Beyond ray optics: building photonics intuition for waveguide modes using digital simulations and games

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ABSTRACT

Engineering students in optics and photonics need robust intuitions for the micron-scale behavior of light in dielectric materials. Educators often use textbook images of ray diagrams and static electric field profiles to introduce the behavior of light, after which undergraduate and graduate students are expected to run commercial software simulations to explore the dynamic behavior of waveguide modes. While incredibly powerful and flexible, complex commercial software tools are difficult for novices to use, preventing students from gaining nuanced conceptual insights about the behavior of optical components and devices.

The Virtual Manufacturing Lab (VM-Lab) at MIT has created a series of simulations that use novel data visualizations and dynamic electric field profiles to teach the fundamentals of photonic circuit components. This work identifies key misconceptions on the topics of fiber optics, waveguides, and photonic integrated circuits which prevent students from building an accurate model for light propagating in a micron-scale dielectric waveguide. A library of interactive photonics simulations helps students learn about silicon photonics by exploring waveguide modes, mode superposition, on-chip interferometers, resonant structures, and more. In addition, interactive learning games introduce students to the application areas of photonic integrated circuits, including on-chip chemical sensing, hyperscale data centers, RF wireless communication, and LiDAR imaging.

Keywords: Modal analysis, dielectric waveguide, integrated photonics, silicon photonics, photonic integrated circuit, digital training, game-based learning, massive open online course

1. INTRODUCTION

There is currently a large training gap in advanced manufacturing, including workforce training for precision optics and photonics manufacturing, requiring new workforce training approaches to meet a growing demand for capable engineers and technicians.[1] The emerging field of integrated photonics is expanding rapidly, with the silicon photonics market valued at $912 million in 2021 and expected to grow to around $4 billion by 2027.[2] Photonics PhD engineers, and specifically photonic circuit designers, are in high demand by advanced manufacturing firms.[3] There is also a large need for middle-skilled photonics technicians, with recent reports estimating around 3,500 new openings in the USA every year between 2021 and 2030.[4] Online learning is a cost-effective and scalable solution that can help meet this demand.[5] Interactive simulations and games can increase student motivation in online courses and help address student misconceptions in physics and STEM fields.[6] Digital simulations have many advantages over laboratory exercises or classroom activities including the scalability of in-browser physics simulations,[7] immersive VR environments to teach 3D concepts like electrostatic fields,[8] and the ability to simulate complex and dynamic systems such as electronic circuits where students can rapidly iterate on circuit design.[9] Dynamic 2D and 3D visualizations are great for communicating conceptual learning goals in optics and photonics, giving students a clear understanding of the micron-scale behavior of light. Careful design and scaffolding of interactive simulations and games is crucial to encourage student exploration, enable comprehension, and address common student misconceptions.[10]

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Seventeenth Conference on Education and Training in Optics and Photonics: ETOP 2023,
edited by David J. Hagan, Mike McKee, Proc. of SPIE Vol. 12723, 127231L
 · doi: 10.1117/12.2670774

2. DIGITAL TOOLS FOR WORKFORCE TRAINING IN PHOTONICS

The Virtual Manufacturing Lab (VM-Lab) was founded in 2019 to support online workforce training efforts in advanced manufacturing. VM-Lab is a cross-university collaboration between MIT, Clemson University, and the University of Arizona to create digital workforce training tools. Figure 1 shows an overview of the three categories of VM-Lab online learning modules: 1) interactive photonics and materials science simulations with micron-scale visualizations (Figure 1 left), 2) desktop and immersive VR simulations for training on equipment and procedures (Figure 1 center), and 3) learning games which explore the applications of advanced manufacturing technologies (Figure 1 right). In addition to simulations or games, each VM-Lab module also includes instructional videos, downloadable slides, and assessment exercises which highlight and expand upon the key learning objectives.

Figure 1. Overview of the Virtual Manufacturing Lab products including (left) micron-scale photonics simulations, (center) macro-scale VR and desktop simulations, and (right) application-focused learning games.

VM-Lab modules have been incorporated into existing online courses, published as stand-alone offerings through simulation libraries, incorporated into classroom teaching, and used in blended learning bootcamps. The VM-Lab modules have been made available to a global audience on Open edX platforms managed by MIT and Clemson University. The USA Manufacturing Innovation Institutes (MIIs)[11] are key education and workforce development stakeholders for the VM-Lab project. The initial focus of our work was to create simulations and games to be distributed by AIM Photonics Academy, the education and workforce training arm of the AIM Photonics MII.[12] In this work we describe our efforts to create novel photonics training simulations and application-focused games.

2.1 Micron-scale simulations for photonics data visualization

Many photonics engineering programs encourage new students to use commercial simulation software such as the Ansys Lumerical or Synopsys tool suites. While powerful and complex optical modeling tools have many advantages, there are also major drawbacks to using commercial software, which is not designed for education, to train undergraduate and early graduate students. The most significant is the cognitive overload students experience when first using these tools. There is a large barrier to entry for novice users who are not familiar with the long list of dropdown menu options and adjustable settings. Students are not focused on the intended photonics learning goals of these activities if they are busy defining finite difference time domain (FDTD) mesh regions, correctly setting up boundary conditions, navigating the software GUI, learning how to write code in custom scripting languages, waiting minutes to hours for each simulation sweep to run, and finally assembling and plotting the results. The feedback loop between initial setup and viewing results is too prolonged (and the parameter space too large) for students to make fast progress in understanding photonics fundamentals. Additionally, many students will be hesitant when interpreting the results from a commercial simulation tool, knowing a small mistake could lead to incorrect outputs, which a more experienced user would easily be able to catch and correct.

A more effective training environment can use expert-vetted simulation results to provide a simpler, intermediate steppingstone between textbook examples and exercises using commercial software. For training in integrated photonics, VM-Lab has created a series of 20 introductory modules featuring scaffolded simulation sequences which allow users to explore waveguide modes and photonic circuit components using sliding bars, graphs, and simple user interfaces.

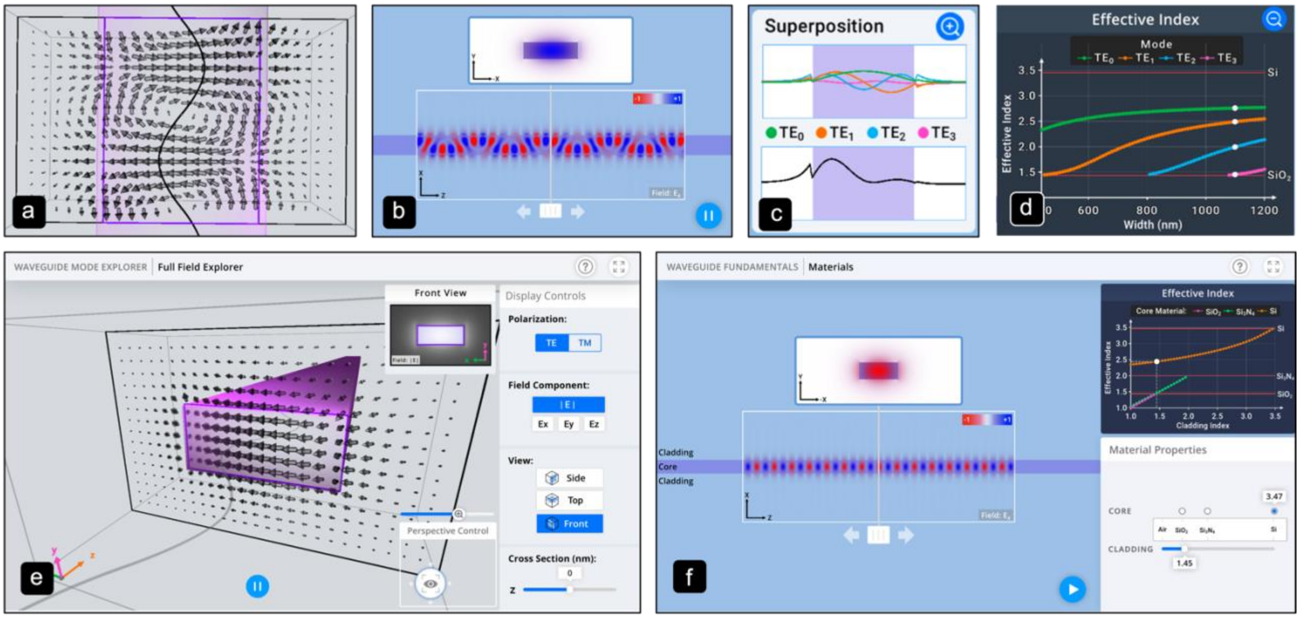

Figure 2. Photonics training simulations showing waveguide modes in a rectangular Si/SiO_2 dielectric waveguide, which use novel visualization training tools including (a) dynamic 3D vector field representation of the waveguide mode, (b) dynamic colorized cross-sectional profiles of field components, (c) linear visualizations of modes to demonstrate mode superposition, and (d) explorable graphs for each simulation parameter space. The lower screenshots show examples of the final GUI layout of the training simulations including (e) Waveguide Mode Explorer (WME) and (f) Waveguide Fundamentals.

As shown in Figure 2, the VM-Lab team has designed web-based photonics training simulations with novel 2D and 3D data visualization tools. Students can view real-time vector field profiles for Transverse Electric (TE) and Transverse Magnetic (TM) waveguide mode polarizations (Figure 2a), colorized mode cross sections (Figure 2b), observe a linear interpretation of mode superposition at different positions along a waveguide structure (Figure 2c), and uncover data across parameter sweeps through an interactive graph (Figure 2d). The final simulation GUI shown in Figure 2e/2f is the result of an iterative multi-year development process used to create and deploy these training simulations, including formative and summative learning science research, described in Sections 3-6 below.

2.2 Educational web game: building photonic circuits for sensing applications

Digital games can be a great way for students to discover the applications of STEM fields and explore complex dynamic systems. For students studying remotely or taking online courses without access to classroom activities, interactive learning games can fill a gap in their studies. Engaging games also increase student motivation and prevent students from becoming disillusioned with poor performance on difficult exercises and tasks.[13] In games, failing before achieving a goal is not only natural to the medium, but can be a rewarding and satisfying experience. When stuck, many players will methodically explore the rules of their environment, get feedback from the game, and try different approaches to achieve an in-game objective.[14] Progressing through the levels of a learning game and seeing measurable success can quickly build student confidence in their STEM skills.[15,16] Games have been successfully used for a wide variety of teaching, including introductions to electromagnetism,[17] demonstrate the intricacies of supply chain management,[18] and to encourage underrepresented youth to pursue careers in STEM fields by creating identity-building narratives.[19]

The Virtual Manufacturing Lab at MIT created four educational web games demonstrating the main application areas of integrated photonics. In addition to the datacenter management game "Databytes, Inc." shown in Figure 1 (right), the team created a drone-building game to teach students about RF communication, an infinite runner where players update the LiDAR imaging capabilities of their vehicle, and a circuit-building web game "Illuminator" shown in Figure 3. In "Illuminator," learners use electro-optic circuit components to design and build a photonic sensor which can detect methane gas. In a sequence of 17 levels, players choose wavelengths of operation, lay out the sensing and reference paths required for the optical circuit design, select the appropriate sensing circuit elements such as spirals or ring resonators, use functionalized coatings to increase signal-to-noise ratio, and select photodetector material systems. The screenshot in Figure 3a shows the chip view where players place circuit components on the grid next to fiber input/output ports. Figure 3b shows the printed circuit board view where players place lasers and detectors. Players are challenged to be efficient in their designs by minimizing chip footprint and foundry costs. Each level has a series of objectives and hints (Figure 3c), available components (Figure 3d), and the ability to expose and coat sections of the circuit to the gas or liquid analyte for chemical sensing (Figure 3e). Students can also test their incomplete circuits with and without the presence of methane and other chemicals and, when they are ready, submit a design to pass the level. Each level of the game introduces a new learning goal for the player, and the levels get progressively more difficult.

Figure 3. The integrated photonics web game "Illuminator", created by MIT and Fire Hose Games studio. Players build (a) photonic integrated circuits laying out electro-optic circuit components for on-chip chemical sensing, and (b) printed circuit boards with lasers, photonic chips, and detectors. Each level includes (c) detailed level objectives, (d) a variety of circuit components which can be placed on the chip grid, and (e) the ability to expose and add a functionalized coatings to elements on the chip, and then test and submit your chemical sensing circuit to complete the level.

The VM-Lab team tested the web games "Illuminator" and "Databytes, Inc." during multiple workforce training programs including residential learning at MIT, the AIM Photonics Academy training bootcamp, and a 15-month technician training program. The games were well received, and participants showed increased motivation during these sessions reporting high levels of satisfaction with the interactive experience.

3. DESIGN AND DEVELOPMENT OF PHOTONICS SIMULATIONS

3.1 Simulation prototyping and formative assessment research

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 – Testing the first iteration of simulations with undergraduate physics students

In Phase 1, the subject matter experts (SMEs) and the learning sciences research team discussed and developed learning outcomes for the simulations. By the end of the simulation sequence, learners were expected to be able to:

1. Correctly connect electromagnetic vector fields to colorized cross-sectional mode profiles and describe the breakdown of the electric field along each coordinate axis into E_x, E_y, and E_z field components.
2. Explain the distinction between the ray optics perspective and modal analysis perspective.
3. Explain the behavior of evanescent fields in dielectric waveguides.
4. Distinguish between transverse electric (TE) and transverse magnetic (TM) waveguide mode polarizations

Additionally, the learning sciences team conducted a cognitive task analysis with SMEs to understand the goals of the simulations and how learners should benefit from them.

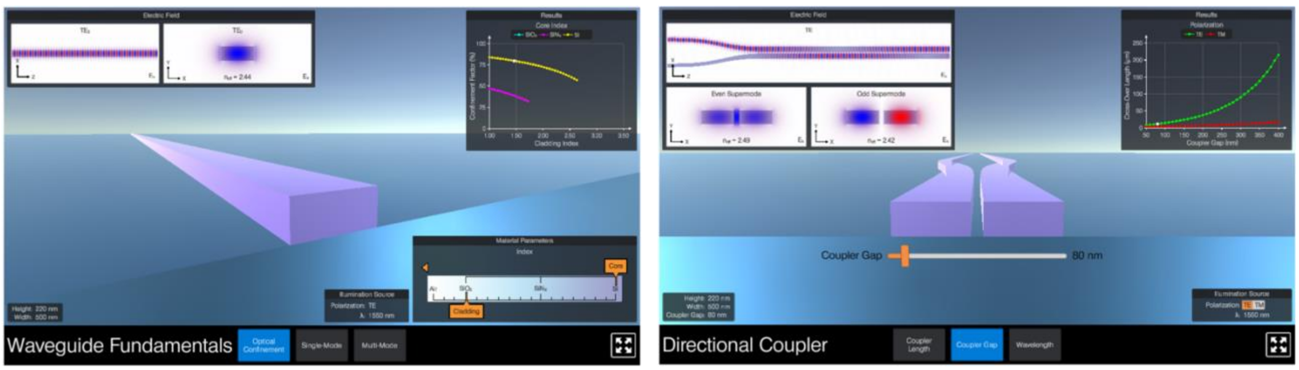

Figure 4. First iteration of photonics simulations for (left) Waveguide Fundamentals, and (right) Directional Coupler.

Participants: An initial playtest was conducted with one industry expert and four undergraduate students from a university in Massachusetts. The students were undergraduates majoring in physics who had a basic background in optics and electromagnetic wave theory. They did not have a background in photonics or waveguides. The playtest was included as part of a field trip to MIT to learn more about photonics work currently being conducted at MIT.

Procedure: After signing a consent to participate in the study, participants heard a brief introduction to the simulations shown in Figure 4. The agenda was planned to include three simulations: (1) Waveguide Fundamentals, (2) Directional Coupler, and (3) The Multimode Interferometer (MMI). Although they were not held strictly to a time limit, participants were allotted approximately 15 minutes to complete each simulation, along with answering assessment questions they received in a separate handout. Participants were asked to 'think out loud,' or articulate their thoughts, as they interacted with the simulations. A researcher recorded their comments or questions and observed their interactions with the simulations. At the conclusion of the session, participants were asked to complete a questionnaire regarding the usability of the simulations. Due to limitations of time, participants did not complete the MMI simulation.

Instruments: The SMEs developed assessment questions associated with each simulation. Participants were free to respond to the questions either during their interaction with the simulation or immediately afterward. The questions were intended to assess participants' understanding of basic concepts related to waveguides and their use. Researchers also utilized an observation tool to record participants' behaviors and articulations as they engaged with the simulation. A standard usability survey was utilized for user feedback on the simulation.

Data Analysis and Results: Data from the assessment questions, researchers' observations, and the usability survey were analyzed to explore participants' experience during the session. For the Waveguide Fundamentals simulation, the participants' mean score was 73% for the five assessment questions, with the largest number of incorrect responses related to the concept of "confinement factor", or how confined the mode is inside the waveguide core. We also observed confusion about mode naming conventions, when an optical mode was supported, and when it was considered excited. Researcher observations conducted during the Waveguide Fundamentals simulation revealed that participants asked questions about the meaning of effective index, confinement, mode order, and mode polarization. When engaging with the simulation, researchers observed that participants did not always explore the entirety of each simulation, thus missing the sequencing and incremental building of knowledge as planned. For the Directional Coupler simulation, the participants' mean score for the six questions was 70%, with the largest number of errors relating to understanding the effect of coupler gap on effective index and oscillation of the field between a top and bottom wave guide. As they progressed through the simulation, participants commented and asked more questions about the representations of simulation elements, e.g., one participant said, "Having [a] red arrow and red signal was confusing." This participant expressed that they would like more detailed explanation of what was on the screen. Students were confused about the red/blue colorized representation of cross-sectional electromagnetic field profiles (e.g., E_x, E_y, and E_z) shown in the top-left of the simulations as in Figure 4 and expressed a desire for a more basic introduction to waveguide modes.

Actions: Analysis of the data collected supported the need for creation of a new teaching simulation that contained a basic introduction to wave propagation. This module should explain the red/blue colorized cross-sectional mode profiles. The SMEs also concluded that an orienting depiction of light propagation through free space would provide a helpful contrast to subsequent simulations showing propagation through a rectangular waveguide. In addition, the design and development team decided to include a tutorial sequence for every simulation to orient the user to each GUI element.

Phase 2 – Photonics expert feedback and review

Following student feedback from Phase 1, the learning sciences team observed photonics faculty and experts in the field who attended an MIT blended learning bootcamp. Only selected sessions which included the simulations were observed. In these sessions, bootcamp participants engaged with a series of photonics simulations. No formal data collection was conducted; however, the research team gathered feedback from participants after their simulation experiences.

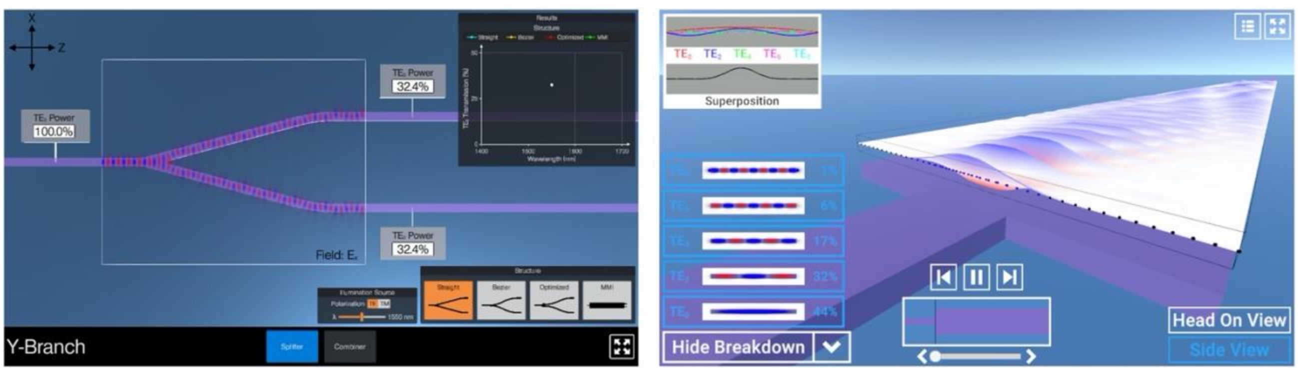

Figure 5. First iteration of the (left) Y-branch Splitter/Combiner, and initial prototype of the (right) Multimode Interferometer MMI simulation.

Observations: When exploring the simulations, bootcamp participants tended to use the plane view rather than the line or point view of wave propagation. Additionally, they articulated additional questions about waveguide behavior as they engaged in the simulations. They expressed lack of understanding of the following areas: 1) Definition of effective index and its relationship to refractive index; 2) Mode coupling from one device to another, and distinguishing between coupling into a standard taper and an inverse tapered structure for edge coupling (in this case, participants articulated a specific misconception around the method of coupling—that inverse tapers are relying on expanding the mode into the cladding, while regular tapers are making the core dimensions larger); and 3) Explanation of device behavior when mode theory was more appropriate than a ray optics interpretation, specifically with the Y-branch splitter/combiner shown in Figure 5 (left), Multimode Interferometer (MMI) shown in Figure 5 (right), and ring resonator (not shown); for instance, many could not explain a 50% drop in power when only one input path is excited in a Y-combiner, as this requires understanding of modal interference.

Actions: Further discussion of bootcamp observations led to a move away from using all three views of electric field profiles (point, line, and plane) in each waveguide simulation. Developers made the decision to rely on a linear "free space" simulation at the beginning of the module and added camera controls and additional animations/illustrations shown in Figure 6 below to orient learners to the wave properties of the light in the direction of propagation. From suggestions from the bootcamp attendees, the developers made significant changes to the simulations which featured more advanced photonic circuit component, including the Directional Coupler, MMI, and Y-branch simulations, including updated UI and additional visualizations to make the circuit components more intuitive.

Phase 3 – Testing new introductory simulations with students enrolled in a 2-year optics program

Based on a strong need for additional introductory content, the development team created a new "back-to-basics" introduction to waveguides, the Waveguide Mode Explorer (WME) module shown in Figure 6. The WME module included an introductory free space simulation, as well as videos and simulations that depicted the x, y, and z components of the fundamental waveguide modes for each polarization (TE_0 and TM_0). The intended learning outcomes for this module were retained from the earlier version. As part of the development process, two SMEs participated in think aloud sessions in which they engaged with module simulations in their current stage of development. During the sessions, they articulated the various ideas and concepts that the simulations were designed to illustrate.

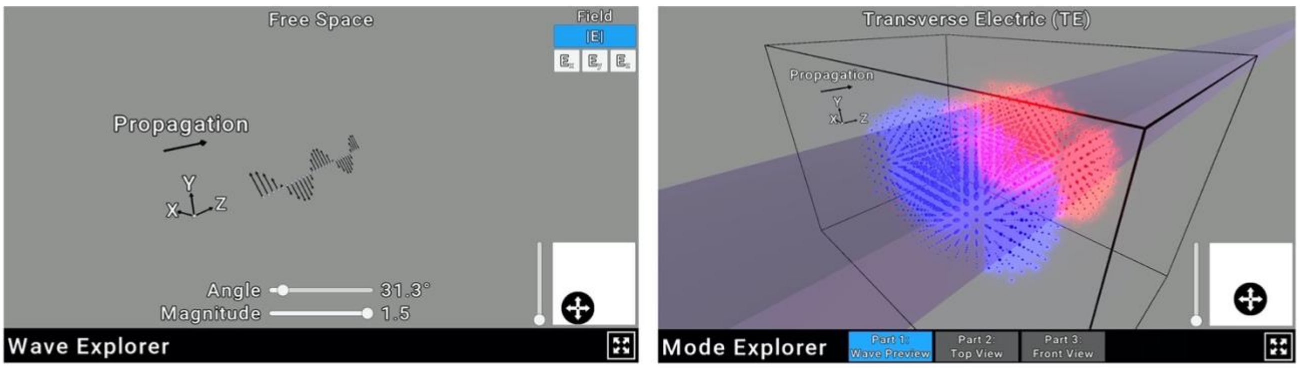

Figure 6. Prototype of Waveguide Mode Explorer simulation sequence with: (left) an introduction to free space EM wave propagation, and (right) new 3D visualizations for guided modes in a dielectric waveguide.

Participants: The second formal playtest was conducted with 15 students from a technical community college in Massachusetts. All students were enrolled in the community college's Optics and Photonics Program, which focuses on the fundamental properties of light and using those properties in practical applications. The playtest was included as part of a field trip to MIT to learn more about photonics work currently being conducted at MIT.

Procedure: After signing a consent to participate in the study, participants completed a pretest. They used an identification number on their pre- and posttest, also used to log into the simulations. They then heard a brief introduction to integrated photonics and its applications and were subsequently introduced to three simulations in the WME module: Free Space Optics, Transverse Electric (TE) Guided Modes, and Transverse Magnetic (TM) Guided Modes. They were allocated approximately 20 minutes to complete each simulation and answer assessment questions they 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.

Instruments: The SMEs developed 13 assessment questions associated with the introductory material and simulations. These questions were designed to help participants focus on important concepts of the experience, and participants were asked to respond to the assessment questions during their interaction with the simulation. The pre- and posttest contained five identical questions and a sixth question was included on the posttest to assess participants' understanding of electric field components. The pre- and posttest was designed to measure the learning outcomes of the WME module. The post experience survey contained four items that asked participants to reflect on their learning from the experience, and to describe any difficulties they had with the simulations.

Data Analysis and Results: Analysis of the pre- and posttest scores showed only small gains in participants' understanding of integrated photonics concepts. The mean score for the pre-test was 41%, whereas the mean score for the same five questions on the posttest was 45%, and 46% when scores for the additional sixth question were added. The normalized gain for questions 1 - 5 ranged from -2.00 to .40, with a mean <g> = -0.06. The negative gain score occurred for a participant that did not have a laptop during the experience; however, this does not explain why that individual answered several questions correctly on the pretest and either omitted them or answered incorrectly on the posttest. As evidenced by the number of participants who answered incorrectly, some test items pointed to areas in which participants' understanding of the concepts did not change after engaging with the simulations. When asked to draw a sketch of light traveling down a fiber or silicon waveguide (question 3), one participant correctly drew a modal view on both the pre- and posttest, whereas the remaining participants continued to draw the ray optics view on the posttest as they had done on the pretest. Identification of a valid guided mode (question 4) continued to be problematic from pre- to posttest, as only 3 of the 15 participants recognized a mode profile in which the electric field was totally confined within the core as being a valid guided mode. A greater number of participants (11) correctly identified a valid guided mode when the electric field was less confined to the core, but 5 of those participants were either unable to explain their reasoning or described light as 'escaping' or 'being lost' when it was outside of the core. Participants also had difficulty depicting the electric field in TE and TM polarizations (question 5); only 4 of the 15 participants drew the TE electric field correctly, and 3 participants were able to correctly depict the TM electric field.

Actions: After analysis of data and synthesis of results, the team determined that undergraduate students and early graduate students would be a more appropriate target group for information at this level of detail. Within our 2-year student sample, participants did not have the prerequisite knowledge about E required to benefit from the WME module.

Important Takeaways: Many 2-year students demonstrated a misconception regarding loss of energy in a waveguide. While these students were familiar with the concept of total internal reflection in the context of fiber optics, they were very confused when presented with a waveguide mode profile which showed an evanescent electromagnetic field extending into the cladding material. Many students, holding to a ray optics interpretation of total internal reflection, described this as loss, with light escaping from the core into the cladding. In reality, this evanescent field is part of the guided mode. We then decided to make this evanescent field misconception an object for further study in Phase 4.

Phase 4 – Final "think-aloud" formative research study with undergraduate and early graduate students

Having identified the correct education level which would most benefit from these simulations (undergraduate and early graduate engineering students), the development team assembled the five-part Waveguide Mode Explorer simulation sequence (Figure 7) into a full online learning module with videos and exercises. One of the learning sciences research team members then conducted a Phase 4 "think-aloud" study to test the full module with the target audience and make final recommendations for changes to the simulations, videos, and exercises.

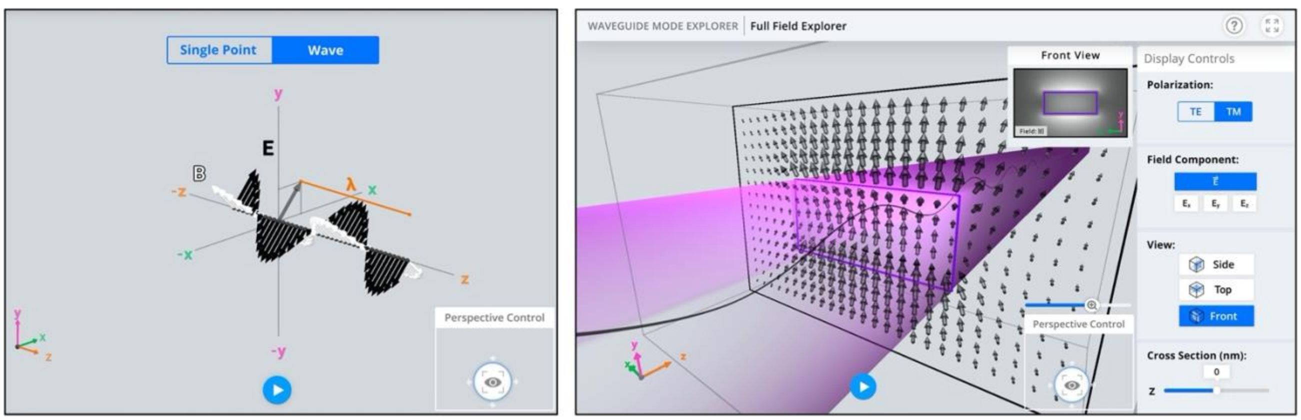

Figure 7. Final version of the Waveguide Mode Explorer simulation sequence with (left) introduction to free space EM field point/wave view, followed by (right) four planar vector field component breakdowns for a dielectric waveguide.

Participants: The sample was composed of 22 volunteer student participants recruited from university engineering programs in the southwestern, southern, and northeastern United States. Eight participants were female and 14 were male. Ten of the participants were graduate students, and the remaining 12 were in undergraduate programs. All undergraduate participants had taken introductory courses on electricity and magnetism, and most of the graduate student participants were enrolled in PhD programs in Optical Physics or Optical Engineering. After the first two participants demonstrated some confusion during the exercises and assessment, the team reduced the number of embedded assessment items and modified them to improve clarity for the remaining 20 students.

Procedure: University faculty contacts were asked to distribute study recruitment announcements to their undergraduate and graduate students. Students responded to researchers via email, signed a consent for participation, and scheduled a teleconference appointment for a think-aloud session. Sessions were conducted via Zoom and the researchers asked for permission from participants to record audio and the student's screen as they used the simulations. All recordings were anonymized; students did not share their video feed and were not referred to by name during the recorded session. Participants took a pretest, went through the module, and then took a posttest. Pretest and posttest questions were answered either verbally or by using Zoom's annotation tools. Students progressed through the full WME training module including instructional videos, exercises, and interactive simulations. Researchers also collected analytics data of participant activity in each simulation through Unity Analytics.

Instruments: A revised pre- and posttest based on the questions from Phase 3 included five multi-part questions that measured learners' understanding of the following: (1) vector field component breakdown along the x, y, and z axes, (2) interpreting colorized cross-sectional field profiles, (3) ray optics vs. modal analysis perspective, (4) optical loss in a waveguide mode with prominent evanescent fields, and (5) waveguide mode order and polarization. The question about evanescent fields was intended to shed light on the misconception that was observed in Phase 3 and verify the presence of this misconception in an undergraduate and early graduate audience.

Data Analysis and Results: All participants except one showed overall learning gains from pre- to posttest due to the WME module. In general, undergraduates made the most progress on the more basic pre/posttest questions and did not make many gains on more conceptual questions. In the pretest, most of the graduate students were able to give satisfactory answers to items 1 and 2 above, and instead showed larger gains than the undergraduates on the more conceptual questions in items 3 and 4 about modal analysis and optical loss. All students made significant progress identifying waveguide modes by order and polarization. Both graduate and undergraduate students showed signs of the misconception about evanescent fields leading to optical loss, with some students describing the mode profile demonstrating power "leaking" out of the core, the mode "losing some of the field" due to the prominent evanescence.

Actions: Data from the think-aloud study provided the development team with student rationale for their responses to assessment questions as well as their pre- and posttest answers. The development team then made changes to the order and wording of the videos, simulations, and exercises. Additional text descriptions were added to explain the presence of evanescent fields in waveguide modes and highlight the fact that this mode did not inherently lead to optical loss.

3.2 Creating the full library of photonic circuit simulations

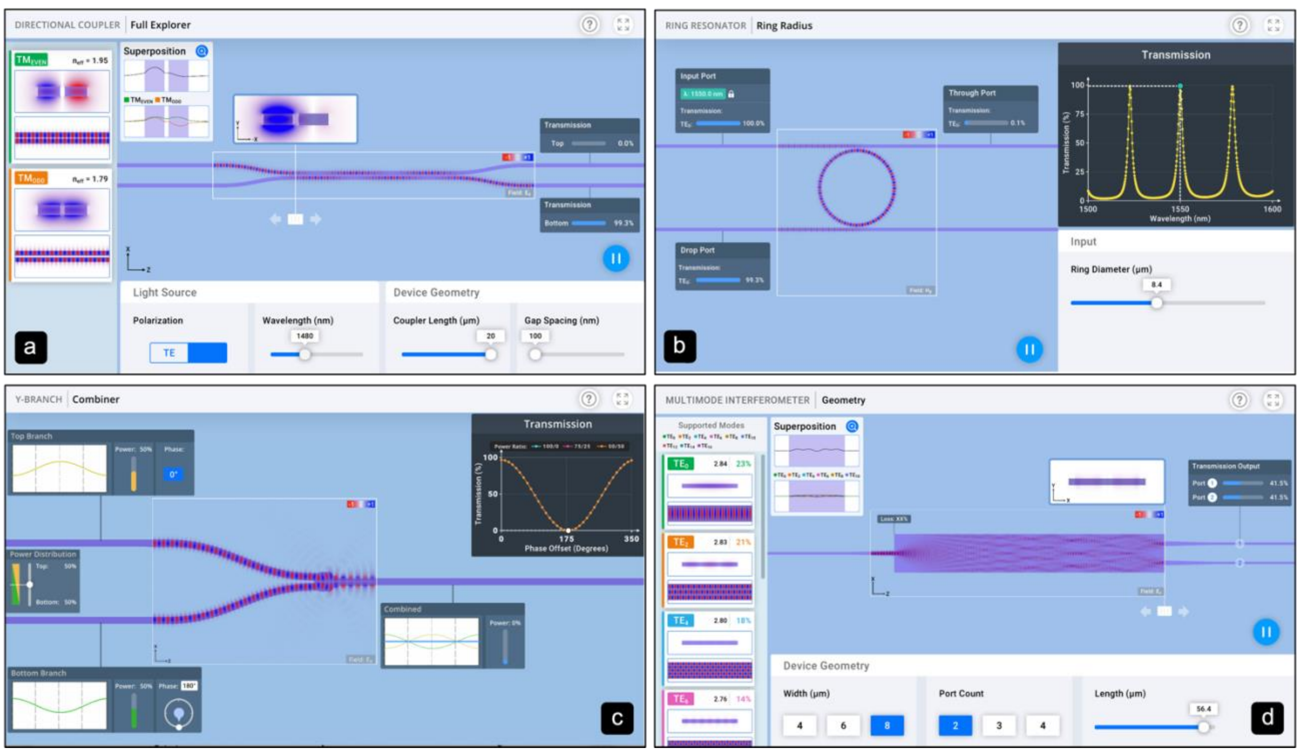

Figure 8. Representative screenshots of the completed simulation sequences for the following photonic circuit components: (a) Directional Coupler, (b) Ring Resonator, (c) Y-branch Splitter/Combiner, and (d) Multimode Interferometer (MMI).

Following feedback and lessons learned from the formative assessment in Phases 1-4, the team finalized the following modules: Waveguide Mode Explorer (Figure 7), Waveguide Fundamentals (Figure 2f), Directional Coupler (Figure 8a), Ring Resonator (Figure 8b), Y-Branch Splitter (Figure 8c), and Multimode Interferometer (Figure 8d).

The team also completed simulation sequences exploring the following photonic circuit components: radial waveguide bends, Mach-Zehnder interferometers, edge and grating couplers, waveguide escalators, 1D Bragg gratings, on-chip photodetectors, waveguide crossings, asymmetrical directional couplers, and polarization splitter/rotators. An optical fiber mode explorer (similar to the 3D vector field profiles in the Waveguide Mode Explorer for cylindrical dielectric waveguides) as well as a desktop training simulation for fiber-to-chip coupling, for both fiber optic and integrated photonic training curricula. All content has been or will be made available in MIT-led online courses and bootcamps.

4. DEPLOYMENT OF PHOTONICS SIMULATIONS

Before releasing the learning modules in massive open online courses (MOOCs) for a global audience, an early release of the direct links to select VM-Lab training simulations on photonic circuit components were made available on the AIM Photonics website, and the simulations were also used in multiple in-person and remote training courses at MIT, the University of Arizona, Clemson University, Stonehill College, and Bridgewater State University. The release of the full modules with instructional videos, simulations, exercises, and photonics learning games are described below.

The flagship offering of this project is the Integrated Photonics Simulation Library 1 (IPSL1) online course shown in Figure 9, first released in February of 2022 with 551 students registered in 2022. This asynchronous course includes five of the introductory modules developed in this work and is offered free of charge to students of all backgrounds interested in an interactive introduction to photonic integrated circuit component behavior and design. The remaining photonics simulations and modules described in Section 3.2 will be released in 2023 and 2024 as part of two sequel MOOC courses Integrated Photonics Simulation Library 2 and 3, which will also be offered on the Open edX platform.

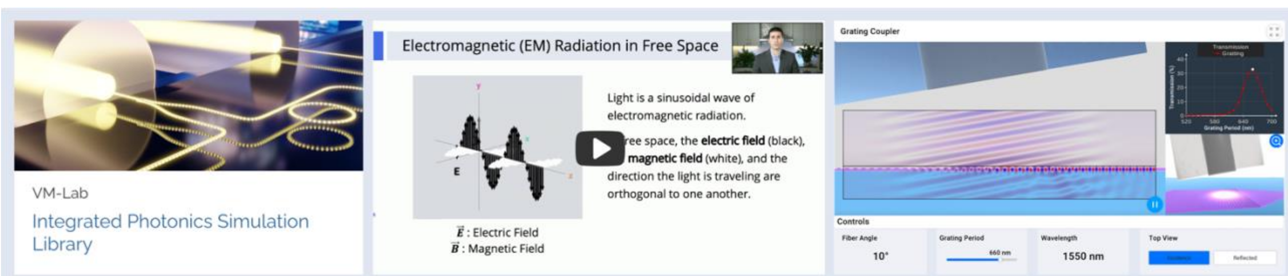

Figure 9. Asynchronous online course offering of Integrated Photonics Simulation Library 1 on Open edX online learning platform BuildYourFuture.us. Lead instructors: Dr. Erik Verlage (MIT) and Dr. Anu Agarwal (MIT).

During this project, select simulations were also featured as part of the Photonic Integrated Circuits 1 (PIC1) online course created by Rochester Institute of Technology (RIT) and MIT to train students to design and simulate a transceiver chip for fabrication at the AIM Photonics facilities in Albany, NY. The PIC1 course was offered in 2019, 2020, 2021, and 2023, which spanned all of the development stages for our photonics simulations. The 2021 PIC1 offering included the final iteration of our photonic simulations had 1,498 auditors, with 56 paying students who completed the rigorous six-week course and submitted a photonic circuit design. Feedback and data from the course are described below.

5. ONLINE COURSE FEEDBACK

During the development of the photonics sims and in parallel with the formative assessment described in Section 3.1 above, each offering of the PIC1 course was used to release a current iteration of select simulations, including Waveguide Mode Explorer and Waveguide Fundamentals. However, the PIC1 course only included an excerpt from our modules, a single stand-alone simulation from each photonic component with 1-2 representative exercises. The course did not include any VM-Lab video content or full simulation sequences.

5.1 Student feedback from Photonic Integrated Circuits 1 advanced online course

The 2021 offering of the PIC1 course included a single "full explorer" simulation from the Waveguide Mode Explorer module with the largest parameter space (right image of Figure 7) which allowed students to explore E_x, E_y, E_z, and $|E|$ for both TE and TM polarizations. The research team embedded a series of survey questions shown in Tables 1-3 below.

Table 1. Survey response from the 2021 Photonic Integrated Circuits 1 online course.

Item (N = 92)	Yes	No
Is this the first time you have seen a dynamic 3D vector representation of the electric field of a waveguide mode?	88%	12%

Of the students who responded to our survey, Table 1 shows a large majority (88%) of students had never seen a 3D vector field representation of a waveguide mode. From our discussions with experts and graduate students, this perspective is seldom shown in static textbooks or as simulation output from commercial photonics simulation software.

Table 2. Survey of student experience during the 2021 Photonic Integrated Circuits 1 online course.

Please respond to the following statements about the Waveguide Mode Explorer simulation					
Item (N = 84)	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
The 3D data visualization in this simulation gave me a new perspective on waveguide modes	6%	1%	11%	43%	39%
I was surprised by the behavior of the electric field in the simulation	8%	13%	27%	31%	21%
I was able to quickly understand how to use the simulation, and was not confused by the user interface	6%	2%	10%	32%	50%
After using this simulation I want to explore additional simulations with dynamic vector fields (e.g. higher-order waveguide modes)	6%	2%	8%	30%	54%
It would be beneficial for all future students of this course to see this simulation	7%	0%	9%	26%	58%

From the survey results in Table 2, 82% of students agreed or strongly agreed that the simulation gave them a new perspective of waveguide modes, and 84% agreed or strongly agreed that they would like to explore similar simulations for higher-order modes (e.g., TE_1, TE_2, TM_1, etc.) and that it would be beneficial for future students to use the Waveguide Mode Explorer simulations. In general, the photonics simulations included in all PIC1 course offerings have been very well received and students are excited to use them.

Table 3. Survey of user satisfaction during the 2021 Photonic Integrated Circuits 1 online course.

How satisfied are you with the following					
Item (N = 85)	**Very Dissatisfied**	**Not Satisfied**	**Neutral**	**Satisfied**	**Very Satisfied**
Quality of the simulation	1%	0%	3%	36%	60%
User interface / ease of use	1%	1%	6%	27%	65%
Simulation load time and browser performance	1%	4%	13%	31%	51%

The development team also included user satisfaction surveys shown in Table 3 to verify ease of use and performance of the simulations. A large majority of users were satisfied or very satisfied with the quality of the simulations.

5.2 Probing student misconceptions through the Photonic Integrated Circuits 1 advanced online course

To further explore the misconception regarding loss of power due to the presence of an evanescent EM field that we observed in our earlier work, we added a revised version of our question to an optional survey in the 2021 PIC1 online course. Even though this course did not directly address photonics theory, we reasoned that it was a difficult course and those who participated would likely have some expertise in the field.

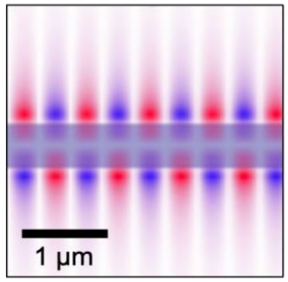

Figure 10. Image provided to the PIC1 course offering as an optional survey question. The core and cladding materials are clearly delineated with a strong evanescent field extending into the cladding.

The visual shown in Figure 10 was provided with a short description and a two-part question so that participants could provide their rationale for each response as shown below.

For light in the guided mode above, if the waveguide continues straight for an additional 100 μm:

1. Will there be any loss of optical power in the silicon core? Why or why not?
2. Will there be any loss of optical power in the oxide cladding? Why or why not?

Of the 41 students in this advanced photonics course who responded to the questions, 39% responded incorrectly, stating ‘yes’ that power would be lost. The rationale provided for the two questions revealed their thinking about evanescent fields. Their responses included statements such as “There are evanescent leakage fields;” “There is a field in the oxide cladding, therefore the field in the waveguide has lost power compared to the input;” and “Cladding radiates light (not guides), leading to radiative modes.” This provided additional evidence to support the presence of this misconception, even in an audience that was likely to have prior knowledge in photonics and were taking a rigorous online course. All module materials were subsequently revised to emphasize information about evanescent fields and power loss.

6. ONLINE COURSE SUMMATIVE RESEARCH STUDY

During the final year of the project, the basic Waveguide Mode Explorer module (Figure 7) was re-designated as Module 1 for the 2022 introductory online course Integrated Photonics Simulation Library 1 shown in Figure 9 and described in Section 4 above. Our team was interested in how students would use the Waveguide Mode Explorer interactive simulations, and if we could verify our findings from the formative studies described in Section 3.1 (Phases 1-4) at scale.

We refined the embedded assessment items for the rebranded Module 1, and in collaboration with the learning sciences and development teams, we utilized incorrect responses to questions from the Phase 4 “think-aloud” study as plausible distractors for the multiple-choice assessment questions embedded in Module 1. In the IPSL1 course, Module 2 was composed of the simulations from the Waveguide Fundamentals module (Figure 2e), updated and improved since the Phase 1 study, covering the following topics: core and cladding material selection, waveguide geometry, higher-order modes for TE and TM polarizations (e.g., TE_1, TE_2, TM_1), simultaneous excitation of modes, and waveguide interfaces.

The learning sciences research team worked in collaboration with the software development team to develop the pipeline for data collection from the course after it was deployed on the new Open edX platform. We developed visuals that would be informative as to the breadth of the parameter space students explored in the sims, as well as data records that tracked numeric values for each of the desired parameters, e.g., total parameter space explored for TE_0 and TM_0 waveguide modes, parameter space explored in each vector, and parameter space explored in each vector component in each of the three views (top, side, and front). In collaboration with the project evaluator, we developed surveys that would provide data critical for understanding how diversity in course enrollees influenced their behaviors during the course.

Our primary research questions for study of the data resulting from this course were as follows:

Utilization of Simulations
RQ1: How do learners explore the simulations?
RQ2: How does prior experience in optics/photonics influence learners' exploration of the sims?
RQ3: How does level of education influence learners' exploration of the sims?
RQ4: How does plan for engagement with the course influence learners' exploration of the sims?

Benefit of exploring simulations
RQ5: Do learners who explore sims perform better on assessment questions?
RQ6: Do learners who explore sims perform better on assessment questions that measure conceptual understanding?

Data sources: We collected data from the asynchronous IPSL1 online course, accessible to a global audience of students, from February 1st to August 31st, 2022, during which 438 students registered for the course and 47 students completed all five modules with a high enough score to earn an AIM Photonics certificate of completion. For these analyses, we utilized data from learners who explored the Module 1 simulations (N=99) and/ or answered assessment questions (Module 1, N=155; Module 2, N=90), along with data from those who completed the course pre-survey (N=155). When the data were merged, the total sample contained 417 learners with some combination of data from the three above-named sources. Sixty-eight learners provided data from all three sources. We obtained the pre-survey data from the Qualtrics survey platform; we obtained the simulation data from an Amazon Web Service server configured by the development team; and we retrieved the embedded assessment responses from the course platform developed by IBL that utilized Open edX code.

Procedure: The three data sets described above were cleaned and merged to arrive at the final sample. Duplicate identification numbers were also removed, as some learners utilized multiple accounts as they engaged with the course. In these cases, we retained the account containing the greatest amount of data. Descriptive statistics were conducted and prior to analysis, extreme outliers were removed from the total time spent exploring each mode. Extreme outliers were determined by calculating the upper and lower bounds with the formula: 3rd quartile + 3.0*interquartile range. The lower bound was not utilized in this case, to allow data from those who did not engage with the simulations at all to be included in the analyses. As the distribution of data remained non-normal after removal of outliers, we utilized non-parametric tests for all analyses.

RQ1: How do learners explore the simulations?

To answer this question, we examined the time spent exploring the simulations, along with the extent of exploration in terms of percentage of possible area explored. Each simulation provided options for exploration of three views (top, side, front) for all field components (|E|, E_x, E_y, E_z) for the TE_0 and TM_0 fundamental modes of both polarizations. Table 4 shows a summary of the descriptive statistics for the primary variable of interest regarding exploration of the simulations, and Table 5 displays the measures of central tendency.

Table 4. Descriptive statistics for time spent and area explored in the simulations of Module 1: Waveguide Mode Explorer.

Variable	**N**	**Min**	**Max**	**M**	**SE**	**SD**	**Var**	**Skew**	**Kurtosis**
TE_0 Total Time (Minutes)	91	0	55.53	11.84	1.19	11.32	128.05	1.87	3.95
TE_0 % Visited	99	0	68.18	9.45	0.99	9.9	97.96	2.64	11.84
TM_0 Total Time (Minutes)	93	0	14.57	3.86	0.36	3.51	12.34	1.22	1.28
TM_0 % Visited	99	0	27.73	6.19	0.6	6.01	36.15	1.44	2.18

Table 5. Measures of central tendency for time spent and area explored in Module 1: Waveguide Mode Explorer.

Item		**TE_0 % Visited**	**TE_0 Total Time (Minutes)**	**TM_0 % Visited**	**TM_0 Total Time (Minutes)**
N	Valid	99	91	99	93
	Missing	318	326	318	324
Mean		9.45	11.84	6.19	3.86
Median		6.36	9.25	3.64	3.23
Mode		0.00	0.00	0.00	0.00
Percentiles	25	3.64	5.09	1.82	1.37
	50	6.36	9.25	3.64	3.23
	75	14.55	14.36	9.55	5.38

The distribution of time spent exploring each mode and extent of exploration (% visited) is shown in Figures 11-12 below.

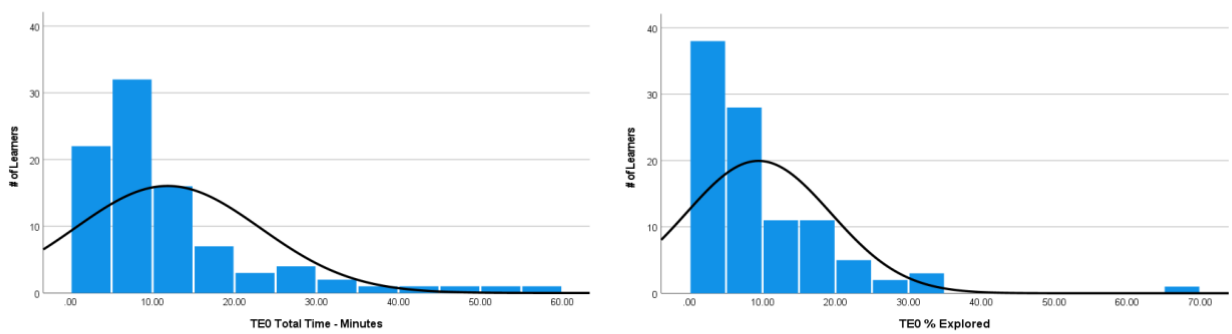

Figure 11. Results for (left) total time spent for exploration of TE_0, and (right) percent of total area explored for TE_0.

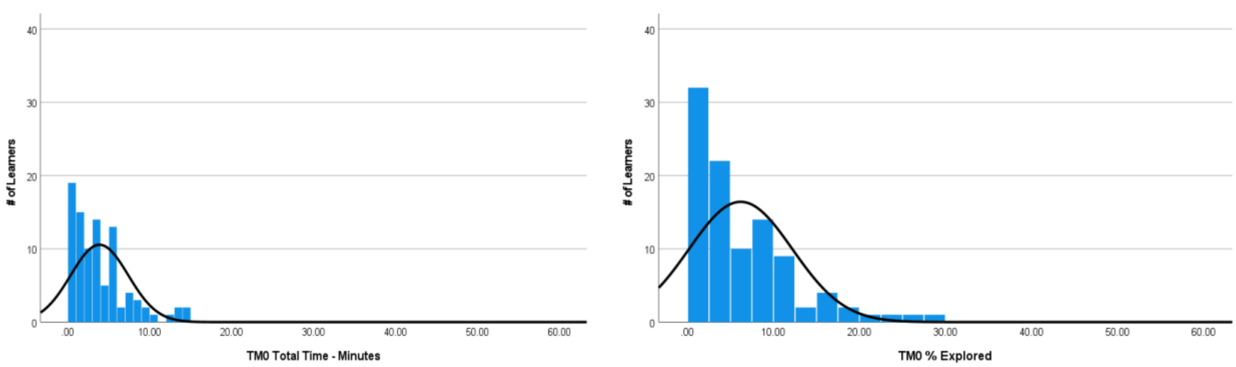

Figure 12. Results for (left) total time spent for exploration of TM_0, and (right) percent of total area explored for TM_0.

As shown in the figures, learners spent, on average, more time and explored more areas within the TE_0 mode than the TM_0 mode. This pattern persisted with all views of all components. In both the TE and TM modes, all components of the front view were explored to a greater extent than the other views.

RQ2: How does prior experience in optics/photonics influence learners' exploration of the sims?

We were interested in whether learners with more prior experience with optics or photonics would engage more with the simulations, or if those with less experience may be more inclined to explore. To answer this question, we utilized data obtained from the course pre-survey in addition to simulation data ($N = 68$). Learners responded to the question 'How long have you worked in the field of optics or photonics?' in one of five categories–less than 4 years, 4-6 years, 7-10 years, more than 10 years, or not currently employed in this field. With learner's prior experience as the independent variable and either time spent or percent of area explored as the dependent variable, we conducted an Independent Samples Kruskal-Wallis 1-way ANOVA to determine if the distributions of time or percent of areas explored differed significantly by learners' prior experience. There were no statistically significant differences between years of experience categories for their time spent exploring TE_0 ($p = 0.482$), or the percent of TE_0 area explored ($p = 0.284$). Similarly, there were no significant differences between the groups for time spent exploring TM_0 ($p = 0.436$) or the percent of TM_0 area explored ($p = 0.356$).

RQ3: How does level of education influence learners' exploration of the sims?

We were interested in whether learners' education level would be related to the way in which they used the simulations, both in the time spent and the total amount of the simulation parameter space they explored. Learners' highest level of education was recorded in nine categories in the course pre-survey–have not completed high school, high school/GED, some college, 2-Year college degree, 4-year college degree, master's degree, doctoral degree, professional degree (JD/MD), or prefer not to say. With learners' highest level of education as the independent variable, and either time spent or percent of area explored as the dependent variable, we conducted a Kruskal-Wallis 1-way ANOVA to determine if the distributions of time or percent of areas explored differed significantly by learners' highest level of education. In all four analyses, the null hypothesis was retained. Surprisingly, we found no statistically significant differences between the categories related to the highest level of education for their time spent exploring TE_0 ($p = 0.259$), or the percent of TE_0 area explored ($p = 0.837$). Similarly, there were no significant differences between the groups for time spent exploring TM_0 ($p = 0.721$) or the percent of TM_0 area explored ($p = 0.252$).

RQ4: How does plan for engagement with the course influence learners' exploration of the sims?

In line with prior research on MOOCs,[20,21] we hypothesized that learners' goals, or plan for engaging with the course may have influenced their utilization of the simulations while learning course material. Accordingly, we utilized learner responses grouped in the four categories of 'I plan to browse the material, but am not planning to complete any course activities (watch videos, read text, answer problems, etc); I plan to complete some course activities; I plan to complete the entire course; or I have not decided if I will complete any course activities' as the independent variable and either time spent or percent of area explored as the dependent variable. The Kruskal-Wallis test results showed that again the null hypothesis could be retained. There were no statistically significant differences in the distributions between their plan for engaging with the course and their time spent exploring TE_0 ($p = 0.511$), or the percent of TE_0 areas explored ($p = 0.652$). Similarly, there were no significant differences between the groups for time spent exploring TM_0 ($p = 0.827$) or the percent of TM_0 area explored ($p = 0.602$).

Procedure: For the research questions RQ5 and RQ6 falling under "benefits of exploring simulations", we utilized learners' attempts and scores for the embedded assessment questions from the course platform in addition to the course pre-survey data and simulation data. For each embedded assessment item, we calculated a score using the points earned divided by number of attempts. For example, if a learner attempted a problem three times before they responded correctly, and one point was awarded for the correct answer, they received a score of ⅓, or .333. This helped to differentiate them from learners who responded correctly on the first attempt, as those students would receive a score of 1/1, or 1.0. In addition to calculating a score for each embedded assessment question, we also calculated the total number of questions attempted for the first two modules in the course.

RQ5: Do learners who explore sims perform better on assessment questions?

In Module 1, 155 learners attempted to answer one or more of the embedded assessment questions; 81 learners attempted all 21 of the questions. For Module 2, 90 learners attempted to answer one or more questions, with 66 of them attempting all 17 of the questions. Three learners attempted questions in Module 2 but did not attempt to answer any questions in Module 1. Descriptive statistics for learners' performance and measures of central tendency for the assessment questions are shown in Tables 6 and 7 below.

Table 6. Descriptive statistics for assessment question attempts and performance.

	N	Min	Max	*M*	*SE*	*SD*	*Var*	Skew	Kurtosis
Total Problems Attempted Module 1	417	0	21	5.62	0.43	8.73	76.24	1.07	-0.75
Total Problems Attempted Module 2	417	0	17	3.24	0.32	6.45	41.56	1.58	0.59
Percent Correct Module 1	155	0	1	0.61	0.03	0.36	0.13	-0.53	-1.39
Percent Correct Module 2	90	0	0.94	0.68	0.02	0.22	0.05	-1.17	0.52
Valid N (listwise)	87	–	–	–	–	–	–	–	–

Table 7. Measures of central tendency for assessment question attempts and performance.

Item		Total Problems Attempted Module 1	Total Problems Attempted Module 2	Percent Correct Module 1	Percent Correct Module 2
N	Valid	417	417	155	90
	Missing	0	0	262	327
Mean		5.62	3.24	0.61	0.68
Median		0	0	0.77	0.78
Mode		0	0	0.95	0.83
Percentiles	25	0	0	0.2	0.55
	50	0	0	0.77	0.78
	75	14.5	0	0.92	0.83

We first explored whether utilizing the simulations was related to the number of assessment questions learners attempted. The results of an Independent-samples Mann-Whitney U test revealed a significant difference in the distributions of assessment question attempts in Module 1 between those who used the simulations and those who did not, $U(N_{\text{with sim}} = 84, N_{\text{without sim}} = 71) = 901.5$, $z = -8.075$, $p < 0.001$. The number of assessment questions attempted by learners who used sims ($Mdn = 21$) was higher than for those who did not use sims ($Mdn = 5.50$). Figure 13 (left) compares the two distributions for Module 1. We then examined simulation usage in relation to learners' overall performance on the assessment questions. Again, the Mann-Whitney U test revealed a significant difference in the distributions of learner performance for the Module 1 assessment questions between those who used the simulations and those who did not, $U(N_{\text{with sim}} = 84, N_{\text{without sim}} = 71) = 933.5$, $z = -7.359$, $p < 0.001$. The percent correct for learners who used sims ($Mdn = 88.5$) was higher than for those who did not use sims ($Mdn = 20.0$). Figure 13 (right) compares the two distributions for Module 1.

We conducted the same tests for Module 2. The Mann-Whitney U test revealed a significant difference in the distributions for the number of Module 2 assessment questions that learners attempted to answer between those who used the simulations and those who did not, $U(N_{\text{with sim}} = 67, N_{\text{without sim}} = 23) = 590.5$, $z = -2.140$, $p = 0.032$. The number of questions attempted by learners who used sims ($Mdn = 17$) was higher than for those who did not use sims ($Mdn = 0$). Figure 14 (left) compares the two distributions for Module 2. When we examined simulation usage in relation to learners' overall performance on Module 2 assessment questions, we did not find the same result as Module 1. The Mann-Whitney U test revealed that the null hypothesis of no difference between the two groups could be retained in this case, $U(N_{\text{with sim}} = 67, N_{\text{without sim}} = 23) = 669.5$, $z = -0.935$, $p = 0.350$. For Module 2 assessment questions, the percent correct for learners who used sims ($Mdn = 78.9$) was not significantly higher than for those who did not use sims ($Mdn = 72.2$). Figure 14 (right) compares the two distributions for Module 2.

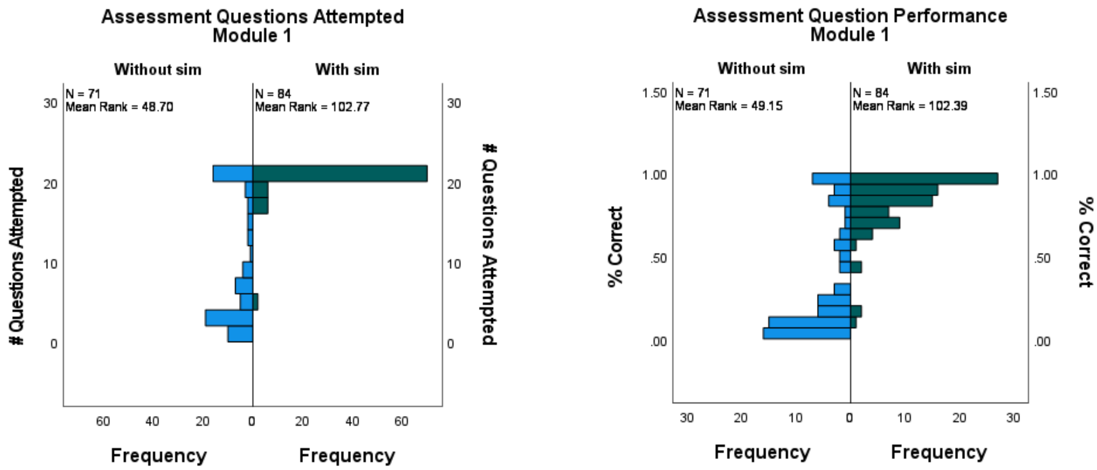

Figure 13. Distribution of (left) assessment question attempts and (right) total scores for Module 1 – without/with sim use.

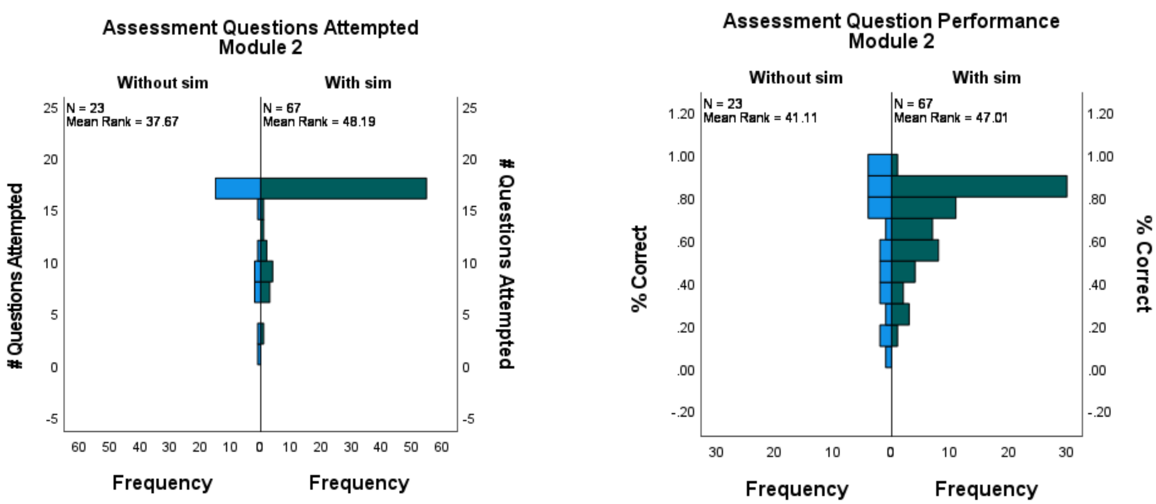

Figure 14. Distribution of (left) assessment question attempts and (right) total scores for Module 2 – without/with sim use.

We then examined simulation usage in relation to whether learners responded correctly on their first attempt. We considered responding correctly on the first attempt as indicative of better understanding of the course material and hypothesized that learners who utilized the simulations would have a greater proportion of correct answers on their first attempt. To test this hypothesis, we categorized learners into three groups based on their number of responses to each assessment question: 1) did not answer the question at all; 2) answered correctly on the first attempt; and 3) attempted to answer multiple times before getting the answer correct. Learners who did not answer correctly were also placed in the third category.

When looking at the number of questions answered correctly on the first attempt, the Mann-Whitney U test revealed that there was a significant difference between distributions of learners who utilized the simulations and those who did not, and thus we could reject the null hypothesis of no difference, U($N$with sim = 84, Nwithout sim = 71) = 970.0, $z = -7.243$, $p < 0.001$. For Module 1 assessment questions, the number of questions answered correctly on the first attempt for learners who used sims ($Mdn = 16.5$) was significantly higher than for those who did not use sims ($Mdn = 4.0$). Figure 15 (left) compares the two distributions for Module 1.

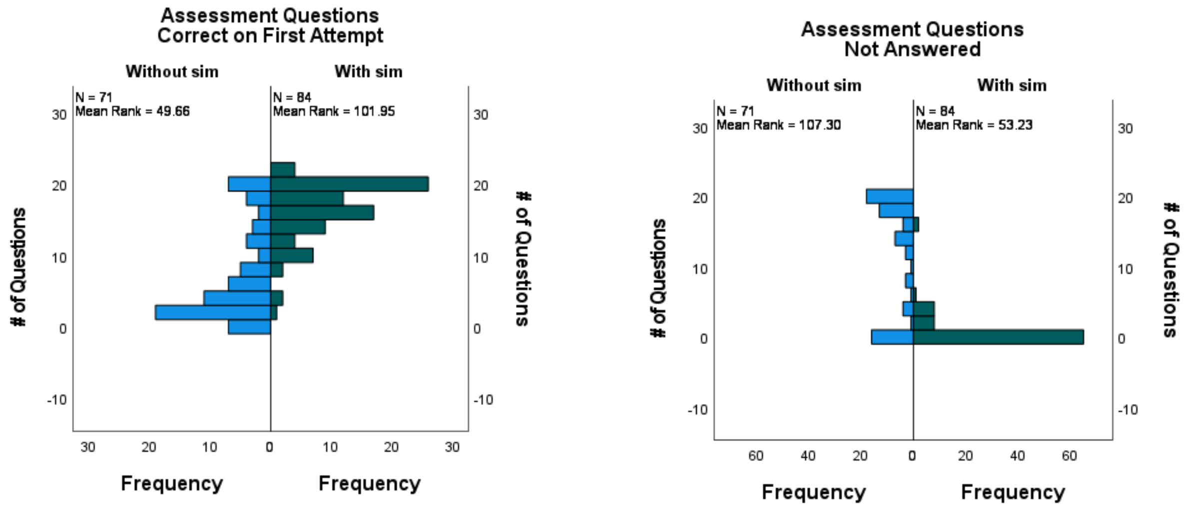

Figure 15. Results for (left) number of questions correctly answered on first attempt and (right) not answered for Module 1 – without/with sim use.

We also examined the number of questions learners did not answer at all and compared the numbers between those who utilized the simulations and those who did not. The Mann-Whitney U test revealed that again, there was a significant difference between distributions of learners who utilized the simulations and those who did not, and thus we could reject the null hypothesis of no difference, $U(N_{\text{with sim}} = 84, N_{\text{without sim}} = 71) = 901.5$, $z = -8.075$, $p < 0.001$. For Module 1 assessment questions, the number of questions that were not answered at all was significantly greater for learners who did not utilize the sims (*Mdn* = 14.0) than for those who did use sims (*Mdn* = 0). Figure 15 (right) compares the two distributions for Module 1.

These same results and patterns persisted for Module 2. For Module 2 assessment questions, the number of questions answered correctly on the first attempt was significantly higher for learners who used sims (*Mdn* = 10.5) than for those who did not use sims (*Mdn* = 0). Similarly, the number of questions that were not answered at all was significantly greater for learners who did not utilize the sims (*Mdn* = 17.0) than for those who did use sims (*Mdn* = 0).

<u>RQ6: Do learners who explore sims perform better on assessment questions that measure conceptual understanding?</u>

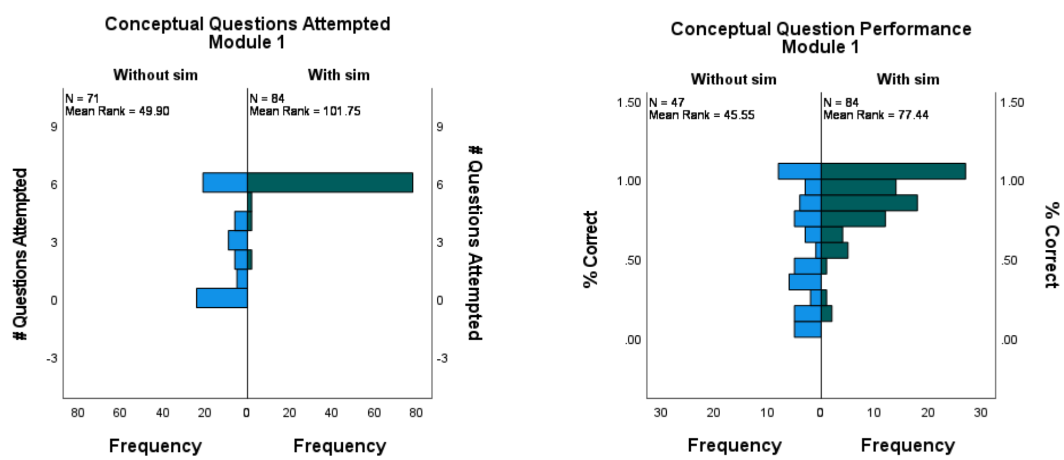

Figure 16. Distribution of (left) conceptual question attempts and (right) performance for Module 1 – without/with sim use.

Lastly, we examined simulation usage with regards to the number of attempts and performance on six conceptual questions present in Module 1. These questions required a deeper understanding of the course material, and we hypothesized that exploring the simulations would increase learners' performance. Here again, results of the Mann-Whitney U test revealed a significant difference in the distributions of learner attempts as well as performance for Module 1 conceptual questions between those who used the simulations and those who did not, $U(N_{\text{with sim}} = 84, N_{\text{without sim}} = 71) = 987.0$, $z = -8.356$, $p < 0.001$ and $U(N_{\text{with sim}} = 84, N_{\text{without sim}} = 71) = 1013.0$, $z = -4.661$, $p < 0.001$ for attempts and performance respectively. The number of attempts (*Mdn* = 6) and percent correct (*Mdn* = 88.8) for learners who used sims was higher than the number of attempts (*Mdn* = 2) or percent correct (*Mdn* = 50.0) for those who did not use sims. Figure 16 compares the two distributions for Module 1.

Upon examination of these results, a key question to be answered was why some learners attempted a significant number of questions and scored well without viewing the simulations available to them.

We utilized the learner information from the pre-course survey to answer this question. There were 16 learners who scored 70% or higher on Module 1 assessment questions without engaging with the simulations. A review of their demographics from the pre-course survey revealed that only 4 of them completed the pre-course survey. Three of the four learners were current graduate students enrolled in master's or doctoral programs, and one of those graduate students was also employed in the field of Optics or Photonics for 4-6 years. The fourth learner held a doctoral degree, but was not affiliated with any education program, and was not employed in the field. These learners also had a high proportion of questions answered correctly on the first attempt. Although we do not know the learners' master's or doctoral field of study, the demographic information suggests that for these four learners, prior knowledge of the field may have increased their success in the course.

Another possibility for the reduced use of simulations is that learners may have depended solely on the course videos for information to answer the assessment questions. A review of the videos in the course segments that contained simulations revealed that for each of the four simulations in the module, the associated video also showed the simulations (time ranging from 29 seconds to 1 minute, 9 seconds) as the instructor explained the salient points that should be observed. Thus, the video introduction to the simulations could have served to aid some learners as they answered the assessment questions.

7. CONCLUSIONS

The interactive simulations and games created by the Virtual Manufacturing Lab can help to rapidly train a photonics workforce through online courses and blended learning bootcamps. By leaning on the many advantages of digital learning, including massive reach, interactive training environments, and dynamic visualizations to help students build intuition, the VM-Lab learning modules have been widely distributed as stand-alone offerings and can also be used by instructors to enhance undergraduate and graduate photonics training programs.

The multi-phase learning science research we have described yielded many key insights which guided the design of the VM-Lab simulations. For novice students with a shaky background in electromagnetism, a detailed introduction to x, y, and z field components and the interpretation of colorized field component profiles is vital. Misconceptions around evanescent fields for waveguide modes are widespread even in advanced audiences, as is the incorrect application of ray optics intuition. Students of all backgrounds have a very hard time letting go of the ray optics perspective of light when thinking about total internal reflection and guided modes. Instructors should emphasize modal analysis derived from first principles as early as possible in undergraduate and graduate photonics programs. When learning about the detailed workings of photonic circuit components (like directional couplers, Y-branch splitters, and multimode interferometers) it is important to help students transition to a wave perspective and envision the evolution and excitation of guided modes with changing waveguide geometries. In-browser tools with interactive graphs, dynamic 2D and 3D visualizations, rapid exploration of waveguide parameters through expert-vetted results, and gaming elements can decrease cognitive load and help students build intuition for photonic integrated circuits. Many of these techniques used to create digital training for integrated photonics can easily be adapted to many other technologies and applications.

ACKNOWLEDGEMENTS

This work was supported by the Office of Naval Research (ONR) through the Manufacturing Engineering Education Program (MEEP), award number N00014-19-1-2753.

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