2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #38176

Skilling for and Acculturation to Integrated Photonics Industry Using VR Simulations, Game-Based Learning, and Augmented Reality Games

Dr. Sajan Saini, Massachusetts Institute of Technology

Dr. Sajan Saini received his doctoral degree in materials science at MIT in 2004, during which he investigated materials and device designs for optically pumped waveguide amplifiers in silicon microphotonics. Sajan has worked with the MIT Microphotonics Center as a postdoctoral associate; he has also been a professor with the physics department at Queens College of CUNY (City University of New York), and lectured with the writing program at Princeton University. In addition to running a graduate research program on nanostructured materials, he has taught courses on photonics, introductory quantum physics, general astronomy, scientific writing, graphic novels and science-fiction, and climate science communications. At AIM Academy, Sajan oversees the production of all teaching and learning materials, including online modules, certification courses, and summer academy offerings. He has taught at SPIE Photonics West, co-authored several patents, and his scientific and science writings have appeared in IEEE and APL publications, book chapters, and Harper's Magazine.

Erik Verlage
Anuradha Murthy Agarwal
Drew Michael Weninger
Samuel Serna Otalvaro

BS, Universidad Nacional de Colombia, Sede Medelln, Colombia MA, Friedrich Schieller University, Germany MA, Paris-Sud University, Institute dÄôOptique Graduate School, France PhD, Paris-Saclay University, France

Dr. Serna received his degree in physics engineering from the National University of Colombia, Sede Medellin, in 2010 and a double masterÄôs degree from the Friedrich-Schiller-University Jena, Germany, in photonics and the Institute dÄôOptique Graduate School Paris, France, in optics, matter and plasmasÄù (Erasmus Mundus Master scholarship: Optics in Science & Technology -OpSciTech), in 2013. During these studies, he worked in digital in-line holography, diffractive optical elements and integrated photonic devices.

He earned his PhD in 2016 at the University of Paris Sud and was postdoctoral researcher at the Centre for Nanoscience and Nanotechnology (C2N-Universit© Paris-Sud-Universit© Paris-Saclay) where he designed, fabricated and characterized passive silicon photonics structures and developed novel techniques to test and exploit their third order nonlinear susceptibilities. He was a postdoctoral associate at the Massachusetts Institute of Technology (MIT), where he is explored novel hybrid devices in the integrated photonics platform for telecom and midIR functionalities. Dr. Serna and BSU are part of the LEAP network, bringing industry, government and academia together for the use of integrated photonics and optical technologies. Dr. Serna is an Assistant Professor at BSU since September 2019.

He is an OPTICA (OSA) Ambassador 2019 and a 2021 SPIE Career Lab Editorial member

Saif Rayyan
Dr. Glenda Simonton Stump, Massachusetts Institute of Technology

Dr. Glenda Stump is an educator and education researcher whose career has spanned multiple disciplines. She currently works as an Education Research Scientist in the Abdul Latif Jameel World Education Lab at the Massachusetts Institute of Technology. In this role, she is engaged in multiple international projects that include technology-enhanced STEM education and teacher professional development/faculty development. Dr Stump conducts research on motivation and pedagogic theory as well as teaching methods.

Trevor Morrisey, Massachusetts Institute of Technology

Trevor Morrisey is a Software Developer working at MIT on interactive simulations, data visualizations, and serious games as part of the Virtual Manufacturing Lab project.

Christian Gabbianelli, Massachusetts Institute of Technology

Christian Gabbianelli is a Software Developer working at MIT on interactive simulations, data visualizations, and serious games as part of the Virtual Manufacturing Lab project.

Ira Fay, Massachusetts Institute of Technology
Ms. Caitlin Feeley, Massachusetts Institute of Technology

Caitlin Feeley designs and researches educational games and related technologies at MIT's Education Arcade. Her areas of interest include participatory narratives, Alternate Reality Games, museums and STEM topics, and financial education. She was the project manager and co-designer for Vanished, a multi-platform science mystery game/event co-developed with the Smithsonian. She also co-designed the award-winning financial literacy games Farm Blitz and Bite Club for Commonwealth, a national-nonprofit working to address financial inequity. Feeley was the 2016 Fellow in Museum Practice at the Smithsonian Center for Learning and Digital Access, and holds a master's degree in Technology, Innovation and Education from Harvard University.

Mr. Jeff Bertrand
Bhargav Vipul Upadhyay
Achint Jain
Richard Eberhardt, Massachusetts Institute of Technology
Dr. Alan R. Kost, University of Arizona

Research Professor of Optical Sciences

Dr. John Ballato, Clemson University
Dr. Kapil Chalil Madathil, Clemson University

Kapil Chalil Madathil holds the Wilfred P. Tiencken Endowed Professorship at Clemson University. His area of expertise is in applying the knowledge base of human factors to the design and operation of human-computer systems that involve rich interactions among 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. He has been a principal investigator or co-investigator for more than 25 research grants and awards, generating more than $23 million in funding. His research work is funded by the United States National Science Foundation, Office of Naval Research, United States Department of Defense, Agency for Healthcare Research and Quality, Department of Labor, National Institutes of Health and several other industry and state agencies. He teaches courses on human factors and ergonomics and graduate courses on accident analysis, human-centered system design and human-machine interaction. He is the Director of the Center for Workforce Development, a South Carolina Commission on Higher Education-approved, statewide initiative to improve workforce. He serves as the Associate Editor-in-Chief of the International Journal of Industrial Ergonomics. He is also the Associate Editor for Ergonomics in Design, and Program Chair for the Human Factors and Ergonomics Society's Computer Systems Technical Group, and a technical reviewer for 30 different journals.

Sri Priya Sundararajan
Kenan Cicek
Dominic Gastaldo
Judith Perry, Massachusetts Institute of Technology
Eric Klopfer
Prof. Randolph E. Kirchain Jr., Massachusetts Institute of Technology
Richard Roth, Massachusetts Institute of Technology
Dr. Frank R. Field III, Massachusetts Institute of Technology
Elizabeth Moore, Massachusetts Institute of Technology
Dr. George Westerman, Massachusetts Institute of Technology
Prof. Lionel C. Kimerling, The Pennsylvania State University

Skilling for and Acculturation to Integrated Photonics Industry Using VR Simulations, Game-Based Learning, and Augmented Reality Games

Introduction

The integrated photonics and fiber optics industries are rapidly expanding and innovating, respectively, to enable transformative new integrated circuit, AI, datacom, wireless, sensing and imaging systems for the cloud and mobile computing, automobile and aircraft, display, medical, and energy industries. This 21st century advanced manufacturing sector is in dire need of a massive increase in its photonics technician and engineer workforce, over the next decade. However, an inadequate pipeline of incoming learners to fiber optic and photonic integrated circuit (PIC) careers at 2- and 4-year colleges is severely limiting the prospects for rapid workforce growth (see Fig. 1)[1,2,3,4].

To support this near-term workforce demand, a modular library of Virtual Reality (VR) and Game-Based Learning (GBL) digital simulations (sims) and blended (digital and hands-on) learning content have been created that may complement or supplement current community college and university courses, help to modernize extant curricula. In addition, professional training workshops and fiber/PIC test training bootcamps may leverage this digital content as virtual instructional material. Finally, the immersive engagement and playful learning affordances of VR and GBL are anticipated to stimulate and nourish a K-12 pipeline of future industry talents.

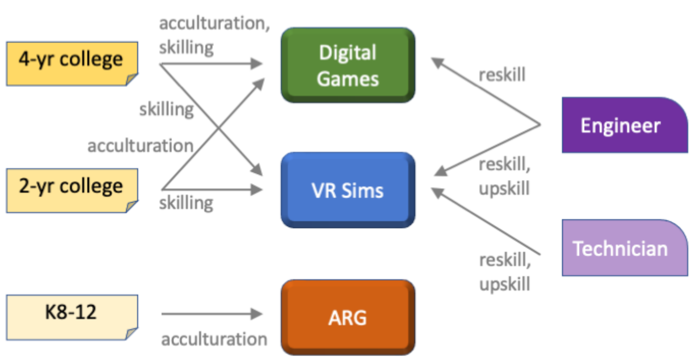


Figure 1. Schematic depicting potential learning pathways for engineers (training at 4-year colleges or incumbent), technicians (training at 2-year community colleges or incumbent), and high-school students when engaging with this project’s digital (GBL) games, VR sims, and ARG game. The games and sims may be packaged within an online MOOC course or implemented in a class setting.

Our team has completed an integrated photonics and fiber optics industry education roadmap, and created a mix of (i) desktop VR tool-training sims, (ii) photonics device visualization sims, and (iii) application-focused GBL games, for both online MOOC learning and blended learning in training bootcamps. In addition, (iv) an Augmented Reality Game (ARG) has been created for K-8 engagement. As indicated by the schematic in Fig. 1, these education assets can facilitate the upskill of photonics-adjacent industry incumbent and incipient workers; the reskill of legacy photonics industry incumbent workers; and acculturate a next-generation workforce to evolving photonics careers. For the purposes of this study, technicians are primarily characterized as matriculants of 2-year community college programs or vocational technology high-schools.

Roadmap Study: Workforce Education and Skills Gaps

An education roadmap survey was developed for manufacturing operations managers across the silicon-based PIC and fiber optics supply chain, to identify and prioritize workforce needs across the supply chain. Over 50 firms evaluated their skills gaps, hiring and training challenges, and future worker demand for middle-skilled technical occupations, commonly known as technician positions. Results confirm an increasing demand for technicians in these two industries, especially for photonics technicians, CNC tool operators, and electrical engineering technicians (see Fig. 2(a)).

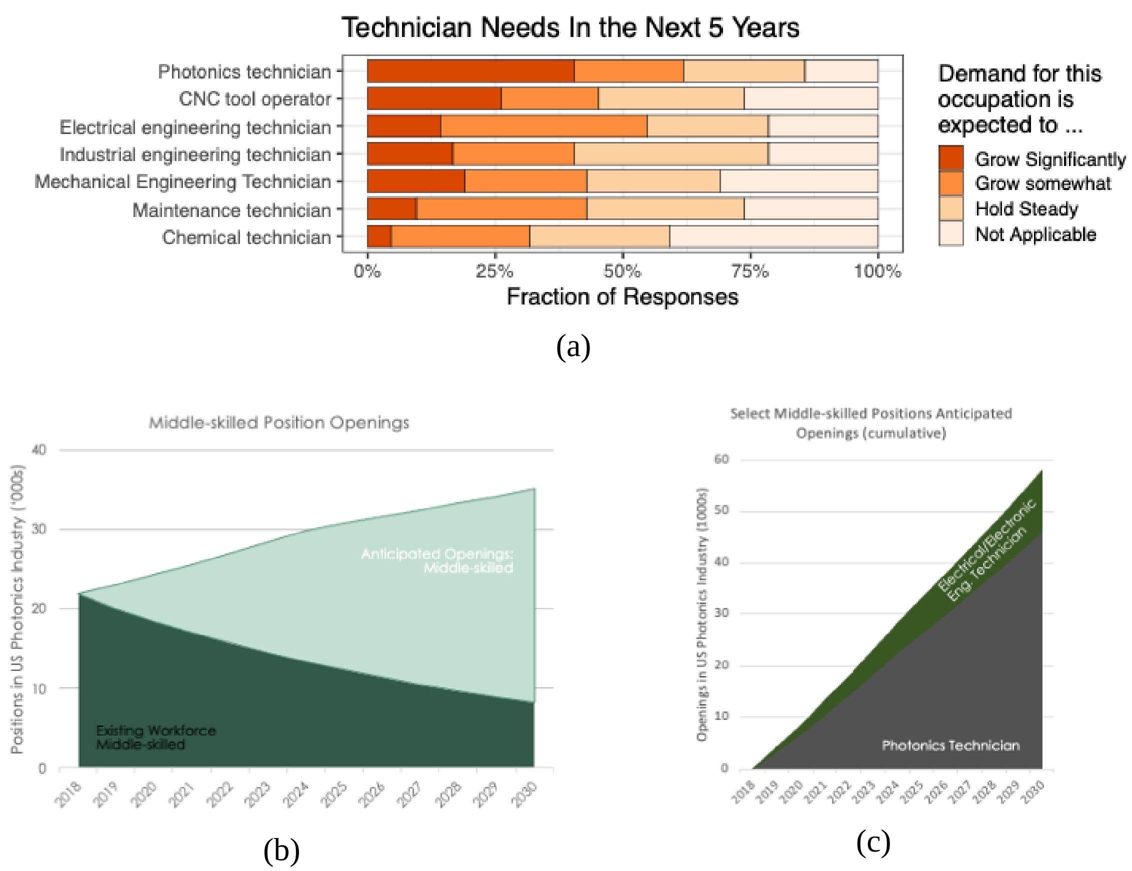


Figure 2. Photonics industry growth roadmap study results: (a) Technicians in the next five years, (b) growth of new middle-skilled openings, (c) photonics versus electronics qualification in new middle-skilled openings.[1]

The growth of these technician careers was estimated for the next decade, in order to assess critical trends across the silicon-based PIC and fiber optics supply chain. Data from the US Bureau of Labor Statistics, market intelligence reports, and survey responses were used to project both anticipated positions and openings. We estimate middle-skilled positions within the two industries to grow from around 21,800 today to 35,100 by the end of the decade (see Fig. 2(b)). This translates to over 16,600 cumulative openings for photonics technicians and electrical engineering technicians, or around 1,400 new photonics and electrical engineering technicians per year (see Fig. 2(c))[1].

Photonics technicians and electrical engineering technicians were two positions identified by firms as requiring extensive on-the-job training and were considered difficult to hire for. Firms emphasized an increasing importance of training in fabrication processes and methods, design of tests, interpretation of test data, and troubleshooting due to the growing skills gap observed by firms. These results underscore the need for continuous improvements in training for middle-skilled technicians in the PIC and fiber optics industries, by cultivating new learning methods that promote online self-paced learning (upskill and reskill of an incumbent industry workforce), and enhance perennial, limited-time professional education workshops or training bootcamps (impacting both incumbent and incipient workforce learners).

Methods

The education roadmap survey was administered via in-person interview with close to twenty-four leading industry firms in PICs and fiber optics[1]. The anonymized results helped to identify and validate or ratify projected skills areas compatible for online digital learning, and define specific learning objectives for VR or GBL-based training simulations.

The four categories (i)-(iv) of training assets were developed using a storyboard process that included coordination between Subject Matter Experts (SMEs) and Unity software code developers[5]. For (i) VR tool training sims, which are akin to digital twins[6,7,8], SMEs reviewed and adapted the Standard Operating Procedure of fiber lathe, optical fiber draw tower, and PIC chip die-bonder tools. SMEs also visually documented tool interface and form factor, to inform the developers' rendering of verisimilitude in their 3D illustrations. In addition, a Computer-Aided Design (CAD) file was consulted and adapted from, for the die-bonder digital twin. Finally, a Graphical User Interface designer refined the online interaction for these sims to preferentially foreground interaction expediency, as opposed to an exact recreation of the physical tool controls.

The (ii) photonic device visualization sims relied on SME modeling of various PIC and optical fiber devices using Electronic Photonic Design Automation (EPDA) software, primarily the

Lumerical/Ansys software tool flow. Electromagnetic confinement modeling of steady-state optical mode profiles and Finite Difference Time Domain (FTTD) simulation provided data sets that the developers populated into look-up tables, for reference by the device sims.

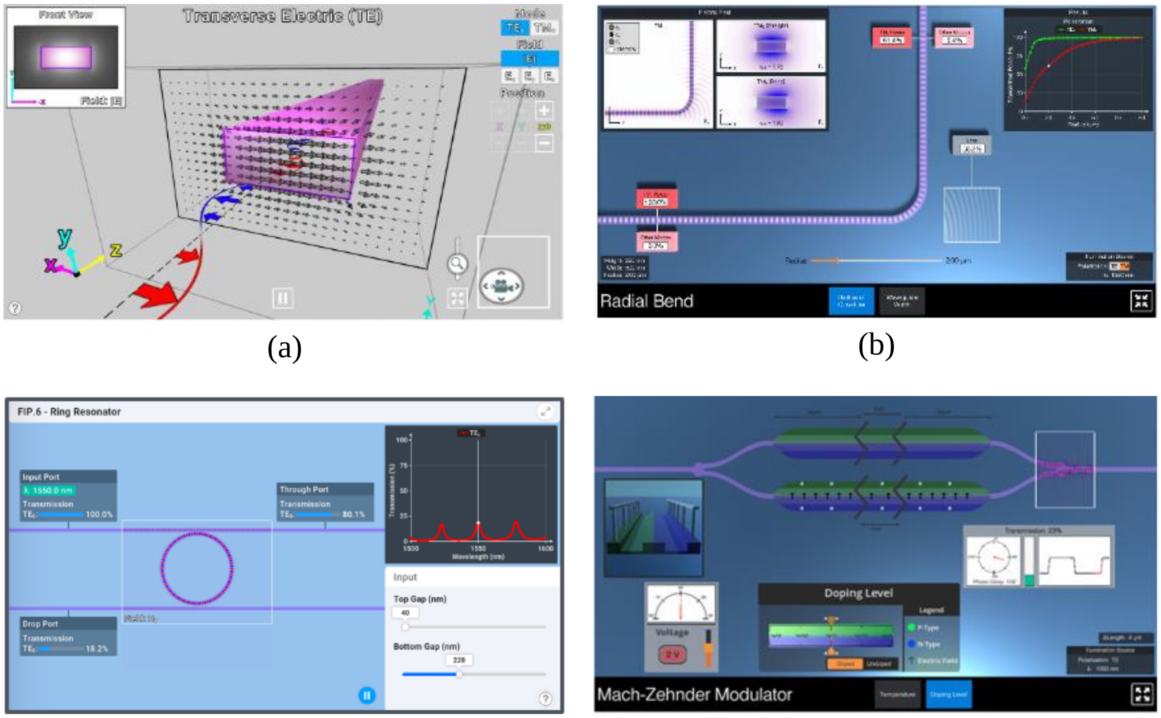
The (iii) application-focused games were designed by game developer on the team, who created narrative storyboards, defined gameplay mechanics and play-time milestone goals, and identified player affordances commensurate with the learning objectives. The complete game architecture was then developed with an external digital games developer[9], and consequently play-tested for operational function.

The (iv) ARG was outlined with advisory feedback from an SME, and workshop discussion with the game developer identified a short-list of learning objectives consistent with nominal K-8 school curricula. The game developers consequently designed interactive digital puzzles using the PhET open education simulation content; produced a video-recorded adventure narrative to define the puzzle challenges, and created supporting documentation for learners and K-8 educators.

Sims (i)-(ii) were packaged within three Massive Online Open Courses (MOOCs), and published on two online education platforms[10,11]. The MOOCs were one-time publicized via the professional society Optica, and made freely accessible to a global audience; prerequisite knowledge to register for these MOOCs presumed up to a second-year college background, including familiarity with vector fields and the wave nature of light. Registered learners' gameplay interactions were selectively recorded (details below) and assessed by learning scientists. In addition, sims (i)-(iii) were deployed in a PIC summer training program and three-day device testing bootcamp, both held at MIT (attended by university graduate students and incumbent industry workers). Players were observed and queried during gameplay, and a few exit interviews were conducted.

Results and Discussion

Desktop Simulations of Microscale Integrated Photonic Devices
We created micron-scale simulations of PIC devices to help students visualize the behavior of light traveling through on-chip silicon waveguides and diverse PIC components. Fig. 3 details the wide variety of PIC device components developed, which learners can systematically explore as a progressive sim library, in the online MOOC format. Learners explore the dynamic behavior of electromagnetic field profiles for waveguide modes (Fig. 3(a)); the design of waveguide bends to minimize radiative coupling loss (Fig. 3(b)); the transmission characteristics of optically resonant microstructures such as ring resonators (Fig. 3(c)); and the performance fidelity of opto-electronic devices such as a Mach-Zehnder Modulator (MZM, see Fig. 3(d)).

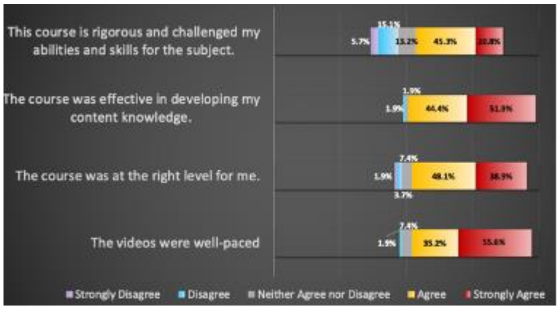


(a) (b)

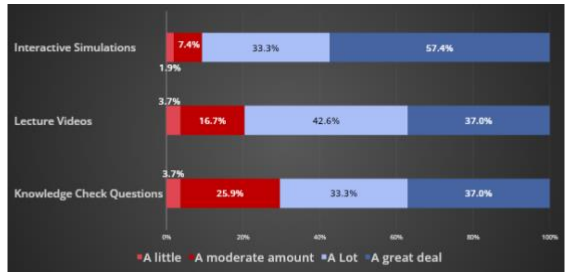
(c) (d)

Figure 3. Examples from the library of photonic integrated circuit web simulations, which includes (a) electromagnetic field confinement and propagation in waveguide structures; (b) radiative coupling loss from waveguide bends; (c) optical transmission of ring resonators; and (d) performance fidelity of MZM modulators.

The PIC device sims were carefully scaffolded [12] to address common student misconceptions [13,14], and were packaged with instructional videos and assessment exercises into the MOOC course format. The MOOC course was published on the Department of Defense's "BuildYourFuture.us" Open edX platform[11]. The first offering of the online MOOC "Integrated Photonics Simulation Library" was released in February of 2022. Of the 438 users who enrolled in the asynchronous course in the first three months after release, 169 completed the initial enrollment survey, 90 completed the first two modules, and 54 completed the post-course survey shown in Fig. 4. The course was well received: approximately 96% of learners who completed the course agreed with the statement "The course was effective in developing my content knowledge", and >90% stated the interactive simulations contributed to their learning "a lot" or a "a great deal" more than the videos or assessment questions, alone.



(a)



(b)

Figure 4. Self-reported course evaluation data for the February 2022 release of "Integrated Photonics Simulation Library" online course on an Open edX platform.

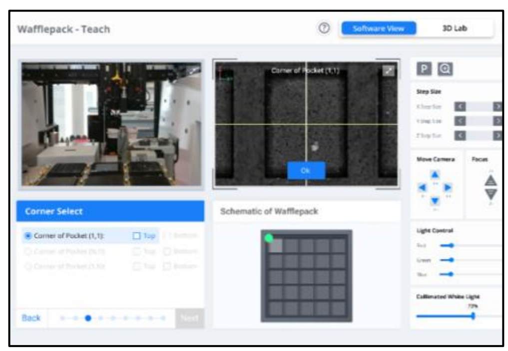
Digital Twin Simulations of Macroscale Photonics Tools

(a)

(b)

(c)

(d)

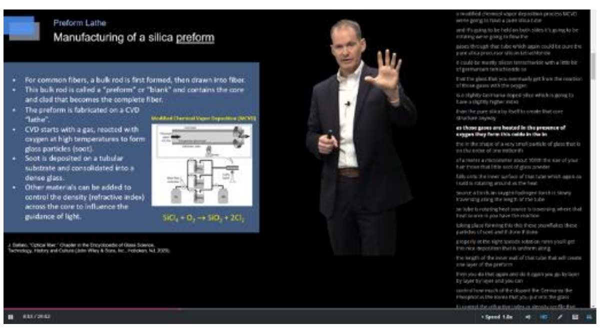


(e)

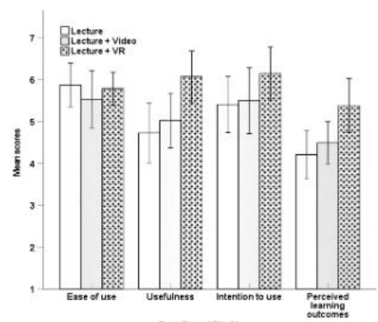
Figure 5. Digital twin VR sim of an MCV lathe digital twin, featuring three distinct learning objective milestone: (a) terminology, (b) guided practice, and (c) open exercise. (d) Digital twin of a fiber draw tower. (e) Interface panel and (inset) digital twin of a PIC die-bonder.

In addition to microscale photonics simulations, our team created macroscale digital twins for training on workhorse tools ubiquitous to the fiber optic and PIC chip manufacturing processes. Fig. 5(a)-(c) depicts a browser-based desktop VR sim of a digital twin to a Modified Chemical Vapor Deposition (MCVD) glass preform tool; Fig. 5(d) depicts the digital twin for a fiber draw tower; and Fig. 5(e) depicts the Graphical User Interface of a microchip die bonder. These tools are costly and not easily available to install at common 2-year community college training institutions. Hence, these VR sims may afford future technician learners the opportunity to virtually train in operating procedures without the overhead demand of a physical on-site tool. The sims were developed using a user-centered design process and standard instructional design practices in a scaffolded learning environment[15]. The simulations were segmented into modules to guide learners through: (a) introduction to components and tools (terminology module); (b) step-by-step walkthrough of the process (guided practice); and (c) evaluation of learner knowledge and early problem-solving skills (open exercise).

Evaluation surveys were included in a MOOC deployment of the fiber manufacture sims, in order to assess the efficacity of the sims to train learners and measure their perception of usability, usefulness, intention to use, and learning outcomes[16,17]. The self-reported surveys compared learning with the VR sims to traditional MOOC video lecture media (see Fig. 6(a)) and a process demonstration video. Results from the evaluation are shown in Fig. 6(b): the VR sim was rated significantly higher than the other instruction media for perceived usefulness and learning outcomes. These results support hypotheses for the effectiveness of sims by, among other things, creating the affordance of a secure learning experience in which leaners have *permission to fail*, and potentially incur catastrophic damage to such costly tools[18]. More research is expected to assess the enduring retention value of such a permission to fail learning paradigm.



(a)



(b)

Figure 6. (a) Excerpt from MOOC course on fiber optic manufacturing. (b) Assessment results of learner comprehension (arbitrary units) for four perception metrics.

Sims (i), (ii) were deployed in 2-, 3-day PIC device characterization bootcamps, co-organized by the collaborators' Laboratories for Education, Application, and Prototyping (Massachusetts LEAP Labs) [19]. A *Three-Legged Stool* (3LS) training model that combined lecture, VR sim training, and lab-site physical tool trainingwas developed to structure and pace this high-volume content, short-duration intensive training experience.

The 3LS emphasis on hands-on *experiential* education in a lab or lab-like setting, is an integral component of most Science, Technology, Engineering, and Math (STEM) learning processes, including in the manufacture of PIC chips. In addition to mastering fundamental concepts in semiconductor electronic and photonic device design and function, technologists (engineers and technicians) in this field must be proficient in the use of equipment for the fabrication, packaging, and testing of semiconductor devices and systems.

Such equipment includes a suite of complex, high throughput, precision tools, an exemplar of which is a die bonder (see Fig. 5(e)) used extensively in semiconductor microchip packaging: it is a tool used to accurately pick, place, and firmly attach a fragile semiconductor chip (die) to a substrate such as a printed circuit board. Hands-on training for proper use of this tool can take days, and increase likelihood of tool breakage during novice learner acclimation. The extended training and risk of breakage present an inevitable cognitive load for both trainer and trainee, enhancing mental stress and mitigating retention of operating insights. This in turn may prompt the need for high-frequency refresher training, for intermittent tool users.

The die-bonder sim was introduced as a pilot training program in the PIC Bootcamp via the 3LS pedagogy sequence[5]. In the tool sim, learners were introduced to the tool's key components and their in-specification use (similar to Fig. 5(a)), and practiced manipulation and accurate placement of dies (similar to Fig. 5(b)). Subsequently, learners performed the identical pick and place operation on the physical twin, within the Bootcamp Lab. A post-Bootcamp survey and exit interviews suggest the 3LS pedagogical sequence helped to increase retention for learners, and also relieve the physical twin's instructor from performing at peak instructional efficiency[20]. Further studies will assess the impact of such cognitive relief for instructors.

Game-Based Learning: Decision-making and analysis of trade offs in applications of photonics technologies

To help early-stage learners to assess the societal value and utility of photonics technologies such as fiber optics and PICs, we designed and developed four GBL sims that position the player in a playful learning environment to experiment with how photonics technology may be employed for particular applications. Each of these games were created for a general audience in mind, but also tailored for a specific use-case: learners in grades 8-12. The games have been also been deployed to facilitate application-specific analysis in a summer photonics training program at MIT, to helps learners define the priority trade-offs inherent to designing and operating complex systems. The games have also been used to illustrate the concept of design of tests, as the players need to collect data while they play in order to make key decisions in order to succeed at the games[21,22].

"Databytes, Inc." (Fig 7(a)) is a data center management game that demonstrates how fiber optic and PIC interconnections can significantly improve hyperscale data center ability to accommodate very large bandwidth while reducing both operating cost and power consumption efficiency. Players are charged to decide whether and when to upgrade their legacy all-electricity data center to photonics based on current demand, while maintaining revenues and profit.

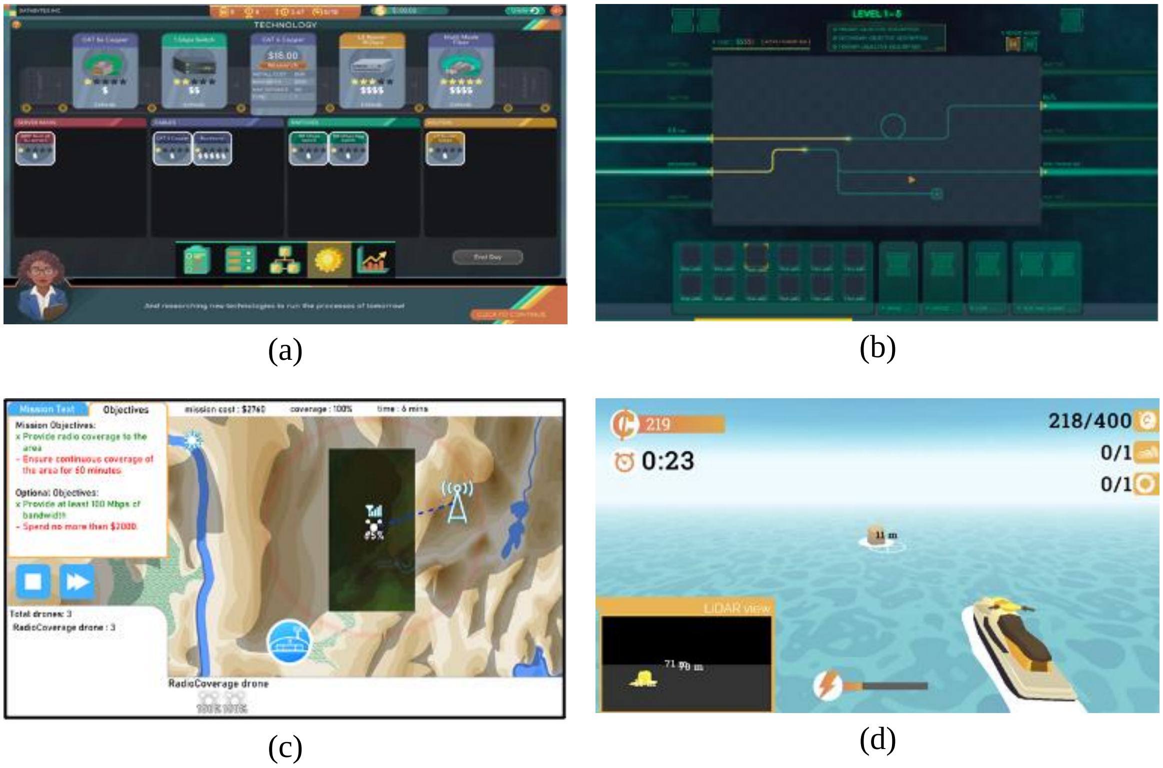


Figure 6. GBL sims developed in the program, for four applications systems that use PIC and fiber optic technologies: (a) a data center game, (b) a chemical sensor game, (c) and RF wireless communications game, and (d) a LiDAR 3D-imaging game.

“Illuminator” (Fig 7(b)) is a photonic sensor design game, structured as a series of puzzles for the player to solve, by building various chemical sensing chips using PIC device components such as ring resonators. Players are presented with performance requirements such as specific wavelengths to detect (corresponding to particular chemistry bonds) and the constraint to design a PIC circuit that is robust to manufacturing process variation, while retaining a low manufacturing cost and small chip footprint. The game is being integrated into a MOOC course for incipient university and incumbent industry learners, to rapidly train in application-specific PIC design.

“Drone Construction Kit” (Fig 7(c)) challenges learners with a series of increasingly complex tasks to create and operate autonomous drones, to complete various imaging and communication tasks for agricultural, search and rescue, and industrial clients. Incorporating RF photonics technologies improves flight times and communications reach of the drones by lowering weight, and thereby increasing power efficiency.

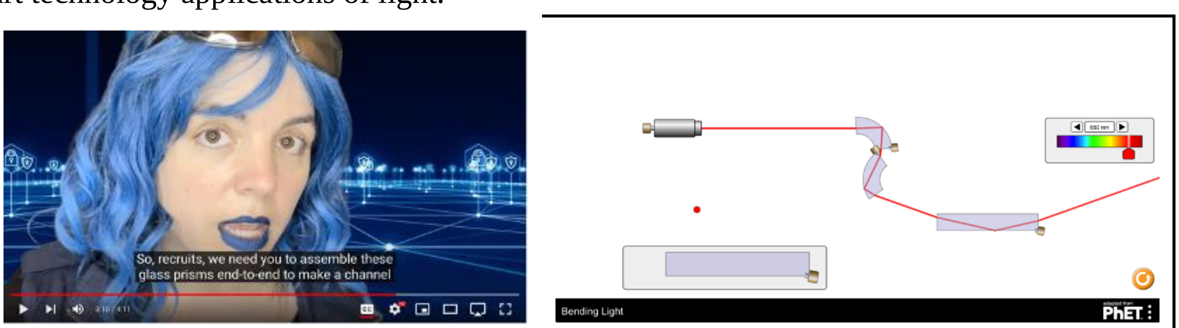
"Jetski Jamboree" (Fig 7(d)) prompts learners to design an autonomous jetski to maneuver through a fantasy obstacle course, by upgrading its processing and sensory capacity through adoption of LiDAR 3D imaging technology.

These games were tested throughout development with a range of learners, both in age and knowledge background. Future use of the games will be in STEAM workshops for high school students, at expos and job fairs to introduce PIC and fiber optic technologies to potential future technicians, and as introductory coursework in MOOCs, to introduce and acculturate early learners to the application-specific needs that increasingly require the unique high data rate, low power capacity of PICs and fiber optic communications.

Learners can access sims (i)-(iii) from anywhere with an internet connection and a standard computer to practice the process steps in a safe, repeatable, and effective manner.

K7-8 Acculturation: Augmented Reality Games

Our most recent exploration of non-conventional learning tools includes the creation of an ARG game [23] designed to introduce young-learners (8^{th} grade focus) to the ray optics phenomena of refraction, total internal reflection, and light-guiding via straight and curved waveguide components (see Fig. 8). The ARG has been designed as a miniature narrative, which a middle-school educator can independently deploy, instead of requiring specialized game designer staff to oversee. This purposeful ARG-in-a-box methodology is intended to enhance portability of the learning puzzle game across a national network of middle-schools, and offer an on-ramp for young learners to consequently engage with the (iii) GBL sims, to begin discovering state-of-the-art technology applications of light.



(a) (b)

Figure 8. ARG game training materials. (a) A video challenge in which a mission leader charges learners to solve a light-tracing puzzle, in order to achieve a narrative goal. (b) The light-tracing puzzle instructs by total internal reflection and light-guiding, based on the ray-optic model only.

The ARG was structured as a sequence of six progressive puzzle-solving tasks, to be solved individually or collectively by a small cohort of students, and discover distinctive light-guiding properties in materials (the waveguiding effect) that tentatively begin to extend learner intuition beyond the implications of Snell's Law, for the ray optic model of light.

The team will soon deploy the ARG-in-a-box with a collaborating middle-school to assess the intelligibility of the game package to the educator, and the attrition and retention rate of 8th grade student learners.

Conclusion

Taken collectively, this program's efforts to create a sequence of progressively more sophisticated education assets—from an introductory ray optic-based ARG, ultimately to state of the art PIC device and circuit design, with an extended digression into new photonics-enabled application functions such as LiDAR and chemical sensing—intend to support an on-ramp to enlist a new generation of photonics learners and workforce practitioners. Keeping in mind the oft-quoted seven-to-two ratio of technicians to undergraduate engineers[24], it is imperative to co-design these education and training tools with affordances to discover, skill, reskill, and upskill, for learners at both 2- and 4-year colleges[25].

In addition, the emphasis in an online learning Agile Continuous Education (ACE) [26] methodology presumes a critical need for life-long skilling, in highly modularized and incremental learning experiences, for advanced manufacturing workers. In the case of integrated photonics, there is a timely opportunity to assess the early-impact of such ongoing reskill and upskill learning, due to the rapid convergence of extant computing, chemical, wireless, and imaging industries towards PIC-enabled new functionalities. This convergence mandates a rapid learning of PIC functions and automation design, by engineers who historically have trained in adjacent disciplines. The constellation of VR and GBL designed sims are intended, via a MOOC interface, to rapidly acclimate these more veteran learners from the incumbent workforce, and prepare them for taking advanced PIC circuit design courses[27], overseen by some of the collaborators on an advanced manufacturing workforce training MOOC platform[11].

References

[1] R. Kirchain, E.A. Moore, F.R. Field, S. Saini and G. Westerman, *Preparing the Advanced Manufacturing Workforce: A Study of Occupation and Skills Demand in the Photonics Industry*, February 2021. [Online]. Available: https://www.ikim.mit.edu/photonics-workforce-roadmap. [Accessed March 20, 2023].

[2] P. Wellener, V. Reyes, H. Ashton and C. Moutray, "Creating pathways for tomorrow's workforce today: Beyond reskilling in manufacturing," *Deloitte Insights*, May 4, 2021. [Online]. Available: Deloitte,https://www2.deloitte.com/us/en/insights/industry/manufacturing/manufacturing-industry-diversity.html. [Accessed March 20, 2023].

[3] BCC Research, *Photonic Integrated Circuits: Global Markets with Special Focus on Silicon Photonics,* Wellesley, MA: BCC Publishing, 2017. [E-book] Available:https://www.bccresearch.com/market-research/photonics/silicon-photonics-technologies-and-global-markets.html

[4] Lightcounting, *October 2020 Market Forecast Report,* Lorton, VA: Lightcounting, 2020. [E-book] Available: https://www.lightcounting.com/report/october-2020-market-forecast-report-20

[5] E. Verlage, S. Saini, A. Agarwal, S. Serna, R. Kosciolek, T. Morrisey and L. C. Kimerling, "Web-based interactive simulations and virtual lab for photonics education," in *Fifteenth Conference on Education and Training in Optics and Photonics: ETOP 2019, Québec City, P.Q., Canada, May 21-24, 2019,* ETOP 2019 Papers (Optica Publishing Group, 2019), paper 11143_136.

[6] M. Batty, "Digital twins," Env. and Planning B: Urban Analytics and City Science vol. 45(5), pp. 817-820, 2018; doi: 10.1177/2399808318796416

[7] A. Fuller, Z. Fan, C. Day and C. Barlow, "Digital Twin: Enabling Technologies, Challenges and Open Research," *IEEE Access* vol. 8, pp. 108952-108971, 2020; doi: 10.1109/ACCESS.2020.2998358

[8] F. Tao and Q. Qi, "Make more digital twins," *Nature* vol. 573(7775), pp. 490-491, 2019; doi: 10.1038/d41586-019-02849-1

[9] Fire Hose Games. [Website] Available: https://www.firehosegames.com [Accessed March 20, 2023]

[10] Educate Workforce. [Website] Available: https://educateworkforce.com [Accessed March 20, 2023]

[11] BuildYourFuture.US [Website] Available: https://buildyourfuture.us [Accessed March 20, 2023]

[12] A. Paul, N. Podolefsky, and K. Perkins, "Guiding without feeling guided: Implicit scaffolding through interactive simulation design," AIP Conference Proceedings 1513, pp. 302-305 (2013); doi: 10.1063/1.4789712

[13] C. D. Porter, J. R. H. Smith, E. M. Stagar, A. Simmons, M. Nieberding, C. M. Orban, J. Brown and A. Ayers, "Using virtual reality in electrostatics instruction: The impact of training," *Phys. Rev. Phys. Educ. Res.* vol. 16(2), p. 020119, 2020; doi: 10.1103/PhysRevPhysEducRes.16.020119

[14] C. Koh, H. S. Tan, K. C. Tan, L. Fang, F. M. Fong, D. Kan, S. L. Lye and M. L. Wee, "Investigating the Effect of 3D Simulation Based Learning on the Motivation and Performance of Engineering Students," J. Eng. Education vol. 99(3), pp. 237-251, 2010; doi: 10.1002/j.2168-9830.2010.tb01059.x

[15] C. J. Chen, "The design, development and evaluation of a virtual reality-based learning environment," Australas. J. Educ. Technol. vol. 22(1), 2006; doi: 10.14742/ajet.1306

[16] K.C. Madathil, K. Frady, R. Hartley, J. Bertrand, M. Alfred and A. Gramopadhye, "An empirical study investigating the effectiveness of integrating virtual reality-based case studies into an online asynchronous learning environment," *Computers Edu. J.*, vol. 8(3), pp. 1-10, 2017.
[17] Z.A. Syed, Z. Trabookis, J. Bertrand, K.C. Madathil, R.S. Hartley, K. Frady and A.K. Gramopadhye, "Evaluation of virtual reality based learning materials as a supplement to the undergraduate mechanical engineering laboratory experience," *Inter. J. Eng. Education*, vol. 35(3), pp. 1-11, 2019.
[18] B. Upadhyay, K. C. Madathil, J. Bertrand, E. Verlage and S. Saini, "Investigating the Learning gains associated with Virtual Reality (VR) Simulations in Photonics Manufacturing Education," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting,* vol. 65(1), pp. 1464-1465, 2021; doi: 10.1177/1071181321651251
[19] S. Serna, N. Hidalgo, J. Tjan, K. McComber, L.C. Kimerling, E. Verlage, J. Diop, J. Hu, S. Saini, A. Agarwal, G. Gagnon, S. Preble, G. Howland, M. van Niekerk, J. Steidle, K. Mcnulty, J. Cardenas, M. Song, M. Popović, A. Khilo, P. Nagarkar, F. Vazehgoo, I. Moskowitz, G. Gu, C. Schnitzer, E. Deveney, T. Kling, D. Petkie, and J. Longacre, "A modular laboratory curriculum for teaching integrated photonics to students with diverse backgrounds," *Fifteenth Conference on Education and Training in Optics and Photonics: ETOP 2019, Québec City, P.Q., Canada, May 21-24, 2019,* ETOP 2019 Papers (Optica Publishing Group, 2019), paper 11143_142.
[20] S. Serna, D. Weninger, L. Ranno, K. Cicek, P. Brown, S. Bechtold, J.J. Arango Uribe, J.A. Laverde Preciado, S. Saini, S. Rayyan, P.B. Rios, C.H. Ballesteros, G. Stump, G. Westerman, E. Verlage, T. Morrisey, C. Gabbianelli, Y. Yuan, J. Bertrand, K.C. Madathil, K. Wada, J. Hu, L.C. Kimerling and A. Agarwal, "Leveraging MOOCs in a hybrid learning bootcamp model for training technicians and engineers in STEM manufacturing," *2022 IEEE Learning with MOOCS: LWMOOCS 2022, Antigua, Guatemala, September 29-30, 2022,* pp. 223-226; doi: 10.1109/ LWMOOCS53067.2022.9928025.
[21] E. Klopfer, J. Haas, S. Osterweil and L. Rosenheck, *Resonant games: design principles for learning games that connect hearts, minds, and the everyday*. Cambridge, MA: The MIT Press, 2018.
[22] E. Klopfer, *Augmented learning: Research and design of mobile educational games*. Cambridge, MA: The MIT press, 2008.
[23] E. Klopfer, J. Haas, S. Osterweil and L. Rosenheck, "I Wish I Could Go On Forever" in *Resonant games: design principles for learning games that connect hearts, minds, and the everyday.* Cambridge, MA: The MIT Press, 2018, pp. 57-89.
[24] K.S. Campbell, Ed. *Manufacturing Workforce Development Playbook: Preparing for the manufacturing renaissance in America.* Chicago, IL: PMMI Media Group, 2014.
[25] E. Dierdorff and K. Ellington, "O*NET and the Nature of Work," in *Workforce Readiness and the Future of Work.* F.L. Oswald, T.S. Behrend and L.L. Foster, Eds. New York: Routledge (Taylor & Francis Group), 2019, pp. 110-130.
[26] S. Sarma and A. Bagiati, "Current innovation in STEM education and equity needs for the future" in *Imagining the Future of Undergraduate STEM education: Proceedings of a Virtual Symposium: Washington, DC, United States, Nov. 12-19,* The National Academies Press, pp. 49-70 (2022).
[27] S. Saini, S. Preble, M. Popović, J. Cardenas, A. Kost, E. Verlage, G. Howland and L.C. Kimerling, "Integrated photonics and application-specific design on a massive open online course platform," in *Fifteenth Conference on Education and Training in Optics and Photonics:*

ETOP 2019, Québec City, P.Q., Canada, May 21-24, 2019, Proc. SPIE vol. 11143, p. 111430Y;
doi: 10.1117/12.2523878