Workforce Training for Optics and Photonics Manufacturing Using Desktop VR Simulations, Data Visualization, and Game-Based Learning

Erik Verlage, Glenda Stump, Saif Rayyan
Massachusetts Institute of Technology
Cambridge, MA
everlage@mit.edu, gsstump@mit.edu, srayyan@mit.edu

Bhargav Upadhyay, Jeff Bertrand, Kapil Madathil
Clemson University
Clemson, SC
bupadhy@g.clemson.edu, jbertra@g.clemson.edu, kmadath@clemson.edu

Alan Kost
The University of Arizona
Tucson, AZ
akost@optics.arizona.edu

Lionel C. Kimerling, Sajan Saini, George Westerman,
Massachusetts Institute of Technology
Cambridge, MA
lckim@mit.edu, sajan@mit.edu, georgew@mit.edu

ABSTRACT

Advanced manufacturing in fiber optics and photonics is undergoing an ambitious revitalization to enhance industrial capacity for a 21st-century high-tech economy. Two major challenges are to create new technology infrastructures and develop digital learning tools, which can help address the severe lack of technicians and engineers.

Groups at MIT, Clemson University, and The University of Arizona are leading the creation of digital learning simulations for workforce training in advanced manufacturing. By targeting knowledge gaps in both industry and government identified by the public-private Manufacturing USA institutes, this effort aims to rapidly reskill and upskill the current manufacturing workforce.

We present a three-pronged digital learning approach using (i) desktop virtual reality (VR) tool-training simulations, (ii) interactive web simulations using a novel methodology for photonics data visualization, and (iii) application-focused digital games to increase engagement for technician and engineering audiences. A holistic approach of interleaving all three learning modes may drive student motivation by connecting procedural skills acquisition with observations of real-world technology implementation, such as low-power cloud computing. This work presents formative assessment interviews and summative research for optics and photonics online learning content teaching into specific technology application areas. Additionally, in-classroom observations of technician and engineering students during blended-learning boot camps demonstrate the viability of these interactive games and simulations for future training.

Applications-grounded content in fiber optics and integrated photonics has the potential to encourage on-the-job training of industry veterans by adapting to their learning needs and schedule constraints. A sustained focus on contemporary applications will promote awareness of leading-edge industry innovation.

ABOUT THE AUTHORS

Erik Verlage, Ph.D., is a Research Scientist in MIT's Initiative for Knowledge and Innovation in Manufacturing (IKIM) and leads the Virtual Manufacturing Lab project for education and workforce development in advanced manufacturing. He designs and builds digital learning tools, interactive VR simulations, and educational STEM games. He has taught optics and photonics in online courses at MIT and blended learning training programs.

Glenda Stump, Ph.D., is an Education Research Scientist in the Abdul Latif Jameel World Education Lab (J-WEL) at MIT. She engages in local and international projects that include technology-enhanced STEM education and teacher/faculty professional development. Dr. Stump's research has focused on STEM and nursing education, teacher and faculty professional development, and skills needed for the workforce of the future.

Saif Rayyan, Ph.D., is Assistant Director of Academic Programs at the MIT Abdul Latif Jameel World Education Lab. He was among the first at MIT to lead digital learning initiatives for creating Massive Open Online Courses (MOOCs), leveraging their content and technology to develop blended learning solutions. He has taught physics at MIT and workshops on blended learning.

Bhargav Upadhyay is a first year Ph.D. student in the Industrial Engineering department at Clemson University specializing in Human Factors Engineering. His research centers around development of Virtual Reality (VR) based courses using human-centered design methodology and evaluating learning behaviors through VR. He holds a master's of science degree in Industrial Engineering from Clemson University.

Jeff Bertrand, Ph.D., is the Director of Visualizations for Clemson University Center for Workforce Development. His responsibilities include developing online virtual training simulations and conducting research on the efficacy of VR training. He completed his Ph.D. in Human Centered Computing at Clemson University. His research interests include VR simulations for training, visualization, applied perception and 3D interaction.

Kapil Chalil Madathil is the Wilfred P. Tiencken Endowed Associate Professor of Civil and Industrial Engineering at Clemson University. His expertise is applying human factors to the design and operation of human-computer systems to develop rich interactions between people and technology. He draws on qualitative and quantitative methodologies including ethnography, contextual inquiry and controlled behavioral experiments to understand how humans perceive, make sense of, and interact with human-machine systems.

Alan Kost, Ph.D., is a research professor of optical sciences at the University of Arizona. He has worked in photonics materials and research for 30 years. His research interests include optical data storage, optical communications, advanced frequency agile optical sources and nano-optics.

Lionel C. Kimerling is the Thomas Lord Professor of Materials Science and Engineering at MIT and the Director of the MIT Microphotonics Center, where he conducts research in the design and processing of semiconductor materials and devices. He is the lead for MIT's Initiative for Knowledge and Innovation in Manufacturing and the AIM Photonics Institute Executive for Education, Workforce Development and Technology Roadmap.

Sajan Saini, Ph.D., is the education director for AIM Photonics Academy at MIT. He oversees teaching and learning materials including online modules, certification courses, and summer academy offerings. His scientific writings have appeared in IEEE and APL publications, book chapters, and Harper's magazine.

George Westerman, Ph.D., is Principal Research Scientist for Workforce Learning at the MIT Jameel World Education Laboratory and senior lecturer at MIT's Sloan School of Management. A pioneering researcher and award-winning author on digital transformation, he now focuses on transforming skill building and career development for workers around the world.

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Clemson University
Clemson, SC
bupadhy@g.clemson.edu, jbertra@g.clemson.edu,
kmadath@clemson.edu

Alan Kost
The University of Arizona
Tucson, AZ
akost@optics.arizona.edu

Lionel C. Kimerling, Sajan Saini, George Westerman,
Massachusetts Institute of Technology
Cambridge, MA
lckim@mit.edu, sajan@mit.edu, georgew@mit.edu

INTRODUCTION AND MOTIVATION

A key feature of modern advanced manufacturing is a faster cycle of revision or disruptive transformation in workforce skills (Bonvillian et al., 2018). In contrast to 20th-century post-war manufacturing, the modern technician and engineer must perennially reskill and upskill. Workforce development requires a practice of ongoing learning at all technical skill levels. At the same time, the processing complexity of modern technologies is narrowing the labor specialization gap between technicians and engineers (Bonvillian et al., 2018); it is becoming increasingly necessary for specialized workers to have an understanding of each other's operating practices and tool-specific standards. Simulations can help technicians gain familiarity with the fundamentals of the technology, and engineers would benefit from a deeper understanding of the standard operation and capabilities of manufacturing equipment. In addition, both audiences would benefit from knowledge grounded in the application areas of emerging technologies.

There is a critical need to create online content with a focus on modular, learner-centered formats for intermittent instruction (Bhagat et al., 2016) to enhance retention of core concepts. Online education is cost-effective, scalable, and can be perennially updated. The use of 3D visualizations and immersive virtual reality (VR) can prime students for limited access to costly on-site training facilities (Sahin & Shelley, 2008). Additionally, game-based learning enables ongoing self-directed upskilling (Kim et al., 2016; Klopfer et al., 2018), allowing students to easily explore complex systems in a fun and engaging environment. Adapting online resources to make use of new digital tools and methods can allow educators to strategically address knowledge gaps in industry, academia, and government.

Workforce Training for Optics Technicians and Engineers

The United States is facing a severe shortage of optics technicians, amidst a shortfall of effective workforce training programs (Vogt, 2019). Optics technicians play a vital role in the manufacturing of optical elements and electro-optical devices. An increasing scarcity of technicians with two-year degrees in optics has forced many companies to train new hires on the job or assign these tasks to engineers (Kirchain et al., 2021; Vogt, 2019). These middle-skilled positions are expected to grow from around 58,000 in the U.S. today to 85,000 by 2030 (Kirchain et al., 2021).

Technicians lack access to expensive state-of-the-art equipment for training. Using interactive digital simulations can prepare students and workers to make efficient use of in-person training. Digital simulations provide a safe environment for users to make mistakes and recognize equipment limits and failure states. A well-designed simulation can provide scaffolded challenges, hints, and feedback systems to enhance learning.

At the same time, a major challenge facing engineering graduate and undergraduate students is developing intuition for electromagnetic waves at the micron scale. Student misconceptions in refraction, total internal reflection (e.g., for fiber optics), and optical interference make this subject particularly difficult for students to master (Mateycik, 2005). Interactive optics simulations allow students to explore the properties of light in an engaging and visual environment, clearing up misconceptions by encouraging direct exploration of optical phenomena. Dynamic visualizations and

interactive simulations are ideal for illustrating complex wave behavior of light without relying on mathematical equations (Adams, 2010).

Finally, for students at all levels, connecting abstract learning goals in the classroom to real-world applications is often very motivating. Observing the benefits of an emerging technology, such as enhanced imaging through light detection and ranging (LiDAR) for use in self-driving cars, strengthens a student's positive identity with a future career in optics manufacturing. Identity-building exercises and games can be particularly well-suited to this task (Klopfer et al., 2018).

Virtual Manufacturing Lab (VM-Lab) Overview

Groups at MIT, Clemson University, and The University of Arizona have created the Virtual Manufacturing Lab (VM-Lab) to generate self-directed online learning content in advanced manufacturing. Short online learning modules built around interactive simulations or games combine an active learning experience with standard video instruction and self-assessment exercises. Each module is designed to be completed in a single session of two to three hours. In addition, VM-Lab modules are designed for compatibility with on-site blended learning boot camps.

The first two years of the three-year project have focused on creating an application-targeted curriculum for specialty fiber optics and integrated photonics manufacturing. A library of short, interactive VM-Lab modules, organized around a hierarchy of learning goals and practice skills (e.g., equipment training, device design, testing, and packaging), and teaching real-world application systems, provides a far-reaching reservoir of à la carte learning to supplement the training needs of optics technician or engineering students. In October 2021 the project will enter its third year and these modules will expand from optics to electronics and robotics.
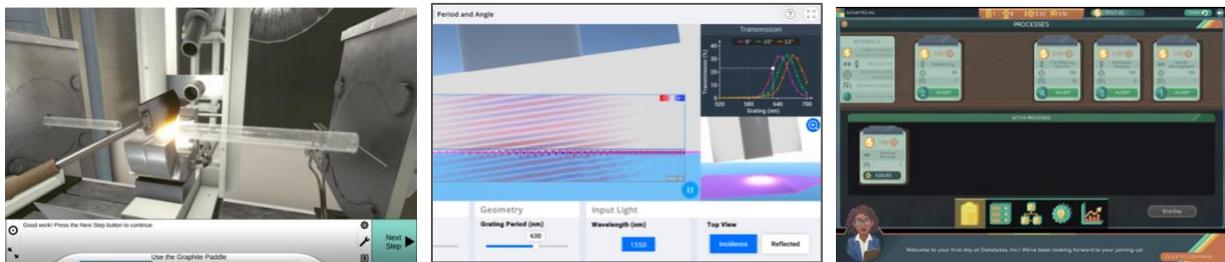

Figure 1 - Three Categories of Interactive VM-Lab Online Learning Modules. *Left*: Tool-Training Using Desktop VR; *Center*: Optics and Photonics Fundamentals; *Right*: Application-Focused Educational Games.

Three distinct module categories are shown in Figure 1, allowing users to explore 1) tool operation, 2) optics and photonics fundamentals, and 3) application areas of interest for these technologies. Each module includes basic and advanced learning goals. The pedagogical design is meant to support adult learners by allowing short bursts of reskilling/upskilling on the students' schedule. Interconnection between modules at various levels also nurtures a technician-to-engineer dual literacy, necessary for leading-edge optics and photonics manufacturing methodologies.

TOOL-TRAINING DESKTOP VR SIMULATIONS

Online learning is an innovative educational approach where instruction and content are focused on interactivity, design, learner-centered approaches, and facilitated learning experiences, primarily delivered through an open, flexible, and distributed learning environment (Wong et al., 2019). Furthermore, it expands the experience of the learner and offers new opportunities through a more robust learning environment with additional tools and resources (Monahan et al., 2008). The most effective online learning models blend many tools and resources including VR simulations, and typically offer more flexibility for students in choice, learning styles, and schedules (Sahin & Shelley, 2008). Further, online learning shifts from a lecture format to more interaction between the students, facilitators, and tools, and acknowledges the learners' diverse skills, backgrounds, and preferences (Rossett, 2002).

Virtual Reality Environments for Tool-Training

Virtual reality (VR) for education has been rapidly expanding in recent years due to rapid technology advancements and the capacity to improve learning outcomes (Bhargava et al., 2018). Desktop VR refers to a virtual environment that can be used on standard computers with a keyboard and mouse. A key advantage for each category of VR is the capability to actively engage the user (Bertrand et al., 2015). Constructivist learning theory states that learning occurs when students are actively involved in the process of knowledge construction, instead of passively receiving information. VR systems require constant engagement with the material and allow for experimentation, which promotes curiosity and involvement. Simulations can be scaffolded, meaning that a large amount of instruction is given initially and reduced over time as the student becomes more proficient in the material. Thus, the learning experience is tailored to the student and the student can proceed at his or her own pace. Studies have shown that retention, concentration, and enthusiasm have been positively linked to active learning models particularly for VR training simulations (Madathil et al., 2017; Parmar et al., 2016). Users may receive real-time feedback, and the students' performance can easily be logged, monitored, and analyzed by an instructor. Users can repeat the experience until they are comfortable with the material and VR can simulate potentially dangerous scenarios where users can practice and make mistakes without the risk of permanent repercussions (Madathil et al., 2017).

Desktop VR Simulation Development

To address the need for skilled technicians in optical fiber manufacturing, a desktop VR simulation was developed. The VR simulation allows the learner to fabricate a fiber glass preform multiple times in a safe virtual environment at minimal cost while allowing them to gain familiarity with tools and equipment used in the process. Our team developed the VR simulation using a user-centered design; the steps used are described below:

1. Cognitive Task Analysis (CTA) of the fiber preform manufacturing process
2. Persona creation and identification of learning objectives
3. Storyboarding
4. Simulation development using the Unity game engine
5. Iterative user interface design through usability testing

The Cognitive Task Analysis technique guided the development of the simulation-based learning course modules. CTA uses observation and interview-based strategies to capture a description of the knowledge that experts use to perform complex tasks. An observation study at a Clemson University research laboratory recorded the steps involved.

Personas were created before the development of the simulation to represent the abstract learner characteristics and motivations. These learner characteristics were used to establish learning objectives based upon different learner types. Through internal team discussions, the following learning objectives were formulated: 1) Learn the lathe components and tools used in the process, and 2) Learn the steps involved in preform manufacturing.

The next step was to create a storyboard, a low fidelity version of the simulation to preview the content that would be presented. Based on the CTA document and the identified learning objectives three phases were identified: terminology, guided practice, and exercise. The storyboard then drove simulation development.

In the Unity game engine, we developed a virtual lab environment containing a modified chemical vapor deposition (MCVD) lathe used for manufacturing optical fiber. The environment was modeled in Blender, a 3D modeling program, using photographs taken of an MCVD lathe. We used Allegorithmic's Substance Painter to create textures which were imported into Unity's rendering pipeline. Several interaction techniques were developed for working with the lathe e.g., dragging the chucks to lock the preform in place and clicking on a button to enable the burner. The bottom of the screen contained instructive text as well as icons for menus such as the toolbox. The final simulation was exported as a WebGL build for online use in a browser with a mouse and keyboard.

The final MCVD lathe simulation contains a terminology, guided practice, and an exercise phase. The terminology phase walks students through each component of the lathe by highlighting each part and providing a brief description (Figure 2, *Top*). The guided practice phase takes the user step-by-step through the process of manufacturing a glass preform (Figure 2, *Lower Left*). In the exercise phase, guidance for each step is removed, and if a mistake is made an error message appears with a hint system to guide the user to the next step (Figure 2, *Lower Right*).
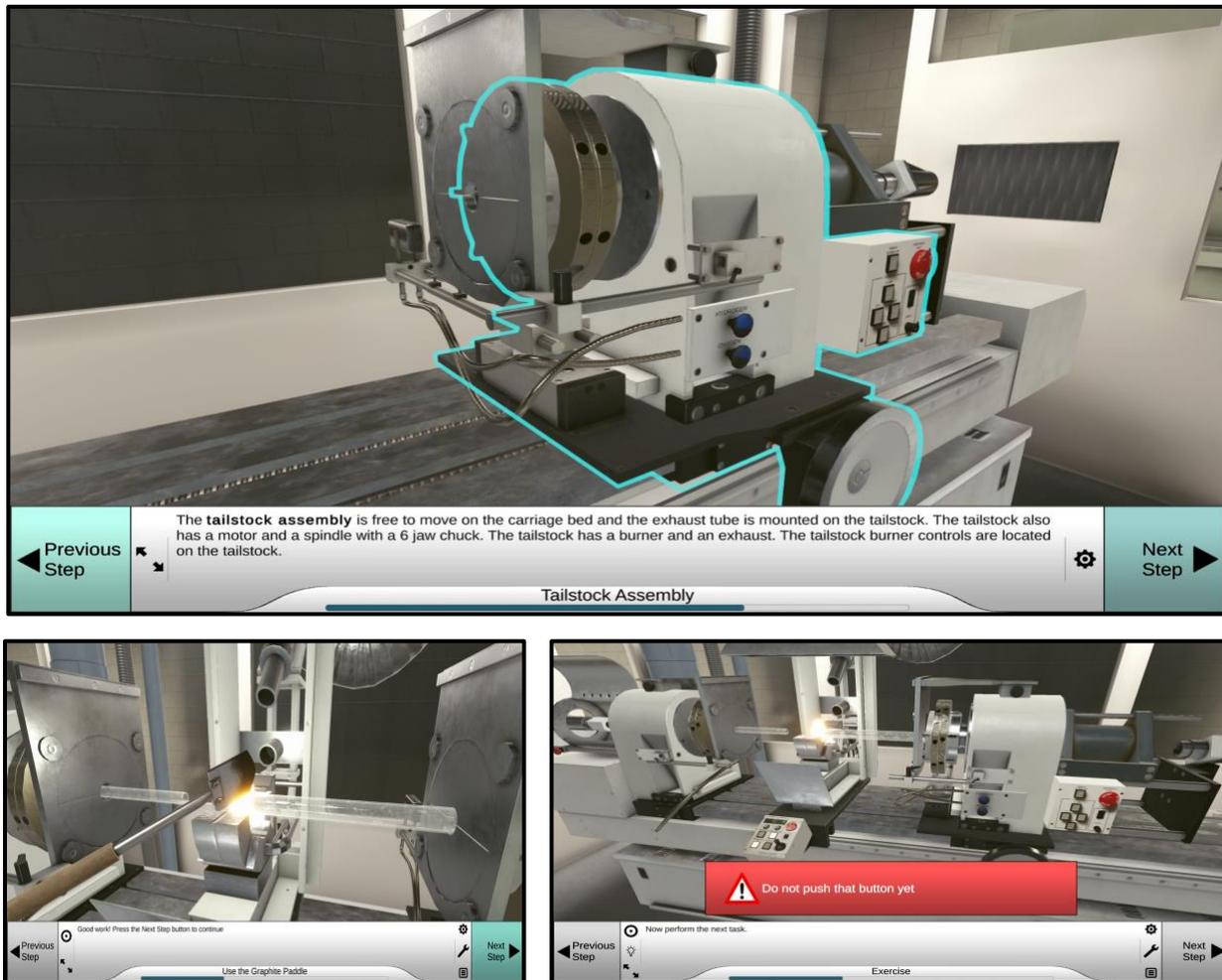
Figure 2 - Procedural Desktop VR Training Simulation. *Top*: **Terminology Phase Lists Each Component of the Fiber Lathe.** *Lower Left*: **Guided Practice Phase Takes the User Step-by-Step Through the Manufacturing Process.** *Lower Right*: **Free Exercise Phase.**

The simulation interface was evaluated by four usability study participants using the remote moderated usability testing technique with a retrospective think-aloud protocol. The usability testing was conducted over Zoom video conferencing software using the retrospective think-aloud protocol. Upon completion of each phase, the participants were asked to finish the IBM Computer Systems Usability Questionnaire (CSUQ) survey (Lewis, 1995) followed by a semi-structured interview. Usability metrics, like time to task completion and errors committed by the user while completing the simulation tasks, were calculated by going through the user testing session video recordings.

As the terminology and guided practice phases were designed to guide users through the process with step-by-step, text-based instructions, users committed no errors while following the instructions in the first two phases. A small number of errors were observed during the exercise phase when participants were independently performing the tasks. The results for both the number of errors and the average time per phase are shown in Figure 3.

The exercise phase was a replica of the guided practice phase which led to a slight reduction in the time required for completion. Errors observed during the exercise phase were primarily due to order of operation, and participants used their notes and hints to identify the next step to move forward. The perceived usability of the overall simulation was calculated based on the participant responses to the IBM CSUQ survey. The IBM CSUQ survey produces four scores: 1) overall score, 2) system usefulness, 3) information quality, and 4) interface quality. The results of the IBM CSUQ survey with scores between 7 (strongly agree) and 1 (strongly disagree), with larger scores indicating a higher degree of satisfaction, are demonstrated in Figure 4.

Ongoing Controlled Research Studies Investigating the Efficacy of Desktop VR Simulations

It is important to test the effectiveness of VR tool-training simulations compared to other training methods to evaluate the efficacy of the VR simulation to promote learning. As the next step, an experiment has been designed using three instruction mediums: a lecture video, a video of the task procedure, and the VR tool training simulation. This will investigate the

Figure 3 - Mean Completion Time and Student Errors Per Phase.

Figure 4 - IBM CSUQ Results.

efficacy of desktop VR simulations compared to other instruction mediums. Procedure videos, lectures, and books are the most commonly used instruction mediums for training in the field of photonics and fiber manufacturing in preparation for in-person training. Therefore, video and lecture training modalities were selected for comparison. A between-subjects experimental design was implemented with the instruction medium as the independent variable comprising three levels. The control condition was a recorded lecture by a photonics expert covering theoretical fundamentals and glass preform manufacturing using a PowerPoint presentation. The second condition consisted of the same recorded lecture along with a recorded video of an expert explaining the fiber lathe parts, tools used for preform manufacturing, and procedural to make a preform. The third condition consisted of the lecture and three-phase VR simulation. The participants in all conditions take a test before and after the stimuli.

The dependent variables of the study are: the pre- and posttest scores used to assess learning gains, the workload experienced by the participants measured by the NASA Task Load Index (Hart & Staveland, 1988), perceived ease of use, perceived usefulness of the instruction, the behavioral intention of use (Venkatesh et al., 2003) and perceived learning outcomes of comprehension, memorization, and ability to apply what was learned. Upon completion of the study, the mean differences of the dependent measures will be analyzed using an analysis of variance to draw conclusions on the effectiveness of the three instruction mediums towards enhancing learning outcomes.
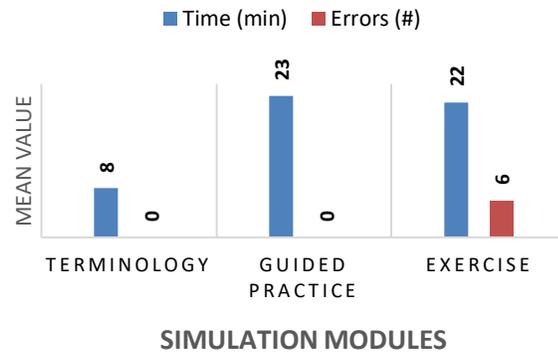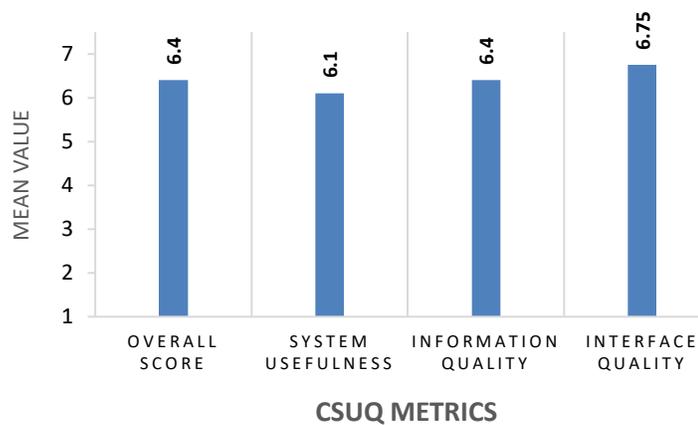
DATA VISUALIZATION FOR OPTICS AND PHOTONICS FUNDAMENTALS

It is often necessary for engineering students in optics and photonics to build a robust intuition for the behavior of light in dielectric materials. In fiber optics and integrated photonics, students must understand how signals of light are transmitted in cylindrical glass fiber or in rectangular dielectric waveguides. Data visualization can play an important role in building student intuition.

Typically, refraction and total internal reflection of light at dielectric interfaces is explained from a ray optics perspective. In 2005, Mateycik et. al. conducted interviews with subjects at all levels of expertise to characterize student understanding of total internal reflection in an optical fiber. Their research uncovered a wide variety of mental models with unique misconceptions to describe how optical fibers carry data using pulses of light (Mateycik, 2005). For a graduate audience, advanced instruction will proceed to use Maxwell's equations and the associated boundary conditions at dielectric interfaces to provide the basis for understanding guided modes, now from a modal analysis perspective. Modal analysis can fully describe the behavior of light in waveguides, including the quantized nature of modes, and the presence of higher-order modes. It also explains the presence of evanescent electromagnetic fields extending outside the core of the waveguide and into the cladding, which would not be expected from the ray optics perspective. However, increased complexity leaves even more room for student misconceptions, especially when tackling the three-dimensional nature of the electromagnetic vector fields.

The Need for 3D Data Visualization of Waveguide Modes

The standard method for visualizing guided modes in dielectric waveguides, used in most textbooks and other static teaching materials, shows field profiles which break down the electromagnetic fields into their cartesian components along the x, y, and z axes, shown in Figure 5 for a rectangular waveguide. Color maps are often used to indicate relative strength and direction of the electric field. While this representation shows the general shape and relative intensity of the waveguide mode along each axis, it has major drawbacks. It does not capture the time-sensitive dynamic behavior of the electric field. It requires students' imaginations to piece together the full 3D vector field.
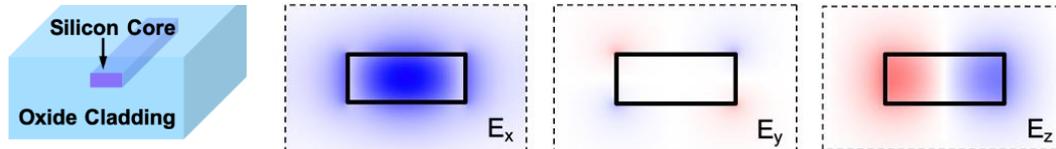

Figure 5 - Electric Field Profile for the First-order Mode of a Rectangular Silicon Waveguide. Field Direction Along Each Axis is Indicated by Color, Positive (Blue) and Negative (Red) Along the x, y, and z Axes.

Instructors often attempt to give undergraduate and graduate students autonomy in exploring the behavior of guided modes by using commercial optical simulation software. These tools allow users to set up and run optical simulations, changing waveguide material properties and dimensions. While incredibly powerful and flexible, commercial software tools are complex and difficult for novices to use. Students are often intimidated by the number of controls in the user interface, and will often make mistakes which result in numerical artifacts. This leads to cognitive overload for students struggling simultaneously to navigate the commercial simulator's user interface and uncover the fundamental properties of dielectric waveguides.

We have identified an opportunity to develop more illustrative and dynamic 2D and 3D visualizations of these waveguide modes. Such a tool would allow users to observe the full vectorial nature of the electromagnetic fields and to visualize the time-dependent nature of these modes, all while navigating a purpose-built simple-to-use interface.

Building a Novel Waveguide Mode Explorer

A great example of prior work in visualizing electric and magnetic fields is the web-based simulation titled "Charges and Fields", created by PhET Simulations at University of Colorado Boulder (*Charges and Fields*, 2021; Paul et al., 2013). Students visualize the intensity of an electric field using a 2D grid of arrows and place positive and negative charges onto the grid, using "sensors" to discover the magnitude and direction of the electric field. Although this is a

useful tool for exploring two-dimensional electric fields, the visualization style is not adequate for exploring three-dimensional vector fields and is insufficient for representing the dynamic behavior of waveguide modes.

We set out to create a dynamic time-varying simulation to show the nature of light traveling in a dielectric waveguide, titled Waveguide Mode Explorer (WME). We designed a 3D waveguide cross-section environment with a simple camera and zoom controller, and a toggle menu, which allows users to select and explore each electric field profile view. During initial user testing, students reported that the 3D perspective and camera controls were useful for observing complex behavior of the vector fields. However, students missed subtle features of the electric field near the corners of the waveguide. When we scaled the vectors to make these features visible, vector overlap made it difficult to understand the behavior of the electric field.

After multiple iterations in data visualization, guided by the first two phases of user testing described in the following section, the final design for the WME simulation is shown in Figure 6. In addition to vector length, the vector arrow's size gives a visual cue to the electric field magnitude and direction. This helped students interpret out-of-plane behavior of the vector field during the simulation. To help students visualize complex electric fields without confusion due to vector overlap, vectors were set to have a maximum length equal to the grid spacing. In addition, guiding lines were added to draw attention to the location of the waveguide edge, and a dynamic sinusoidal wave was used to illustrate the electric field behavior at the center of the waveguide.
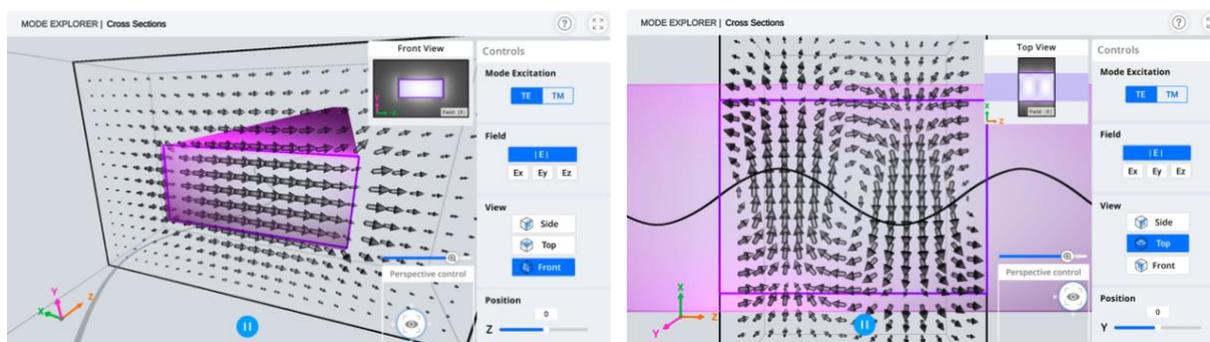

Figure 6 - Final Design of the Waveguide Mode Explorer (WME) Simulation. Both Vector Length and Arrow Size are Used to Indicate Electric Field Intensity to Increase Visibility of Complex Field Lines.

Development and Testing of Photonics Simulations and Online Learning Modules

We developed and tested our interactive simulations, as well as full online-learning modules, complete with videos and assessment exercises, in three phases. During each phase we recruited volunteers from a pool of students and workers who were likely to engage with simulations as part of their education, reskilling, or upskilling.

Phase 1 – Initial testing with undergraduate students

In Phase 1, the subject matter experts (SMEs) and the learning sciences (LS) team developed learning outcomes for the simulations. By the end of the module, learners were expected to be able to 1) Correctly connect electromagnetic vector fields to cross-sectional mode profiles for both front view (x, y) and top view (x, z), and describe breakdown into x, y, and z vector components; 2) Explain the distinction between the ray optics perspective and modal analysis perspective; 3) Explain the behavior of evanescent electromagnetic fields extending into the cladding in dielectric waveguides, and distinguish between these evanescent fields which do not cause loss, and optical loss due to scattering; and 4) Distinguish between the Transverse Electric (TE) and Transverse Magnetic (TM) polarizations in waveguide modes. Additionally, the learning sciences team conducted a cognitive task analysis with subject matter experts to understand the goals of the simulations and how learners should benefit from them.

An initial playtest was conducted with one industry expert and four undergraduate students enrolled in a university in the northeastern United States. Participants engaged with simulation prototypes and answered assessment questions they received in a separate handout. Participants were asked to think aloud as they interacted with the simulations. Researchers recorded their comments, questions, and observed their interactions. At the conclusion of the session,

participants completed a questionnaire regarding usability of the simulations. Analysis of the data collected and synthesis of results supported the need for a basic introduction to wave propagation. In addition, SMEs concluded that an initial simulation depicting light propagation through free-space would provide a helpful contrast to subsequent simulations showing propagation through a rectangular waveguide.

Phase 2 – Expanding to a broader audience

Next the development team created the Waveguide Mode Explorer (WME) module which included videos and simulations that depicted the x, y, z components of wave propagation. The intended learning outcomes for this module remained the same. The second playtest was conducted with 15 students from a technical community college in the northeastern region of the United States. At the beginning of the session, participants took a pretest, followed by a brief introduction to integrated photonics and its applications. They were subsequently introduced to the WME module that included three simulations—Free Space Optics, Transverse Electric (TE) Guided Modes, and Transverse Magnetic (TM) guided modes. They were allocated 20 minutes to complete each simulation, along with assessment questions received in a separate handout. At the conclusion of the session, participants were asked to complete a posttest, as well as a questionnaire regarding their perception of the experience.

After analysis of data and results, the team determined that many community college participants did not have the prerequisite knowledge about electromagnetism required to benefit from the module. They also evidenced several misconceptions regarding optical loss which they misattributed to evanescent fields in the waveguide cladding.

Phase 3 – Module research and evaluation study

This phase focused on evaluating the module intended learning outcomes and answering research questions related to the effect of gentle guiding questions versus an open conceptual question on learning outcomes (Adams, 2010). Prior to initiation of the research, content of the WME module was supported by five simulations that would allow learners to incrementally build their mental model of wave propagation. The five simulations included (1) wave propagation in free space, (2) a 3D view of confinement, (3 & 4) selected cross-sectional views of both TE and TM polarizations, and (5) a full field explorer in which all cross-sectional views (top, front, and side) could be explored.

Our sample for this study was composed of 20 volunteers recruited from four schools of engineering located in three U.S. regions. Study participants were divided into two groups, each composed of 10 students. Group 1 contained six males and four females; five were in graduate programs, and five were undergraduates. Group 2 also contained six males and four females, four graduate students and six undergraduates. Although our small sample size did not allow us to determine statistically significant differences between groups, our goal was to qualitatively explore differences suggested by the data to inform future research using simulations embedded in massive open online courses.

Following an introduction to the study, participants took a pretest, engaged with the module, and then took a posttest. They were asked to think aloud as they progressed through the module. Group 1 viewed all videos and engaged with the five simulations and embedded assessment questions; Group 2 did not engage with the third or fourth guiding simulations and their related videos, and did not complete the embedded assessment questions related to the fifth full exploration simulation. Instead, they were asked to consider an open, more conceptual question as they explored the fifth simulation. The protocol differed for the two groups in order to answer our research questions regarding type of questions during simulation exploration, similar to work conducted at The University of Colorado Boulder (Adams, 2010). Afterwards, participants responded to a four-question survey and received a $15 gift card for their time.
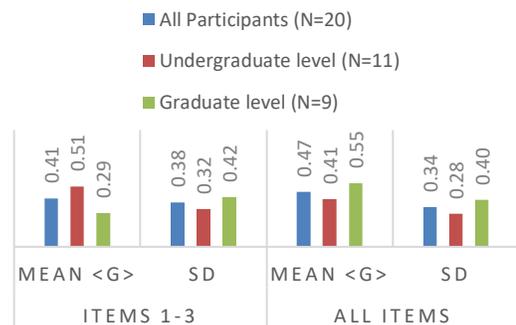

Figure 7 - Mean Normalized Gains <g> From Module Participation.

Figure 7 shows the results from analysis of the data related to overall learning gains from the module. Results related to type of question utilized during exploration will not be discussed here. We used a normalized gain score for comparison, with the equation: <g> = (posttest score - pretest score) / (total possible score - pretest score). Our results

revealed that all participants showed overall learning gains from participation in the module, with one exception. Because the module emphasized the first two learning outcomes more than the latter two, we also explored learning gains using participants' responses to only test items 1-3. Additionally, we were interested in the suitability of this material for different levels of learners, and thus we examined differences between participants enrolled in university undergraduate versus graduate programs.

When participants showed little to no normalized gain from pre- to posttest, it was often because they scored well on both tests. However, some differences in learning gains appear to be related to level of education or pre-requisite knowledge. When all items of the pre-posttest were considered, the normalized gains for graduate students were greater than for undergraduate students. However, when only the first three items of the test were explored, the undergraduate students showed greater normalized gains.

This finding can be explained by the fact that undergraduate students scored significantly lower on the pretest than the graduate students in these areas, suggesting that they began the module with low prior knowledge. At posttest, the undergraduate students' scores increased considerably in these three areas, contributing to their large normalized gain. Conversely, the graduate students demonstrated the greatest learning gains for the two pre-posttest items testing knowledge that was not the explicit focus of the module. This suggests that their advanced prerequisite knowledge enabled them to grasp more difficult concepts that the module did not cover in detail.

The pre- and posttest also confirmed the presence of a misconception that we identified in an earlier playtest—the idea that an evanescent field extending outside the core of a waveguide is directly responsible for optical loss. At posttest, only 50% of the participants responded correctly that there would be no decrease in optical power as light traveled down a rectangular waveguide with no sidewall roughness. The waveguide depicted in the question showed a prominent evanescent field extending into the waveguide cladding. Those who responded incorrectly often articulated the misconception that ideal conditions would entirely eliminate the possibility of an evanescent field.

Data Visualization Conclusions

In conclusion, our work supported use of the introductory waveguide mode simulations for increasing participants' understanding of wave propagation via a rectangular waveguide. All study participants benefitted from engagement with the module, regardless of their pre-requisite knowledge, although those with a better understanding of optics were able to grasp more difficult concepts. Our work also uncovered a significant misconception related to loss of energy through the evanescent field. Future work will explore potential mitigation strategies in order to better prepare individuals for work in integrated photonics.

APPLICATION GAMES IN OPTICS AND PHOTONICS

Critical needs of reskilling and upskilling, and cultivation of a dual-literacy in technician-through-engineer practices and standards, can be effectively addressed by establishing a novel pedagogy framework that continually prompts the workers to become and remain lifelong learners. Application-focused active learning practices offer opportunities for reflection and perspective-taking, which have been advanced in education research as eliciting enthusiasm for learning. This also reorients the student to think of learning as a lifelong practice, instead of a transient stage of instruction that leads to a static workforce skillset (Mayhew et al., 2008). The founding hypothesis of this work is that a lifelong learning practice is upheld by the learner's evolving motives to learn, and that creating an interconnected library of modular units that highlight connections between levels of learning will catalyze this motivation.

Interactive games give players ongoing feedback, which has been linked to higher transfer of STEM concepts (Moreno & Mayer, 2005). STEM topics have congruent goals: presenting complex material, active participation of learners, inquiry around systems, and a focus on critical thinking (Boyle et al., 2016; Kim et al., 2016). Well-designed educational games prompt players to "probe, hypothesize, reprobe, and think" while playing in an interactive environment (Gee, 2003). As educational goals expand beyond rote memorization of content to include processes such as scientific inquiry and engineering design, there is a need for activities that give learners a rationale to investigate, collect and analyze data, identify patterns, and design solutions—activities that STEM games can achieve (Morris et al., 2013). These experiences bolster the student's identity as a life-long learner who can solve complex problems (Klopfer et al., 2018).

Integrated Photonics Application Games

The VM-Lab project is in the process of creating four application-focused games for integrated photonics. The application areas include: (i) low-power computing using optical interconnects, (ii) on-chip chemical and biological sensing, (iii) high-speed wireless communication, and (iv) LiDAR imaging. These four application areas were chosen to capture the most promising commercial uses of photonic integrated circuits. The first game is scheduled for release in the fall of 2021 (see Figure 8). In the game, players manage a data center through the optical data revolution, expand infrastructure to meet demand, research new technologies, and time upgrades to network topology.
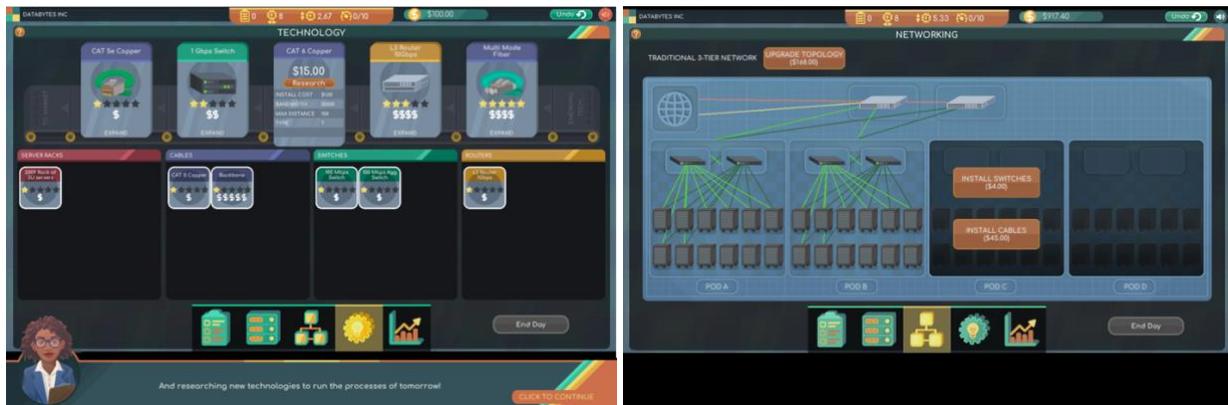

Figure 8 - Pre-Release Screenshots of Educational Game "Databytes Inc". Players Manage a Data Center by Upgrading Data Center Capabilities Using Fiber Optics and Integrated Photonics.

The photonics games, and the short learning modules built around them, will be included in multiple blended learning boot camps for optics technicians and massive open online courses on the edX and Open edX platform in the coming years. Starting in early 2022, research studies with multiple cohorts will be used to determine the effects these games have on student performance, self-reported motivation, and online course completion rates.

CONCLUSIONS AND FUTURE WORK

To address the workforce training needs of optics and photonics manufacturing, the VM-Lab project is striving to create a large library of online learning modules built around interactive simulations and games. Our preliminary research has shown promising results for student engagement with desktop VR tool-training simulations in optical fiber manufacturing, and increased learning outcomes using 3D photonics data visualizations. Upon release, the application-focused educational games have the potential to increase engagement and motivation, allowing students to connect procedural skills and fundamental learning with optics/photonics technology application areas.

Over the next year, additional research studies will be conducted through the inclusion of these short modules in massive open online course offerings on the edX and Open edX delivery platforms. The VM-Lab desktop VR tool-training simulations could also be adapted for immersive headset VR to build muscle memory for specific tasks. Although browser-based simulations and games have many advantages including scalable distribution through online learning platforms, there are still many challenges for full adoption and acceptance. It is important for this content to exist in a workforce development ecosystem including professional societies and advanced manufacturing institutes.

High-bandwidth delivery of interactive online learning content to rural America and at-risk, working-class urban populations can help meet the increasing demand for optics technicians and engineers. By preparing a 21st-century advanced manufacturing workforce that adopt an agile, lifelong-learning practice, US manufacturing can adapt to the rapid evolution of modern industry and regain a competitive advantage on the international stage.

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