-world possibilities. Just as Google Docs, for example, has changed how collaborative writing is done, so too do VR and AR environments enable collaborative manipulation of digital models. At FIU, 3D models are imported into game engines such as Unreal, making these models multiplayer, just like a VR game.

One such multiplayer environment is the Community project at FIU, described above. Students must build a shelter for themselves, paths, and communal spaces out of blocks that have various acoustical and aesthetic properties. This project is a large-scale architectural design-and-construction task requiring the manipulation of an entire environment and many objects within it. But beyond that, it is an exercise in community building, stewardship of the environment, communications, and the ethics of design and technology.

On a smaller scale, VR can also foster interpersonal collaboration. The MIT project discussed earlier, in addition to developing a scale-accurate VR walkthrough of a cell, has another component: teamwork. In this project, something is wrong with the cell, and the VR user must fix it from within the simulation. The VR user, however, can see only what is in front of her, just as if she were really there; a second individual has a tablet and sees a large-scale overview of the cell. As in the VR game Keep Talking and Nobody Explodes, these two individuals must communicate continually and effectively in order to fix the cell.

Collaboration is leverage, amplifying what it is possible to accomplish. An important upshot of the use of 3D technology is that it encourages novel collaborations. This is of course a common occurrence with the application of technology to new areas. The advent of digital humanities, for example, encouraged collaboration between computer scientists and historians; computer-aided design fostered collaboration between artists and programmers; the list goes on. In the context of deploying 3D technology, IT units and centers for teaching and learning are almost compelled to collaborate to provide support for faculty wishing to integrate this technology into their teaching. Beyond that, however, use of 3D technology has fostered interdisciplinary collaborations between students and faculty across academic boundaries: visual arts and computer science, medicine and media studies, bioengineering and game design. This sort of interdisciplinarity is extremely fruitful for both research and development, especially if the institution has an office for technology transfer (or some campus unit with a more or less equivalent name and function). Interdisciplinarity is also something that institutions of higher education strive to create, because it leads to a vibrant and active campus environment.

Community Outreach

The Miami Beach Urban Studios (MBUS) at FIU frequently hosts K–12 classes from the local community, which puts it in the company of other local anchor institutions, such as museums, that intersect with K–12 education in a variety of ways. While this report is primarily about 3D technology in higher education, it is not possible to talk about higher education in isolation: K–12 education is of course the pipeline to higher education. This sort of community integration is therefore valuable for fostering interest in STEAM and higher education generally among K–12 students.

Taking a class of K–12 students on a field trip, however, is logistically complicated: Permission forms must be signed, a bus must be rented, chaperones must be recruited, etc. It is in some ways easier to reverse the visiting arrangement: Instead of a class coming to the anchor institution, the anchor institution can come to the class.

Researchers at Syracuse University are pursuing this avenue. Syracuse University, unique among the participants in the Campus of the Future project, had an HP Z VR Backpack PC. This PC is similar to the HP Omen Desktop (see appendix) but is comparatively flat and designed to fit into a backpack harness that allows it to be worn while the user moves freely. Researchers at Syracuse University have conducted, and are planning more, "popup" events, where they take VR Backpack rigs to local schools or community events, or even just onto the campus quad, and allow users to experience VR environments. This serves the dual purpose of getting feedback on ongoing research and development from new users and generating interest among the community.

Addressing the Project Evaluation Questions: Learning Goals Served by 3D Technologies

The ability to support and promote shared experiences and collaboration is one of the most powerful affordances of 3D technology. And this leads to arguably the most significant outcome of the use of 3D technologies in higher education: their ability to enhance active and experiential learning.

To dramatically oversimplify, experiential learning is learning through doing and then thinking about what one has done. A critical component of experiential learning is this "metacognition," whereby learners reflect on their current understanding and further information needs.[31] This, of course, generally requires an instructor to monitor the learner's reflection and self-assessment, which is not necessarily enabled by 3D technology. What *is* enabled by 3D technology is the *experiential* part of experiential learning. By dramatically expanding the range of tasks and activities with which a learner can gain hands-on experience, 3D technology can enable active and experiential learning where it may not have previously been possible. And it is precisely this ability to provide such experiences that makes 3D technologies useful for education. 3D printing can literally provide hands-on experience of things that were previously inaccessible to hands, such as molecules. AR can enable hands-on experience of things that are not physical, such as electromagnetism. And when wearing a VR headset (provided one's nonvisual sensory inputs do not conflict with the simulation), one tends to accept the simulation as a genuine experience, perceived as actually being there.

And thus here is an answer to the first of the evaluation questions motivating the Campus of the Future project: *Experiential approaches to teaching and learning lend themselves to the use of 3D technologies.*

The answer to the second of the evaluation questions motivating this project is more complex. What are the most effective 3D technologies for various learning goals? It almost goes without saying that it depends on the learning goal. There are of course as many learning goals as there are disciplines, as many as there are instructors, as many as there are students. And it is probably also true that the Campus of the Future project did not identify all possible uses of 3D technologies. Nevertheless, we can at least start to answer this question. Table 1 identifies some learning goals from projects at participating institutions, some

Experiential approaches to teaching and learning lend themselves to the use of 3D technologies.

3D technologies that are effective for meeting those learning goals, and the mechanisms by which those technologies can help meet those learning goals.

Table 1. Learning goals that 3D technologies are effective in helping to meet

	3D Technology				
Learning Goal	**VR**	**AR**	**3D Scanning**	**3D Printing**	**Mechanism**
Develop ethical awareness	X				Simulations designed to require empathy or communal approaches to solve
Develop analytical skills	X	X			Simulations designed to structure the achievement of learning goals
Gain practice	X	X			Shared simulations
Develop strategies for collaboration	X	X			Shared simulations
Gain self-confidence in practical tasks	X				Iteration of simulated experiences
Develop scientific literacy	X			X	Interaction with objects too large or too small to interact with in the physical world
Develop artistic literacy	X	X	X	X	Interaction with materials difficult or impossible to manipulate in the physical world, and the ability to iterate designs
Develop spatial and 3D visualization skills			X	X	Iteration of design work
Increase student ownership of their own learning	X	X	X	X	Learning new skills to use the technology; conceptualizing one's own uses for the technology
Develop teaching and mentoring skills	X	X		X	Collaboration with peers on shared experiences and/or simulations
Develop oral communication skills	X	X	X	X	Collaboration with others on shared experiences and/or simulations
Develop systems-thinking skills	X	X	X	X	Simulations designed to require mental modeling and abstraction

Again, there are a nearly infinite number of possible learning goals, of which these are only a few. Like any technology, 3D technology has many uses, not all of which may even have been discovered yet. Still, the Campus of the Future project identified a diverse set of important learning goals for which 3D technologies are effective, across a wide range of disciplines.

The Future of 3D Technology in Higher Education

For decades, science fiction has envisioned a future for 3D technology. William Gibson's cyberspace and Neal Stephenson's metaverse are entirely immersive, VR-like environments. (Not to mention, of course, *The Matrix*.) Vernor Vinge's novel *Rainbows End* explores a future in which AR is ubiquitous through the use of contact lenses that project overlays on top of what the wearer is seeing. A decade after the publication of *Rainbows End*, such contact lenses are under development.[32]

There is no necessary distinction between AR and VR; indeed, much research on the subject is based on a conception of a "virtuality continuum" from entirely real to entirely virtual, where AR lies somewhere between those ends of the spectrum.[33] One can easily imagine a future headset (a pair of glasses, a pair of contact lenses, a prosthetic eye, etc.) that the user can "dial" back and forth, from entirely transparent to entirely immersive, depending on the use case. Indeed, science fiction has already envisioned this future, from the display that Tony Stark sees in his Iron Man mask in Marvel superhero movies, to the gesture-based computing in the movie *Minority Report*.[34]

Zeynep Tufekci, in her book *Twitter and Tear Gas*, argues that the online and offline worlds are often seen as being entirely separate, that "the online world is somehow less real than, and disconnected from, the offline one."[35] Tufekci argues that this is no longer the case, if it ever was … that the online world is as much a part of the offline world as any form of human communication over distances, as integrated into the real as email, snail mail, telephone, radio, or pigeons. Indeed, Tufekci never even uses the term "real world" except to critique it and suggests that the term "virtual" betrays this same falsely dualist mode of thinking.

Tufekci was discussing the use of social media specifically, and in the context of political protest movements, not education. Nevertheless, this view of the online world as being integrated into— indeed, being part of—the offline world is critical to imagining the future of 3D technology— indeed the future of any technology—and not just in higher education.

For the future of 3D technology in higher education to be realized, that technology must become as much a part of higher education as any technology: the learning management system (LMS), the projector, the classroom. New technologies and practices generally enter institutions of higher education as initiatives. Several active learning classroom initiatives are currently under way,[36] for example, as well as a multi-institution open educational resources (OER) degree initiative.[37] When massive open online courses (MOOCs) were new, many institutions launched MOOC initiatives. Even mobile devices were first introduced into many institutions of higher education as initiatives.[38] Now, however, mobile devices are owned by nearly all faculty and students, and both groups want to use more video in their courses.[39] These technologies, and the practices around them, have moved beyond the initiative stage and have become relatively standard in higher education.

We are currently still in the initiative stage of 3D technology adoption into higher education. Over time, 3D technologies will inevitably become more common in higher education. Indeed, this is already happening, though, like all technological advances, it is not evenly distributed yet: Some 3D technologies are more integrated into institutions than others. Specifically, 3D scanning and printing are well on their way to being commonplace in the institutions that participated in the Campus of the Future project. In particular, 3D scanning was used at participating institutions mostly as an input to VR, a mechanism for producing 3D models that could be manipulated in VR; 3D printing was used mostly as an output from VR, a mechanism for producing physical objects that were designed in VR. Certainly these are not the only uses of 3D scanning and printing, but they were the predominant uses in projects at participating institutions. 3D scanning and printing have certainly not yet become standard in higher education, but it is worth noting that these technologies are being used as access points, or avenues into the use of even more experimental technologies.

Most campuses have a printing policy governing students' use of campus printers: Students have a quota of so many pages printed in black and white and so many in color per semester. (These quotas are often enforced only loosely, when they are enforced at all.) Filament for 3D printers is much more expensive than printer paper and ink, but that will probably not always be the case. And while desktop 3D printers (such as the Dremel Idea Builder) are considerably more expensive than desktop paper printers, they are considerably less expensive than the type of networked photocopier/printers that students generally have access to on campuses. Forthcoming EDUCAUSE research from the 2018 study of undergraduate students and information technology has found that 3% of students have access to 3D printers on campus. It is easy to imagine a not-too-distant future that sees this number growing, as 3D printers emerge from makerspaces and other restricted spaces on campus and are made available in libraries and student unions, as accessible as other ubiquitous technologies supported by campus IT units and under similar terms of use.

Networked photocopier/printers are commonly made available to students on campus because reading and writing are critical to the work of being a student, probably part of every course. To enable this critical piece of the student experience, many institutions of higher education provide students with technology guidelines—recommendations for the hardware and software configuration of any computer in order to operate in the campus computing environment (e.g., see the guidelines from Syracuse University and Hamilton College). In addition to recommendations for software for purchase, some institutions also provide software to students and other institutional affiliates

We wouldn't have this VR equipment if it weren't for this project. But now that we do, it's taking on a life of its own.

—Brian Slocum, Lehigh University

(e.g., the list of software licensed by Lehigh University for use by affiliates). Even if an institution does not provide software, academic units often recommend specific software to students in their program (e.g., Photoshop for fine arts departments, CAD software for architecture departments). It is easy to imagine a not-too-distant future in which institutions of higher education or specific departments recommend that students arrive on campus with computers configured to support 3D technology. Institutions might also recommend or even provide CAD/CAM software or game engines for 3D modeling, alongside the currently more common antivirus software, word processors, and statistical analysis packages. For students to purchase or, in some cases, for institutions to provide this type of software might be prohibitively expensive today. But this will likely not always be the case. Ten years ago, mobile devices were seen on campuses mostly as part of technology initiatives; now nearly every student brings their own to campus. Five years ago, 3D printers were rarely available to students at institutions of higher education; now makerspaces are increasingly commonplace.

Storytelling

Personal experience is one of the most effective elements of acquiring an education. Alongside personal experience, however, there must be a component of narrative and storytelling in effective education—to generate interest, to provide structures for remembering, and to assist students to contextualize what they are learning.[40] Some scholars have argued that all human communication is based on storytelling;[41] certainly advertisers have long recognized that storytelling makes for effective persuasion,[42] and a growing body of research shows that narrative is effective for teaching even topics that are not generally thought of as having a natural story, for example, in the sciences.[43]

VR's ability to immerse the user in a simulation—in other words, to enable a narrative developed by others to become a personal experience—makes it a particularly powerful vehicle for providing educational experiences. In particular, there is a growing body of research that shows that VR holds a great deal of promise for teaching empathy.[44] One participant in the Campus of the Future project mentioned the United Nations project Clouds over Sidra, which is the story of a 12-year-old Syrian girl living in a refugee camp in Jordan. Other project participants mentioned other possible uses of VR to reconstruct historical events and put users in the middle of them—for example, the 1965 Selma to Montgomery march or battles on the Western Front during the First World War. These could be structured like the popular *Choose Your Own Adventure* children's books, so that one's actions in a simulation change one's future options.

A research team at Syracuse University is currently investigating the use of VR in teaching. Among other research questions, this project is investigating where a user's attention is directed while in a VR simulation and how that affects the user's later recollection of the events in the simulation. Some early work along these lines has been conducted in police simulations, where the stakes for correctly directing one's attention, taking action, and being able to recall events later are quite high.[45]

Accessibility

The experience of Gallaudet University highlights one of the most important areas for development in 3D technology: accessibility for users with disabilities. Accessibility is often something of an afterthought in the design of new technologies, and 3D technology is no exception. Yet designing for accessibility is critical for some users to even be able to use 3D technology at all.

Gallaudet is a school primarily for deaf and hard-of-hearing students. In the United States, deaf individuals often communicate via American Sign Language (ASL). ASL is a visual communication system, which means that once a deaf user dons a VR helmet, she cuts herself off from all communication from the outside world. The user wearing the VR helmet may sign to others, but there is no simple way for others to communicate back. AR is therefore arguably a more "deaf-friendly" technology, as the user can see *through* an AR headset.

One possibility for communicating with a deaf user in VR is a popup box appearing in the user's field of vision, like a text message. This is a slow (slower than either speech or signing) form of communication, however, and potentially breaks the immersion of the VR simulation. Another possibility is for a VR environment to be designed with "stop points"—locations or activities that are established in advance as points when the user must take off the headset and communicate with others. This too, however, takes the user out of their immersion.

The Americans with Disabilities Act provides standards for accessible design of physical spaces of various types. The ADA also provides technical assistance and guidance for accessible technology, though this primarily deals with web accessibility. Individuals and companies developing VR environments for deaf and hard-of-hearing users should consult these standards, though neither is exactly on point for VR. It is probably time for a new version of the ADA standards to be developed that addresses VR and AR technologies.

Another issue for VR, one not confined to deaf and hard-of-hearing users, is simulator sickness. Given that this is a form of motion sickness, individuals differ in their susceptibility, but it can occur without the user actually experiencing any motion.[46] Many solutions have been proposed to combat simulator sickness, including dimming one's headset, keeping one's time in a simulation short, slowing down the refresh rate of the simulation, and operating a VR simulation

When I read a book, when I watch a movie, when I play a video game, I'm an observer. I'm learning a lot, I'm taking in the experience, I'm imagining myself in the footsteps of whomever the characters are. But I'm not there. In a virtual reality experience, you're there. Your body interprets, your brain interprets this as an authentic experience. Something happens in the room, your heart rate goes up, you start to sweat.

—Randall Rode, Yale University

on an empty stomach. These are suggestions, however, and little research has been done to establish their efficacy. One method that has been shown to be effective in combating simulator sickness, however, is to insert a static object into the user's field of vision: a frame, like a cockpit, or some other static object, like a nose.

Instructional Design

Students want technology integrated into their courses, and they want their instructors to make more use of technology in their teaching.[47] This is a persistent finding of much prior EDUCAUSE research, even for those tools that are quite well established, such as the LMS and lecture capture. Certainly 3D technologies have a greater "cool factor" than these comparatively staid tools. Yet, 3D technologies, like any technology, must serve a meaningful pedagogical function.

For that to be the case, 3D technologies must be incorporated into the instructional design process for building and redesigning courses. And for that to be the case, it is necessary for faculty and instructional designers to be familiar with the capabilities of 3D technologies. And for *that* to be the case, it may not be necessary but would certainly be helpful for instructional designers to collaborate closely with the staff in campus IT units who support and maintain this hardware.

However, staff in IT units and centers for teaching and learning often do not collaborate and may not have much contact at all. Every institution of higher education has a slightly different organizational structure, of course, but these two campus units are often siloed. This siloing may lead to considerable friction in conducting the most basic organizational tasks, such as setting up meetings and apportioning responsibilities for shared tasks. Nevertheless, IT units and centers for teaching and learning are almost compelled to collaborate in order to support faculty who want to integrate 3D technology into their teaching. It is necessary to bring the instructional design expertise of a center for teaching and learning to bear on integrating 3D technology into an instructor's teaching, and it is necessary to bring the technical expertise of the IT unit to bear on the deployment of 3D technology in the classroom.

Even assuming that an institution has a workable mechanism for instructional designers and IT staff to collaborate, some effort is still required to meaningfully integrate any technology into the teaching and learning experience. Therefore, one of the most critical areas in which IT units and centers for teaching and learning can collaborate is in assisting instructors to develop this integration and to develop learning objects that use 3D technology. Instructional designers can help faculty develop pedagogically sound uses for 3D technology in their courses, but they may lack the skills to help faculty deploy this technology. IT staff may have the deployment skills but may lack the skills to develop new tools, such as simulations and models in platforms such as Unreal Engine and Steam. Instructional designers may understand the uses of learning analytics and the gamification of learning, but game designers can bring to the table engagement analytics and an understanding of gamification honed in the game industry. Collaboration among IT staff, instructional designers, software developers, and game designers has the potential to enable extremely creative uses of 3D technology in teaching and learning, and across campus.

The process for developing learning objects that use 3D technology, as described here, is quite labor intensive, involving a team that includes, at a minimum, an instructor, an instructional designer, and an IT staff member, one or more of whom possess the skills of a software developer and a game designer. For 3D technology to really gain traction in higher education, it will need to be easier for instructors to deploy without such a large support team.

Sites such as Thingiverse, Sketchfab, and Google Poly are libraries of freely available, user-created 3D models. Among other freely available tools for building 3D models is Google Blocks. A third component that is critical for 3D technology to gain traction in higher education is freely available tools to help instructors develop their own learning objects that use 3D technology. Some instructional uses that could benefit from this sort of tool have already been discussed: developing simulations of historical events or conducting "popup" events in the local community. Such events could be extremely powerful instructional opportunities if it were possible for instructors to build custom simulations for the specific user community. Some tools, such as Minecraft: Education Edition, are already available to assist in the development of virtual environments; the world of 3D technology needs a tool that provides instructors with a similar framework for development.

In particular, a tool is needed that allows for the development of instruction for entire classes. Many current educational VR simulations allow for only a single user. Even popular VR games often allow for only a small number of users: *Star Trek: Bridge Crew*, for example, is designed for four players. What instructors in higher education need (and instructors at other educational levels too, of course) are simulations that can accommodate an entire class of students simultaneously. ClassVR is a tool that enables the simultaneous delivery of a simulation to multiple headsets, though the simulation itself may still be single-user. A combination of an easy-to-use development platform for instructors, the ability to create "multiplayer" educational simulations, and low-cost headsets would be a powerful tool for integrating 3D technology into higher education.

Mobility

The project team at Syracuse University has an HP Z VR Backpack PC. This rig has enabled researchers at Syracuse to conduct what they call "popup" events, discussed above, where the public can experience VR environments. The "cool factor" of VR makes this a particularly effective form of outreach. But it also has a more pedagogically useful function: It enables an educational simulation to be set up and used anywhere, any time. And as the development process gets easier, the more responsive the simulation can be to the local context and educational needs.

The VR assignment in a first-year experience course at FIU was described earlier. It requires groups of students to manipulate a model of a hypothetical plot of land under 18 inches of water. Given the rapid rate of sea-level rise in the Southeastern United States,[48] this is just barely a hypothetical scenario. Imagine a group of environmental engineers going into the field (or wetland) with AR headsets and collaboratively designing buildings and earthworks virtually. Those buildings could then be 3D printed. Of course, industrial-scale 3D printers for construction are quite a bit different (and more expensive) than desktop 3D printers. But the process is similar and, as with all architecture, benefits from the designers having an understanding of the environment the building will occupy.

Recall the VR walkthrough of the Vishnupada Temple, which enables the user to peel away surfaces and virtually look through walls. Imagine combining this with the type of AR overlay being designed at Harvard for electronic components. Now imagine combining all of that with a radio-frequency sensor, which is already commercially available as a smartphone app. Users would be able to see through walls, a superpower that any archaeologist, architect, or electrician might desire. Indeed, the C-THRU firefighting helmet has already implemented some of this functionality to enable firefighters to see through smoke via the use of thermal sensors and AR displays.

One can imagine an immense range of possible applications of untethered AR and VR in a wide variety of settings and educational disciplines. In a classroom or a lab, of course, any possible simulation can be deployed, particularly if the instructor has some lead time and has collaborated with an instructional designer. However, the real power of mobile VR and AR rigs comes from their flexibility—the ability to deploy a simulation anywhere, anytime, combined with a development process that (one assumes) will only continue to get easier. Thus any location can be a classroom, any time can be a teachable moment.

> The VR backpack is kind of what we've always been waiting for.
>
> *—Jason Webb, Syracuse University*

Data Management

A 3D scanner operates like a combination of a digital camera and a LIDAR range finder: Lasers are bounced off an object to identify its shape, and digital photos are taken of its surface; photogrammetry software then “wraps” the photos around the 3D model of the shape. Depending on the physical size of an object and the complexity of its surface, a 3D scan may comprise dozens, hundreds, or even thousands of photos. As anyone who has ever looked at the storage use on their smartphone knows, digital photos can be fairly large and take up a lot of space. A single 3D scan might not tax the storage capabilities of a campus IT department, but once a 3D scanning program is in place, for courses or for research, the number of scans that must be stored will increase rapidly.

Hamilton College encountered this very problem. The GeoSciences 3D Scanning Project has the goal of scanning the entire collection of mineral samples acquired by faculty, students, and alumni over 200 years. While these mineral samples are not physically large, they have uneven surfaces; therefore the photo set for the 3D scans of the objects is quite large. By the end of this project, Hamilton College will need to devote significant storage space to maintaining this data set. Furthermore, the institution may want to make this data set available to others. The original mineral samples at Hamilton College are used by several neighboring institutions; it seems likely that these same institutions, and perhaps others as well, may want to use the 3D scans of these samples.

Institutional repositories are often the mechanism by which institutions of higher education make such data sets available. An institutional repository is a collection of an institution’s intellectual output, often consisting of preprint journal articles and conference papers and the data sets behind them.[49] An institutional repository is often maintained by either the library or a partnership between the library and the campus IT unit. An institutional repository therefore has the advantage of the long-term curatorial approach of librarianship combined with the systematic backup management of the IT unit.

On a larger scale, the issue of data management for 3D scans, 3D models, VR environments, and other large data sets associated with 3D technology is significant in general. Several websites allow users to upload and share 3D models: Thingiverse, Sketchfab, and Google Poly, among many others. Use of such sites takes the storage burden off the institution. There may be an advantage, however, to maintaining local copies of this data instead of, or in addition to, sharing it, even if only as a backup.

Sharing data sets is critical for collaboration and increasingly the default for scholarship. Data is as much a product of scholarship as publications, and there is a growing sentiment among scholars that it should therefore be made public.[50]

Institutional repositories are often the vehicle by which data sets are made available. But for data sets to be managed locally, as well as to be found by others, institutions must adopt both policies and metadata for data sets. Fortunately there has been some work to develop both. Data governance policies are commonplace, as are guidelines for creating your own policies.[51] The CARARE Metadata Schema Version 2.0 enables the capture of metadata and provenance data describing the creation of 3D models. It would behoove institutions to adopt data governance policies for the maintenance of 3D data sets as well as appropriate policies for descriptive and provenance metadata[52] about those data sets.

Recommendations

Every institution of higher education is unique in terms of its organizational structure and the resources dedicated to IT and support for teaching and learning. Some of the examples and lessons learned that have been discussed in this report will therefore not be applicable to all institutions. Nevertheless, all recommendations are presented here for institutions of higher education that are interested in deploying 3D technologies, with the understanding that your mileage may vary.

Concerning the Organizational Structure of Institutions of Higher Education

- **Provide adequate time and resources for setting up 3D technology.** Even prior to these tools getting used, hardware must be set up and software installed and possibly updated, which may require the involvement of IT staff. If 3D technology is going to be used during a specific semester, it is best to start setting up that equipment well in advance, several months before the start of the semester.
- **Provide adequate time for faculty to adopt 3D technology.** Faculty may not complete revisions to their syllabi until days before the semester starts, but they are often thinking about and planning those revisions months ahead of time. Faculty require at least a semester's lead time to implement any new technology in the context of a course, as it is challenging to change or implement new tools midsemester.
- **Provide adequate resources to faculty during their adoption of 3D technology.** Even early adopter faculty can benefit from support from instructional designers and instructional technologists when planning how to appropriately deploy 3D technology in a course. Indeed, early adopters in particular may get caught up in the "wow factor" of new technology; working with instructional designers and instructional technologists may help keep their focus on the pedagogical efficacy of that technology. These consultations can take many forms: one-on-one consultations, small group training sessions, larger group workshops, and "train the trainers" programs in which early adopter faculty mentor their colleagues.[53]
- **Allocate a budget to 3D technology initiatives.** Institutions of higher education often allocate a budget to new technology initiatives, and this is no different. Supporting the adoption of 3D technology on campus requires staff support from the campus IT unit, instructional designers and instructional technologists, and other instructor support units on campus,

> There are things we'd like to be able to do with this technology that we just can't do yet because of staffing, and staff experience with the technology. It could be taken so much further.
>
> *—John Stuart, Florida International University*

at least initially. These campus units may need to devote staff time for consulting with faculty and students and for developing training sessions and workshops. Furthermore, if the institution is attempting to encourage adoption of 3D technology (or any new technology), prior EDUCAUSE research has shown that stipends and especially course release time are effective motivators for faculty.[54]

- **Consider new staffing models for providing support.** Supporting faculty may require high-touch consultations. Supporting students may require staffing after regular business hours. Supporting students is critical, as it is a matter of equity of opportunity. Students with different backgrounds and experiences will come to campus with different levels of comfort with 3D technology and varying levels of ability to learn it on their own. These high-touch support mechanisms all require staff time and perhaps changes to staffing models at the institution.
- **Develop mechanisms for campus IT and instructional design staff to collaborate.** Every institution of higher education has a slightly different organizational structure, of course, but campus IT and instructional designers are often siloed. Nevertheless, IT and teaching and learning staff are almost compelled to collaborate in order to provide support to faculty who want to integrate 3D technology into their teaching. Many mechanisms might be developed to facilitate collaboration between staff in these campus units: standing meetings, shared project leadership across campus units, codevelopment of workshops and other training programs, and even physical proximity of office space on campus.
- **Hire or train developers and designers.** In some ways this is a subset of the above recommendation concerning budget allocation, as hiring and training staff obviously has budget implications. But this recommendation is more than budgetary. If an institution wants to deploy 3D technology widely and to have faculty integrate it into their courses, the institution must hire dedicated staff or provide professional learning opportunities for current staff to develop expertise with this technology. Specifically, an institution needs software developers and game designers. Instructional designers can help faculty to develop pedagogically sound uses for 3D technology in their courses, but they may lack the skills to help faculty deploy this technology. IT staff may have the deployment skills but lack the skills to develop new tools, such as simulations and models in platforms such as Unreal Engine and Steam. Instructional designers may understand the uses of learning analytics and the gamification of learning, but game designers can bring to the table engagement analytics and an understanding of gamification honed in the game industry. Collaboration between IT staff,

instructional designers, software developers, and game designers has the potential to enable extremely creative uses of 3D technology in teaching and learning, and across campus.

- **Hire a project manager.** New technology initiatives at institutions of higher education are complex undertakings requiring collaboration across campus units that may not have a history of collaboration. Furthermore, such initiatives are often subdivided into subprojects—small research grants, course development, etc.—some of which will need more support than others. A large umbrella project with many moving parts benefits from a dedicated, at least part-time, project manager. As 3D technology is integrated into the normal operation of whatever campus unit(s) it ultimately falls under, a dedicated project manager may not be necessary. But the position is extremely valuable at the new technology initiative stage.
- **House 3D technology in public spaces.** In general, the more publicly accessible a technology is on campus, the more use it gets. Participating institutions in the Campus of the Future project that made 3D technology available in public spaces (e.g., a makerspace, a library, a dedicated media lab space) found that it got more use, particularly by students; institutions that made 3D technology available only behind locked doors or with permission of a faculty or IT staff member unsurprisingly found that it got less use. If an institution wishes to promote the use of 3D technology, and particularly to encourage student experimentation with this technology, it should make the technology as publicly available as possible. "As possible" is, of course, the tricky part: Institutions naturally need to ensure the security of their technology. And students often work late into the night, on weekends, etc., so the staffing of these public spaces is an issue that may need to be addressed by the institution.
- **Work toward integrating 3D technology into institutional operations.** Institutions of higher education often allocate a budget and staffing to new technology initiatives, but initiatives eventually end. An initiative is useful as a proof of concept, giving new technologies time to gain traction on campus and serving as a mechanism to experiment with new staffing models. But once 3D technology has become relatively widespread on campus, it must become part of the operations of IT units, instructional design staff, and other appropriate campus units. Moreover, it must be explicitly aligned with the institution's strategic goals and its teaching and learning mission. It may, of course, take several years for a new technology to move from initiative to operational. But 3D technology will ultimately move that way, just as the LMS, mobile devices, laptops, and many other technologies have before.

Concerning Development and Implementation of 3D Technology

- **Develop policies for the campus community around 3D technology.** Technologies tend to get less expensive and easier to use as time goes on, and this has certainly been the case with 3D technology, even as adoption on campus has increased. As this continues, the technology will inevitably be adopted by more users on campus. Even if a campus IT department does not support 3D technology, its increased use at least requires the development of relevant policies. In this way, 3D technology may be like smartphones or other common consumer technologies: Campus IT departments often do not support smartphones, but there are policies regarding their use on campus—for example, requiring the use of a secure Wi-Fi network or prohibiting access to secure data on mobile devices.
- **Provide support to the campus community for 3D technology.** As 3D technology gets less expensive and easier to use, its adoption on campus will increase, and as that happens the more sophisticated its uses will become. As with any technology, as users learn to use 3D technology, some will think of more and more sophisticated things to do with it, and some will want to develop tools that do not yet exist. Support for 3D technology will require both collaboration across campus units and high-touch service for at least some users. Institutions must consider the level of service around 3D technology that it is feasible for staff to provide.
- **Provide differentiated levels of support for different use cases.** There is an important distinction with 3D technology (as with all media) between content consumption and content creation, which require different types of user support. Those wishing to use preexisting VR simulations, or AR layers, or to print existing 3D models may need assistance to find such resources, technical support to deploy them, or instructional design support to integrate them into their teaching. A user wishing to develop new simulations or models, on the other hand, requires a much deeper and more technically involved level of support, perhaps even requiring software development expertise. Institutions must be able to staff IT units and centers for teaching and learning appropriately for existing and future use cases on campus.
- **Provide support for 360-degree video.** A 360-degree video camera (such as the GoPro Omni) is relatively inexpensive, and 360-degree video is a relatively low-bar mechanism to get into production of VR simulations. A 360-degree video is not a full VR simulation, because it is "flat" and not interactive. But it is possible to create simple simulations using 360-degree panoramas, and 360-degree cameras are easily available commercially and relatively inexpensive. IT units, libraries, or makerspaces supporting 3D technology on campus may wish to purchase some 360-degree cameras

and provide some support for their use (training, workshops, instructional design support, etc.) to the campus community.

- **Provide support for 3D modeling tools.** Many online repositories exist where users can find preexisting 3D models: Thingiverse, Sketchfab, and Google Poly, among many others. There are also many applications (both commercial and free) for creating new 3D models and manipulating existing ones. IT units, libraries, or makerspaces supporting 3D technology on campus may wish to provide support (training, workshops, instructional design support, etc.) to the campus community in the use of these sites and applications.
- **Develop curricula for training sessions and workshops, and standards for support of 3D technology.** Early adopters of 3D technology on campus may require a great deal of support, or very little. Either way, these early adopter users are unusual. As the use of 3D technology becomes more widespread on campus, more users will require training and support. Institutions must develop curricula for training sessions on 3D technology-related topics, and standards for the level of support that can be provided to users of the technology. These training sessions and policies must of course be customized to the particular context: user, academic discipline, etc.
- **Integrate 3D technology into the curricula of academic programs.** Technology that is used in courses sees the most use. This is unsurprising, as such technology is integrated into both students' and instructors' work. This suggests, however, that if it is an institutional goal to increase the use of 3D technology (or any technology) on campus, an important strategy is to encourage its adoption into courses and within academic programs. The lower bar is to integrate 3D technology into courses first, by working with early adopter instructors. Once the success of those integrations has been demonstrated, it will be easier to integrate this technology into entire programs.
- **Encourage community building and word of mouth.** The example of Hamilton College makes for an excellent case study here. Hamilton is smaller than any of the other participants in this project[55] and yet had more projects ongoing throughout the duration of this study than any other participating institution except Yale, which had been working with 3D technology for a year longer than any other participant. How did this come to pass? The project team at Hamilton puts it down to good old-fashioned grassroots outreach and word of mouth. Grassroots outreach may be easier to achieve at a small institution, where it may be more feasible for the staff of the IT unit and the center for teaching and learning to provide high-touch services. Even at very large institutions, however, grassroots outreach is both possible and desirable, achievable largely by leveraging the inherent

communities within academic and other campus units and identifying faculty and other individuals who are “network hubs”—both formal and informal leaders on campus.

- **Deploy easy-to-use platforms for instructors who want to develop 3D models and simulations.** Early adopter faculty may be willing to spend the time to learn to use tools for 3D modeling and creating AR layers. But many more faculty are less willing or able to do so. To encourage widespread adoption of 3D technology, easy-to-use tools must exist. Just as LMSs are so easy to use that faculty can (mostly) develop their own course shells with little or no assistance, so too must 3D technology become easy to use. This report has identified many tools currently available for VR, AR, and 3D scanning. But few of these are specific to developing educational simulations or learning objects. Development of such a platform, targeted at the education sector, would probably not be a task for a single institution; rather it should probably be taken on by a consortium of institutions (as was development of the Sakai LMS, for example) or a collaboration between a commercial software company and an open-source development community (as was the Canvas LMS).

Conclusion

The Campus of the Future: 3D Technologies in Academe project identified current innovative uses of 3D technologies, investigated which educational activities lend themselves to the use of 3D technologies, and identified the most effective 3D technologies for various learning goals. This project is not the first effort to integrate VR, AR, or 3D printing and scanning technologies into educational experiences, but it is the broadest such project that we are aware of, spanning a larger and more diverse sample of institutions and learning environments, and reaching a larger number of users. Much of the prior work on the integration of 3D technologies into education focuses on individual courses with specific learning objectives. This project addressed not specific learning objectives but more broadly the use of 3D technologies to achieve particular learning goals. The technologies investigated here—and the wider range of XR technologies—hold a great deal of promise for teaching and learning. This project is, we believe, a significant first step toward establishing a baseline of empirical evidence about 3D technologies for education. We now call for a broader research agenda to expand on this work and to investigate which educational activities lend themselves to the use of XR technologies broadly and identify the most effective XR technologies for specific learning goals.

The author William Gibson is credited with having said, “The future is already here, it’s just not evenly distributed yet.” Well-resourced academic units are able to purchase cutting-edge tools and technologies and make them available for students and faculty, as well as provide the staffing to implement them. It is the students and faculty in less well-resourced academic units that need institutional support. These users may be just as enthusiastic about using new technology and have just as many ideas, but lack the resources to realize them. These users need a campus unit to be the early adopter, to purchase this technology before they can purchase it commercially for themselves. Often it is shared campus facilities (libraries, makerspaces) that provide access to technologies (3D or otherwise) that are on the edge of or beyond current consumer availability. But while providing access to this technology to the campus community is important, providing support for the technology is equally important. Technical support to help users scale the learning curve of a new technology is critical, but that is just the first step; instructional design support to help users figure out how to integrate new technology into their teaching, research, or coursework is equally critical. All new technology is a learning experience, and learning experiences are of course the point of higher education. The future is not evenly distributed yet. Part of the purpose of higher education is to help it become so.

> The question is, how to get research and teaching in better dialogue with each other.
>
> *—Alan Cattier, Dartmouth College*

> We call for a research agenda to identify the most effective XR technologies for specific learning goals

Methodology

The Campus of the Future project was an exploratory evaluation[56] and as such utilized a mixed methods approach. The use of multiple methodologies was necessitated by several factors:

- the duration of the project,
- the emergent nature of the projects at participating institutions,
- the existence of multiple forms of documentation for projects at many participating institutions, and
- the fact that participants were engaged in implementing the technology and learning how to use it while the research was ongoing.

Three primary mechanisms were used for data collection during this project:

- **A start-of-project survey.** This was an in-depth survey to collect data about the intended use(s) of the 3D technology at each institution. Respondents were asked to upload syllabi for course-related uses and/or grant proposals (or other write-up) for research-related uses of the technology. This survey asked respondents to articulate things such as (1) the learning objectives of the course(s) and/or the research objectives of the project for which the equipment would be used, (2) the evaluation criteria for the course or project, and (3) what would constitute success upon completion of this project. Content analysis was conducted on the documents provided by project participants as part of their responses to the start-of-project survey.
- **Biweekly status report surveys.** These were lightweight surveys that participants were asked to fill out throughout the course of the project, with a break over the December holidays. These surveys asked participants (1) to do some rough time-tracking, asking approximately how many hours the project team spent working on the project over the previous two weeks, and (2) about any progress and successes, delays, or setbacks that the project team experienced over the previous two weeks.
- **In-depth interviews.** These were semistructured interviews with the project leader or project team during which the EDUCAUSE research team asked project participants to provide more depth of detail about their teaching and research using the provided 3D technology—for example, unexpected or unplanned uses or outcomes that emerged, processes developed over the course of the project, and lessons learned.

In addition, several secondary mechanisms were used for data collection during this project:

A LISTSERV was set up to facilitate communication among project participants. At the start of the project, the researchers asked participants to post a brief description of the courses and/or projects for which they would be using 3D technology. Analysis of these brief descriptions informed the development of the start-of-project survey. Throughout the course of the project, this listserv saw light but steady use by the participants, to ask and answer questions, to coordinate across institutions, and to plan events. Content analysis was conducted on posts to the listserv that contained information about individual projects.

An extensive literature review was conducted on 3D technologies for both educational and noneducational uses.

Informal, unstructured interviews were conducted with a small number of project nonparticipants at institutions that have done significant work in developing makerspaces or in deploying AR, VR, and 3D technology similar to what current project participants deployed. While the institutions that participated in the Campus of the Future project were not representative of the state of higher education in the United States or globally, collecting some data from project nonparticipants provided a rough benchmark for evaluating just how unrepresentative project participants were.

Finally, the teams at several participating institutions created blogs to document the progress of their projects. These blogs were created primarily as a means to disseminate information about the activities of the teams for an audience of the local community at the institution, not for HP or EDUCAUSE specifically. Nevertheless, these blogs were extremely useful as a data source, since their presentation was tailored to the institution and the specific pedagogical needs of the faculty and students at the institution. Content analysis was conducted on the posts to these blogs that discussed work relevant to the project.

Acknowledgments

The EDUCAUSE Center for Analysis and Research (ECAR) team wishes to thank HP for sponsoring this project, and in particular Gus Schmedlen, Vice President, HP Worldwide Education, for being a valuable partner on this project. Thanks to all of the institutions that participated in the Campus of the Future project. In particular, thanks to the faculty, students, and staff who participated in the many projects at all of these institutions: Without your spirit of experimentation, the project would not have happened. In particular, thanks to Randall Rode and the entire Blended Reality Research Project team at Yale for being out front. Finally, thanks to several longtime and valued colleagues for being a sounding board during the early stages of my writing this report, and for letting me pick your brains about the 3D technology work your institutions are involved in: Kimberly Eke, Associate University Librarian for Teaching, Research, & Learning Services at the University of Pennsylvania Libraries; David Woodbury, Department Head of Learning Spaces & Services, and Adam Rogers, Head of Making & Innovation Studio, at the NC State University Libraries; Shawn Miller, Director of Learning Innovation, and Elizabeth Evans, Manager of the Duke Digital Initiative, at Duke University; and Hunter Janes, data scientist and game designer at Red Storm Entertainment, Inc.

Notes

1. L. Castaneda, A. Cechony, and A. Bautista, *All-School Aggregated Findings, Virtual Reality, 2016–2017*. foundry10, Seattle, WA (2017).

2. *Virtual Reality*, Distance Education and Learning Technology Applications (DELTA), North Carolina State University.

3. Charity Hancock, Clifford Hichar, Carlea Holl-Jensen, Kari Kraus, Cameron Mozafari, and Kathryn Skutlin, "Bibliocircuitry and the Design of the Alien Everyday," *Textual Cultures: Texts, Contexts, Interpretation* 8, no. 1 (2014): 72–100.

4. Sheldon Krimsky, "Do Financial Conflicts of Interest Bias Research? An Inquiry into the 'Funding Effect' Hypothesis," *Science, Technology & Human Values* 38, no. 4 (2013): 566–87.

5. This analysis was conducted using variables from the Carnegie Classification of Institutions of Higher Education, 2015 Update Public File. Since the Carnegie Classification data includes only institutions in the United States, and since non-US institutions of higher education are generally organized differently from US institutions, this analysis includes only the US institutions that participated in this project.

6. Other institutions, beyond the current project participants, also have campus units with similar scope; for example, the PennImmersive initiative at the University of Pennsylvania.

7. Neil Kleiman, "Striking a (Local) Grand Bargain," National Resource Network (2015).

8. Howard Rheingold, *Virtual Reality* (New York: Simon & Schuster, 1992).

9. Simon Parkin, "Virtual Reality Startups Look Back to the Future," *MIT Technology Review* (March 7, 2014).

10. "Windshield TV Screen to Aid Blind Flying," *Popular Mechanics* (March 1955): 101.

11. Joan Horvath, "A Brief History of 3D Printing," in *Mastering 3D Printing* (Berkeley, CA: Apress, 2014).

12. Mark Horton, "Meet LiDAR: The Amazing Laser Technology That's Helping Archaeologists Discover Lost Cities," *Scientific American* (June 15, 2016).

13. EDUCAUSE Learning Initiative, *7 Things You Should Know about Photogrammetry*, January 9, 2018.

14. Jason Griffey, "3-D Printers for Libraries, 2017 Edition," *Library Technology Reports* 53, no. 5 (2017): 1–30.

15. Sivaramakirshnan Somasegar and Linda Lian, *XR Is a New Way to Consider the Reality Continuum*, TechCrunch (May 2, 2017); *What Really Is the Difference between AR/MR/VR/XR ?* North of 41 (March 20, 2018).

16. Malcolm Getz, John J. Siegfried, and Kathryn H. Anderson, "Adoption of Innovations in Higher Education," *The Quarterly Review of Economics and Finance* 37, no. 3 (1997): 605–31; David Matthews, "Fear of Looking Stupid," *Inside Higher Ed* (July 6, 2017).

17. Everett M. Rogers, *Diffusion of Innovations*, 5th ed. (New York: Simon and Schuster, 2003).

18. Jeffrey Pomerantz and D. Christopher Brooks, *ECAR Study of Faculty and Information Technology, 2017*, research report (Louisville, CO: ECAR, October 13, 2017).

19. D. Christopher Brooks and Jeffrey Pomerantz, *ECAR Study of Undergraduate Students and Information Technology, 2017*, research report (Louisville, CO: ECAR, October 18, 2017).

20. Ibid.

21. John Dewey, *Experience and Education* (New York: Macmillan, 1938).

22. Bryan Sinclair and Glenn Gunhouse, "The Promise of Virtual Reality in Higher Education," *EDUCAUSE Review* (March 7, 2016).

23. Andrew Curry, "Rome Reborn," *Smithsonian Magazine* (June 30, 2007); Bernard Frischer, "Cultural and Digital Memory: Case Studies from the Virtual World Heritage Laboratory," in *Memoria Romana: Memory in Rome and Rome in Memory*, ed. Karl Galinsky (Ann Arbor: University of Michigan Press, 2014).

24. The Sacred Centers in India project is directed by Abhishek Amar and produced by the Digital Humanities Initiative at Hamilton College with funding from the Andrew W. Mellon Foundation.

25. "London Charter for the Computer-Based Visualisation of Cultural Heritage," Draft 2.1 (February 7, 2009); and P. Reilly, "Towards a Virtual Archaeology," in *Computer Applications and Quantitative Methods in Archaeology 1990* (CAA90), eds. Sebastian Rahtz and Kris Lockyear, BAR International Series 565 (Oxford: Tempus Reparatum, 1991): 132–39.

26. I. M. Bullock, T. Feix, and A. M. Dollar, "Human Precision Manipulation Workspace: Effects of Object Size and Number of Fingers Used," in *Proc. 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (August 2015).

27. The 1977 film Powers of Ten is famous for its visualization of scale.

28. Phoebe Braithwaite, "Google's 3D Models Are Saving the World's Most At-Risk Heritage Sites," *Wired* (April 16, 2018).

29. A *creole* is an emergent culture or language that arises from the mixing of populations, often in the wake of colonization. *Creolization* is therefore the process by which these cultures and languages emerge. In the current context, the "creolization of sculpture," it means the emergence of new forms, techniques, etc., in the wake of the mixing of the traditional and the new.

30. S. E. Sampson and C. M. Froehle, "Foundations and Implications of a Proposed Unified Services Theory," *Production and Operations Management* 15, no. 2 (2006): 329–43.

31. National Research Council, How People Learn: Brain, Mind, Experience, and School: Expanded Edition (Washington, DC: National Academies Press, 2000).

32. Doug Bolton, "Samsung Patents Design for 'Smart' Augmented Reality Contact Lenses," *The Independent* (April 6, 2016).

33. Paul Milgram and Fumio Kishino, "A Taxonomy of Mixed Reality Visual Displays," *IEICE Transactions on Information Systems*, vol. E77-D, no. 12 (1994); Steve Mann, "Through the Glass, Lightly," *IEEE Technology and Society Magazine* 31, no. 3 (2012): 10–14.

34. Strictly speaking, even what we now consider VR is augmented reality. VR replaces what the user sees with an entirely constructed visual environment, along with perhaps a constructed auditory environment, and the ability to manipulate some of that environment with one's hands. It is a testament to how much humans rely on our sense of vision that we consider a constructed visual-only environment to be virtual *reality*. One could even argue that there is no such thing as VR, really, and that the only true VR would be a complete replacement of one's full sensorium with a construct, as in *The Matrix*. Part of the philosophical fun of that movie, of course, is the question of how it would even be possible to know that one is inside a perfect construct. Can *The Matrix* even be considered VR at all? Is the virtuality continuum not actually a continuum but rather a circle, where VR loops back around to the real?

35. Zeynep Tufekci, *Twitter and Tear Gas: The Power and Fragility of Networked Protest* (New Haven, CT: Yale University Press, 2017): xxvi.

36. Anastasia Morrone, Anna Flaming, Tracey Birdwell, Jae-Eun Russell, Tiffany Roman, and Maggie Jesse, "Creating Active Learning Classrooms Is Not Enough: Lessons from Two Case Studies, *EDUCAUSE Review* (December 4, 2017).

37. Rebecca Griffiths, Jessica Mislevy, Shuai Wang, Linda Shear, Nyema Mitchell, Michelle Bloom, Richard Staisloff, and Donna Desrochers, *Launching OER Degree Pathways: An Early Snapshot of Achieving the Dream's OER Degree Initiative and Emerging Lessons* (Menlo Park, CA: SRI International, 2017).

38. Yvonne Belanger, "Duke University iPod First-Year Experience Final Evaluation Report" (June 2005).

39. Brooks and Pomerantz, *ECAR Study of Undergraduate Students and Information Technology, 2017*; Pomerantz and Brooks, *ECAR Study of Faculty and Information Technology, 2017.*

40. Melanie C. Green, "Storytelling in Teaching," in *Lessons Learned, Vol. 2: Practical Advice for the Teaching of Psychology*, eds. B. Perlman, L. I. McCann, and S. H. McFadden (Washington, DC: American Psychological Society, 2004), 175–84.

41. Walter R. Fisher, *Human Communication as Narration: Toward a Philosophy of Reason, Value, and Action* (Columbia, SC: University of South Carolina Press, 1989).

42. Harrison Monarth, "The Irresistible Power of Storytelling as a Strategic Business Tool," *Harvard Business Review* (March 11, 2014).

43. Michael F. Dahlstrom, "Using Narratives and Storytelling to Communicate Science with Nonexpert Audiences," *Proceedings of the National Academy of Sciences* 111, no. 4 (2014): 13,614–20.

44. Sarah Zhang, "Can VR Really Make You More Empathetic?" *Wired* (September 1, 2016); Virtual Human Interaction Lab, *Empathy at Scale*, Stanford University (December 20, 2015).

45. See Addy Hatch, "Counter-Bias Police Training Simulator Gets First Large-Scale Test," *WSU Insider*, October 4, 2017; and Eddie L. Reyes, "How Do Police Use VR? Very Well," *Police Foundation*.

46. David Johnson, "Introduction to and Review of Simulator Sickness Research," research report 1832, U.S. Army Research Institute for the Behavioral and Social Sciences (2005).

47. Brooks and Pomerantz, *ECAR Study of Undergraduate Students and Information Technology, 2017.*

48. Arnoldo Valle-Levinson, Andrea Dutton, and Jonathan B. Martin, "Spatial and Temporal Variability of Sea Level Rise Hot Spots over the Eastern United States," *Geophysical Research Letters* 44, no. 15 (August 16, 2017): 7,876–82.

49. Clifford A. Lynch, "Institutional Repositories: Essential Infrastructure for Scholarship in the Digital Age," portal: *Libraries and the Academy* 3, no. 2 (April 2003): 327–36.

50. Christine L. Borgman, *Big Data, Little Data, No Data: Scholarship in the Networked World* (Cambridge, MA: MIT Press, 2015).

51. Jon Bruner, "Data Governance: What You Need to Know," *O'Reilly* (March 6, 2017); Jill Dyché and Analise Polsky, *5 Models for Data Stewardship: A SAS Best Practices White Paper*, SAS Institute, Inc.

52. Jeffrey Pomerantz, *Metadata* (Cambridge, MA: MIT Press, November 2015); Marcia Lei Zeng and Jian Qin, *Metadata*, 2nd ed. (Chicago: ALA Neal-Schuman, 2016).

53. Pomerantz and Brooks, *ECAR Study of Faculty and Information Technology, 2017.*

54. Ibid.

55. According to data from the National Center for Education Statistics, Hamilton College had a total enrollment of 1,883 in fall 2016 (the most recent NCES data available). Compare this to Harvard or Syracuse University, with enrollments in the tens of thousands. Even Dartmouth, the next smallest institution that participated in this project, had more than double the enrollment, at 6,409 in fall 2016.

56. Kathryn E. Newcomer, Harry P. Hatry, and Joseph S. Wholey, *Handbook of Practical Program Evaluation*, 4th Ed. (Hoboken, NJ: Jossey-Bass, 2015).

Appendix: Equipment Configurations

Institutions participating in the Campus of the Future project were provided with packages of HP-branded 3D technology. HP provided the equipment, and EDUCAUSE was responsible for the shipment of the equipment to participating institutions. HP was then responsible for technical support and addressing any issues that participating institutions had in setting up and deploying this equipment.

Three distinct packages of equipment were provided to participating institutions, based on the nature of the research project(s) and course(s) at the institution that this equipment would be supporting. This appendix contains a list of the equipment in each of these packages, the institutions that received each package, and a brief description of each piece of equipment.

Equipment in Each 3D Technology Package

Package A:

- Sprout Pro G2
- zWorkstation Z640
- HP DreamColor Z27x Studio Display
- HTC Vive
- Dremel Idea Builder 3D
- HP 3D Structured Light Scanner Pro S3
- Automatic Turntable Pro

Package B:

- Sprout Pro G2
- zWorkstation Z440
- HP DreamColor Z27x Studio Display
- HTC Vive
- Dremel Idea Builder 3D
- EliteDesk 800
- HP VR1000

Package C:

- HP Omen Desktop PC
- HP Omen Mobile Workstation
- HP VR1000
- HP Omen 32-inch display

Description of Equipment in Each Package

Computers

zWorkstation Z440 and zWorkstation Z640

The HP Z Workstation series consists of desktop PCs running the Windows operating system. HP describes the Z440 and Z640 as being "VR Ready," meaning that they are configured with a CPU and a graphics card capable of supporting the speed and display requirements for VR.

HP Omen Desktop PC and HP Omen Mobile Workstation

The HP Omen series consists of PCs running the Windows operating system. The Desktop PC is a desktop tower; the Mobile Workstation is a laptop. These computers are customized for gaming, meaning that they are configured with a CPU and a graphics card capable of supporting the speed and display requirements for gaming and VR.

EliteDesk 800

The EliteDesk 800 series PCs run the Windows operating system. They are powerful computers but not specifically configured for VR.

HP Omen 32-inch display and HP DreamColor Z27x Studio Display

These are high-resolution desktop monitors that can support the graphics required of VR. The Omen display is designed to accompany the Omen Desktop PC.

3D Scanners

Sprout Pro G2
Image courtesy of HP Inc.

The Sprout Pro is a desktop PC running the Windows operating system. It has a projector that projects onto a touch-sensitive Touch Mat. The Sprout Pro enables scanning of 3D objects and the subsequent manipulation of the 3D model.

HP 3D Structured Light Scanner Pro S3
Image courtesy of HP Inc.

The HP 3D Structured Light Scanner Pro S3 is a rig for 3D scanning. It contains an HD camera, a video projector, a tripod, a rail, a camera slider, and all cables and dongles necessary to connect the rig to a computer.

Automatic Turntable Pro
Image courtesy of HP Inc.

The Automatic Turntable Pro is a turntable containing a small motor to enable 3D scanning of objects.

3D Printers

Dremel Idea Builder 3D
Image courtesy of Dremel

The Dremel Idea Builder 3D printer uses extruded plastic filament and has a build volume of 402 cubic inches (10" × 6" × 6.7", approximately the size of a shoebox).

VR/AR Rigs

HP VR1000
Image courtesy of HP Inc.

The HP Windows Mixed Reality Headset VR1000 is a VR/AR system containing a headset and two handheld controllers. It is designed for VR gaming and enables full immersion in a VR environment, but it can also be made "transparent" so that the wearer sees an AR overlay over the real world.

HTC Vive
Image courtesy of HTC

The HTC Vive is a VR/AR system containing a headset, two handheld controllers, and two base stations (which help the headset and controllers track their locations in space). It is designed for VR gaming and enables full immersion in a VR environment, but it can also be made "transparent" so that the wearer sees an AR overlay over the real world.

Equipment Package Received by Participating Institutions

Institution	Equipment Package
Case Western Reserve University	Package A
Dartmouth College	Package A
Florida International University, College of Communication, Architecture + The Arts (CARTA)	Package A
Gallaudet University	Package A
Hamilton College	Package A
Harvard University, Graduate School of Education	Package B
Lehigh University, The Wilbur Powerhouse	Package A
MIT, Scheller Teacher Education Program	Package B
Syracuse University, Newhouse School of Communications	Package A
University of San Diego	Package B
Yale University	Package C

Please note that Yale University is the only institution that received Package C. This is because, as noted earlier, Yale and HP have a partnership concerning 3D technology that predates the Campus of the Future project by a year. Yale therefore already had some of the equipment in Packages A and B.