

Web-based interactive simulations and virtual lab for photonics education

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ABSTRACT

There is large industry demand for qualified engineers and technicians in photonics advanced manufacturing. Current workforce training methods require expensive state-of-the-art laboratory equipment, as well as commercial licenses for photonic design software, which can be prohibitively costly for many universities. Virtual laboratories and Massive Open Online Courses (MOOCs) can help fill this training gap by providing a scalable approach to photonics workforce education for an international audience. In this project, AIM Photonics Academy—the education initiative of AIM Photonics, a Manufacturing USA Institute—is creating a virtual laboratory to enable self-directed learning for the emerging photonics workforce. Students learn photonic device and circuit modeling in a 3D online virtual lab environment with interactive simulations of micron-scale photonic visualizations. An intuitive interface highlights the most critical device design parameters and their optimal operational settings for applications in Datacom, wireless communication, sensing, and imaging. Simulations include silicon waveguide propagation and loss, radial waveguide bends, and directional couplers for photonic integrated circuits (PICs). In spring of 2019, AIM Academy has integrated these simulations into an online course focused on PIC-chip design, with a fundamentals course expected in fall of 2019. Additionally, these online tools will be used in a blended learning curriculum in 2020 to train engineers and technicians in semiconductor design, testing and packaging for photonics applications. Following online module completion, students can take blended learning on-site workshops at affiliated university laboratories to capitalize on their simulated training with hands-on experiments in chip design, packaging, and optical or electrical testing.

Keywords: virtual lab, interactive simulation, MOOC, digital learning, blended learning, manufacturing, workforce training

1. INTRODUCTION

1.1 Advanced manufacturing workforce training in integrated photonics

Across the nation, Manufacturing USA (M-USA) institutes are engaged in revitalization programs to enhance American industrial capacity for a 21st century high-tech economy. Several years into these programs, it is apparent that in addition to creating a new technology infrastructure, an equal if not greater challenge will be to develop a modern online workforce education platform to upskill and reskill engineers and technicians. Technology roadmap projections¹ from the AIM Photonics Academy program at MIT have identified a critical need for an online education vehicle that enables upskilling and certification across the integrated photonics manufacturing workforce.

AIM Academy develops education tools and provides workforce development for technologies that are still emerging, where few learning tools already exist. The market for silicon photonics is projected to reach \$2 billion in 2023, growing at a rate of more than 20% per year.² This corresponds to a large increase in workforce needs for both engineers and technicians with specialized skills in integrated photonics design, testing, assembly, and packaging. These technologies are highly relevant to the US Department of Defense, and used in applications such as data communications, LiDAR, sensors, and high-speed wireless communication. AIM Academy has closely collaborated on education initiatives with industry and community college partners to create a network of training laboratories across the state of Massachusetts, and is developing a technician training curriculum for photonics and robotics in collaboration with the Advanced Robotics Manufacturing (ARM) institute, finding common training needs across the M-USA institutes.

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1.2 Digital learning for workforce education

Online digital learning would enable ongoing upskilling that can flexibly train this new workforce, enabling remote learning that conforms to the student's schedule. A self-directed, autonomous pedagogy is a powerful tool for creating distributed, open, sustainable, scalable, and readily available learning environments that can meet these workforce demands.³⁻⁶ Effective online learning must not only digitize and distribute existing curriculum, but increase motivation and engagement through active learning, allowing student autonomy to choose between learning styles, pathways, and timelines.⁷ Online learning can also help to create a robust and varied learning experience that facilitates interaction between instructors and students of diverse skills and backgrounds.⁸

1.3 Web-based interactive simulations

Interactive simulations and virtual laboratories in 2D and 3D environments have been very effectively deployed in K-12 and higher learning STEM education.⁹⁻¹¹ When combined with digital/blended learning, interactive simulations can play a large role in the scalability and sustainability of photonics training for both engineers and technicians. A key advantage when using interactive simulations is the ability to actively engage the user through a series of guided self-paced modules. In constructivist learning theories, learning occurs when students are actively involved in the process of knowledge construction as opposed to passively receiving information through classroom or video lectures. Interactive simulations require the user to be constantly engaged with the material by promoting exploration and experimentation of a system or environment. Scaffolded instruction can be heavily used at first and reduced over time as the student becomes more proficient with the material. Additionally, implicit scaffolding design methodologies can guide the user through unencumbered exploration of a system all while achieving the desired learning outcomes.^{12,13}

Within a simulation, learning experiences are tailored to the student's current level by allowing users to proceed at their own pace, and the digital format offers versatility to easily meet the needs of multiple audiences on the same platform. Users can repeat the experience until they are comfortable with the material, and studies have shown that retention, concentration, and engagement have been positively linked to active learning models during interactive training simulations.^{9,10,14} Elements of game-based learning can be incorporated into simulations to encourage users through achievements, competition, and immersion.^{14,15} Different scenarios can be algorithmically spawned, using procedurally generated content that is unique every time the user runs the simulation.¹⁶ Users can receive real-time feedback on how well they are performing certain tasks and the simulation can guide them on how to improve. The students' performance can easily be logged, monitored, and analyzed by an instructor.^{14,16}

1.4 Coordination with community colleges

In 2018 AIM Academy received federal funding to partner with Bridgewater State University (BSU) and Stonehill College (SC) to create an integrated photonics technician 15-month certificate program, and is collaborating with the state of Massachusetts to stand up a state-wide network of integrated photonics packaging and test Laboratories for Education and Application Prototypes (LEAPs), located at area universities and community colleges. AIM Academy is collaborating closely with its community college and industry partners to perform needs assessment studies to inform educational content.

2. PHOTONICS VIRTUAL LAB DEVELOPMENT

A goal of the AIM Virtual Lab project is to build photonics intuition by addressing pedagogical gaps in current engineering training, which present many unique training challenges. Veterans in the electronics industry with many years of experience in integrated circuit design and manufacturing require rapid retraining to work with photonic circuit components. Meanwhile, rising masters and Ph.D. researchers would benefit from introductory overview material for photonic circuit design.

A problem area for this target audience that is widespread in current training practices is to simultaneously learn about the fundamental behavior of photonic circuit components while running advanced photonic simulations using powerful and complex optical simulation software tools. When introduced to new photonic devices, students will often be required to run parameter sweeps to explore the fundamental behavior of the device, but become lost in troubleshooting advanced electronic/photonic design automation (EPDA) software. Even if a student-created simulation runs smoothly with few errors and few artifacts in device behavior, there is often a significant delay between the initial question and an answer, with most of that time spent setting up a simulation (e.g. defining structures, adjusting materials properties, selecting mesh sizes and boundary conditions, programming parameter sweeps, etc.). For computationally-intensive simulations

(e.g. finite-difference time-domain) a parameter sweep could take hours or even days to complete. In addition to this delay in learning, there is a significant cognitive overload inherent in switching between the tasks of analyzing complex device behavior and struggling to program optical simulations (usually due to complex software UI). In order to isolate the learning goals of understanding physics fundamentals and learning to use commercial software tools, students should have access to a library of pre-run and expert-verified simulation results. For this project, pre-run simulation results are presented through a scaffolded approach that covers the most important parameters for each photonic component in isolation. This ensures learners do not get lost in a sea of simulation results, and that learning objectives are met.

Simulations created for an engineering audience could be easily modified to provide a simpler interactive environment for the technician audience, where appropriate. Future simulations covering topics in test, assembly, and packaging (TAP) would also be ideal for training technicians for equipment use and fab floor activities (e.g. fiber coupling).

2.1 Platform selection

In order to simultaneously meet the needs of both engineering and technician audiences, we selected Unity3D, a popular engine and development platform for commercial entertainment games and interactive simulations, to create micron-scale 3D simulations of each photonic component. This choice allows maximum flexibility for export to the web, desktop, and iOS/Android apps, and leverages *Unity Analytics*, a powerful and versatile data collection system.

2.2 Data integration process

The continuous wave (CW) data integration process used in the AIM Virtual Lab is illustrated in Figure 1. Data is obtained from simulations using high-performance nanophotonic simulation software from Synopsys RSoft suite and/or Lumerical Finite Difference Eigenmode (FDE) / Finite-Difference Time-Domain (FDTD) Solutions. Individual numerical results are stored in a .json array together with the indexing parameter. Together, these are used to generate the graphs and other values displayed as the user varies each parameter. To generate a data-driven animation, an array of the index of refraction and the electric field components are extracted and stored in image files. Both the real and imaginary components of the electric field are used as images, and the set phase offset allows them to be combined within a graphical shader to exhibit the expected oscillatory behavior. The material geometry image shows the index of refraction in the region of interest, and combined with the electric field creates an accurate animation of the continuous wave response of the structure.

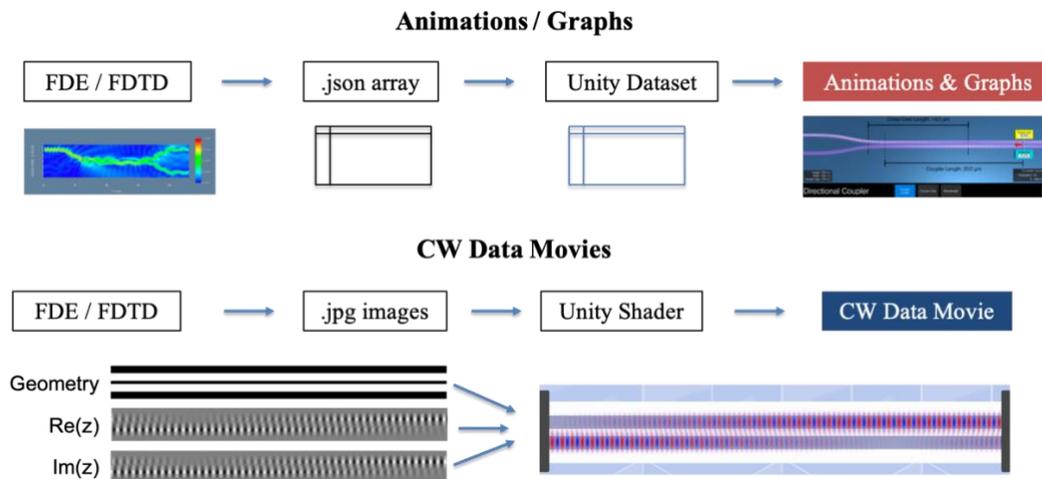


Figure 1. Data integration process between photonic device simulation results (using Lumerical FDE/FDTD Solutions and Synopsys RSoft) and the Unity engine. For world-space animations overlaid on 3D models, data was saved within .json arrays, while single wavelength continuous wave (CW) results are saved as images and reconfigured in a Unity shader to make use of image compression for fast file transfer.

More information about creating a CW movie and the data integration process used in the Virtual Lab can be found on the Lumerical FDTD Solutions website.¹⁷

2.3 User testing and iterative development

The AIM Virtual Lab went through several iterations with usability testing and feedback from photonics subject matter experts, as can be seen in Figure 2. A series of tabs guide the user to advance through each of the learning objectives for the simulation. On each tab, user-friendly handles or sliding bars enable exploration of a carefully-selected parameter space, with the user adjusting only the most important parameters for each photonic component and observing device behavior. This provides key advantages to the student: (i) direct access to important device behavior by sweeping important parameters with no delay time; (ii) the user can trust expert-vetted results appearing on screen without worrying about runtime errors or artifacts; (iii) a simple user interface eliminates time spent learning complex software, allowing the user to stay on-task, observing the underlying photonic behavior and building photonic intuition. (Note: for design engineers, experience using photonic simulation software is an important learning objective to be learned separate from understanding device behavior.)

Future iterations of these simulations will include a sandbox mode for each component that will allow users to explore a larger parameter space. This feature will allow instructors to pose assessment questions within the AIM Virtual Lab environment. One method of student response would be to use the parameter controls to select a device design and submit their parameter configuration, with auto-generated feedback that guides the student to the correct answer.

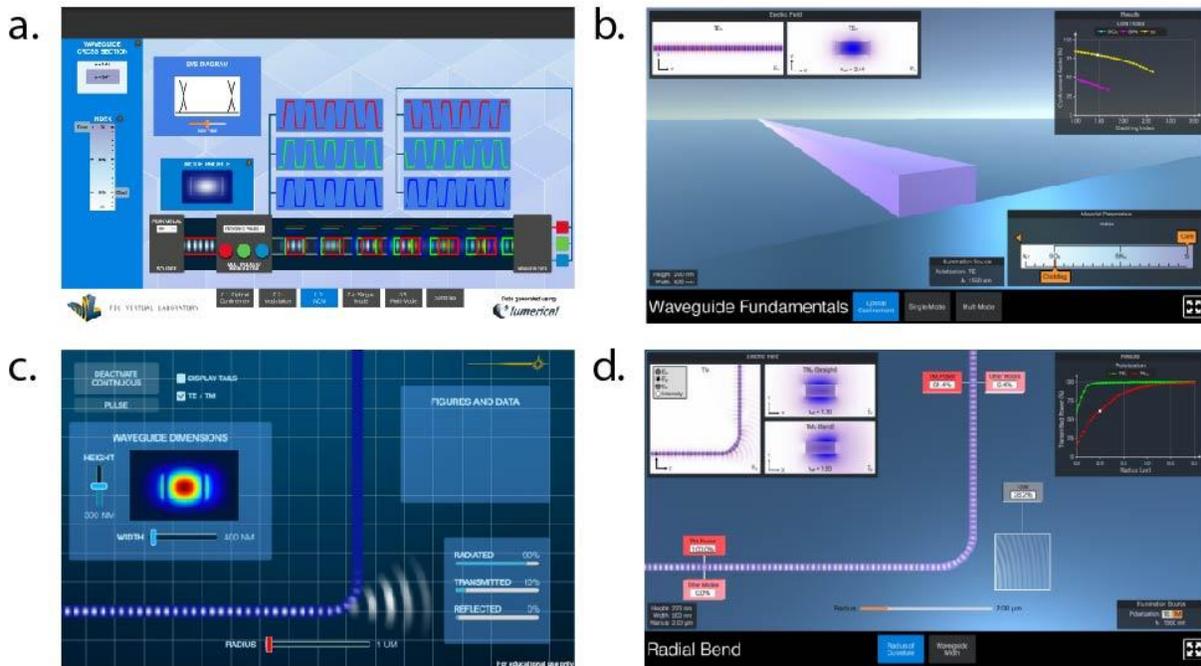


Figure 2. Iterative development of the AIM Virtual Lab simulations guided by expert feedback and usability testing. [a-b] Sim #1 – Waveguide Fundamentals, beta version (left) and final version (right); [c-d] Sim #2 – Radial Waveguide Bend, beta version (left) and final version (right).

2.4 Final release of the AIM Virtual Lab for MOOC integration

Figure 3 shows an example of one of the three completed 3D AIM Virtual Lab simulations. The FDE mode profiles and FDTD-driven CW data movies of the TE electric field are displayed (top left), while cross-over length is plotted in the results panel (top right). In the “Coupler Gap” tab, the user has direct control over the gap spacing and can switch between TE/TM polarization to observe how these parameters affect the effective index of the even and odd supermodes of the structure.

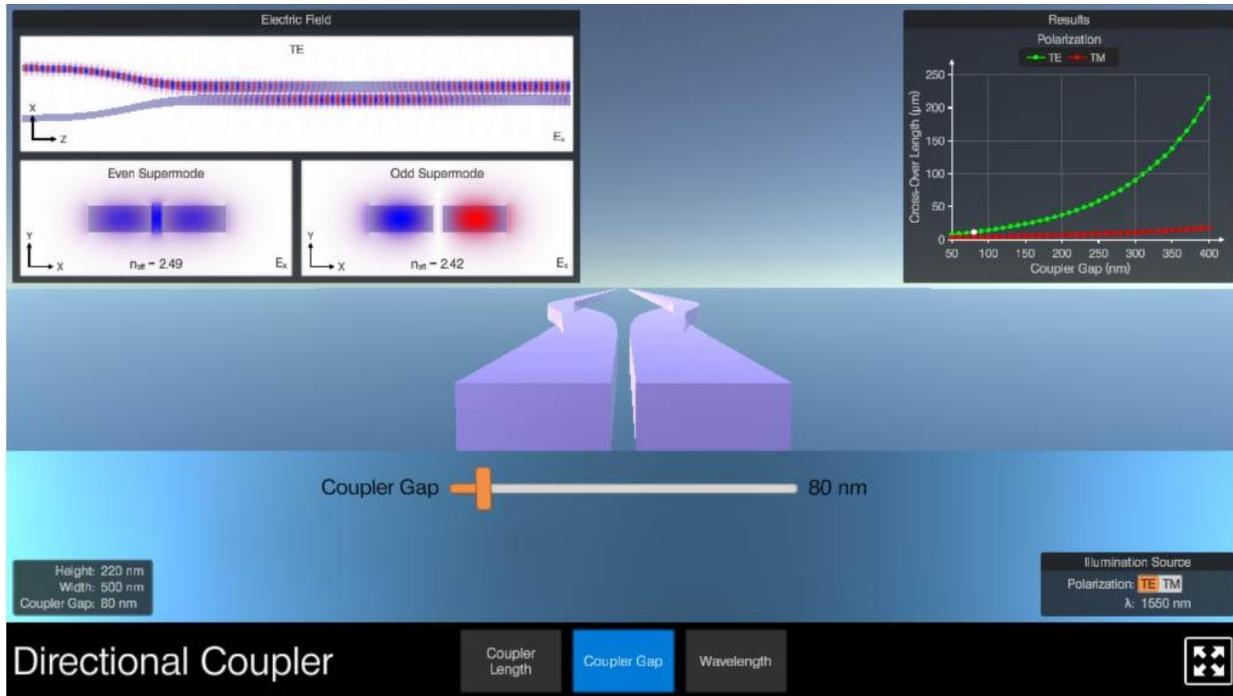


Figure 3. Final version of Sim #3 – Directional Coupler for the Spring 2019 offering of Photonic Integrated Circuits 1 (PIC1)¹⁸ online course.

3. INTEGRATION WITH THE EDX ONLINE LEARNING PLATFORM

3.1 AIM Academy’s online course offerings in integrated photonics

Starting in 2019, AIM Academy is releasing a series of online MITx courses for integrated photonics engineers that will be hosted on the edX platform.

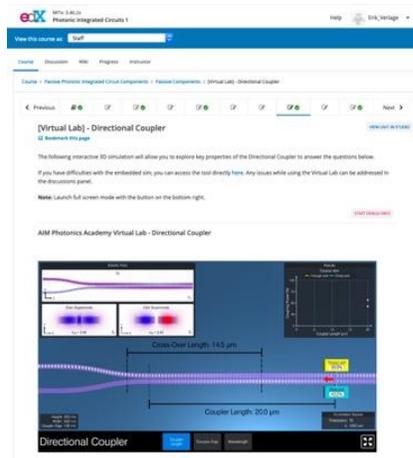
The first of these courses, released in April of 2019, is Photonic Integrated Circuits 1 (PIC1),¹⁸ an MITx course led primarily by Professors Lionel C. Kimerling (MIT) and Stefan Preble (Rochester Institute of Technology). This course is intended for engineers interested in PIC design using a standardized Process Design Kit (PDK) library and Electronic Photonic Design Automation (EPDA) software. Students review passive silicon photonic devices and model these photonic devices using a cloud-based interface with access to multiple EPDA software vendor tools (only available to registered students). Starting with a basic transceiver, students design their own PIC components from simulation to layout file, and the course ends in a final project submission that can be fabricated in the Multi-Project Wafer run at the AIM Photonics Institute.

Two additional courses are scheduled for release in 2019: Photonic Integrated Circuits 2 (PIC2) and Fundamentals of Integrated Photonics (FIP). The latter will be an asynchronous MOOC that makes heavy use of the AIM Virtual Lab simulation modules, with a focus on building photonics intuition and introducing both passive and active PIC-chip components to a wider audience.

In addition, AIM Academy intends to release multiple courses focused on Testing, Assembly, and Packaging (TAP) in integrated photonics, targeting both engineering and technician audiences.

3.2 AIM Virtual Lab simulations directly embedded in MITx MOOC

As shown in Figure 4, the AIM Virtual Lab interactive simulations were featured in the inaugural release of the first AIM Academy-led online course offering. For this offering of the PIC1 course, the three AIM Virtual Lab simulations from Section 2 were embedded in the Passive Components unit of the first week of the course.



- Interactive design exploration tool
- Open to all registrants
- Directly embedded in edX platform
- Sequential, level-based pedagogy
- Prepares verified students for cloud-based EPDA software tools



Figure 4. Embedded AIM Virtual Lab simulation on the edX platform using an IFrame. Students can access all controls directly in their browser window or enter full-screen mode. Future integration tasks include assessment problems directly in the AIM Virtual Lab environment and communication with the edX gradebook for reporting problem completion.

3.3 IFrame integration

AIM Virtual Lab simulations are embedded into edX using inline frames. This gives learners a consistent, seamless experience as they move between lectures, simulations, and other content. To ensure usability in the first release of the course, we also included detailed instructions that highlight the interactive UI components within each simulation.

3.4 Graded assessment on the edX platform and within the AIM Virtual Lab

Currently, simulations are followed by several multiple-choice questions on the edX platform about the concepts taught or data available in the AIM Virtual Lab simulation. This style of assessment outside of the simulation, while not seamless, is sufficient for measuring student learning and encouraging exploration within every tab of the simulation, covering all device parameters. However, with the current iteration of the AIM Virtual Lab, learners often have to scroll back up the page to re-explore the simulation in order to answer the multiple-choice assessment questions.

In future versions of the course, simulations will be more directly linked to the edX platform to allow assessment and self-assessment within the Virtual Lab environment itself, that will then be communicated to the edX gradebook. Instructors would be able to ask questions within the simulation world, allowing a smoother user experience and the use of open-ended questions that encourage users to explore the full parameter space of the photonic device. A simple example would be designing a ring resonator filter for a specific wavelength, where multiple ring sizes would be acceptable responses that meet design criteria. Advanced problems might allow users to provide their own unique solutions to circuit behavior using a block-based circuit designer, allowing users to link multiple components together to build their own photonic circuits in a safe, easy-to-understand environment. This digital design space could be linked to the device component interactive simulations, allowing users to explore circuit-level and device-level functionality within the same online environment.

3.5 edX student surveys and self-assessment regarding the AIM Virtual Lab

The first online course released by AIM Academy in April of 2019 (PIC1) primarily targets an audience of experienced photonics / integrated circuit design engineers, spanning the range between having little or no prior knowledge of optics and photonics, to full-fledged photonics researchers interested in PIC circuit design.

The PIC1 course enrollment included 338 verified learners and 1259 auditors, with a total of 631 active learners. Course analytics from the *edX Insights* student tracker indicated a large number of active learners chose to remain in auditor status, foregoing access to the cloud computing tools; additionally, many of these auditors relied only on video content, passively watching without answering assessment questions. For this cohort of learners, the AIM Virtual Lab tool and a series of interactive notebooks were the only active learning experiences in the course.

As shown in Table 1, user feedback about the AIM Virtual Lab on the edX platform was very encouraging, with 97.3% reporting a somewhat positive or very positive experience, and the vast majority – 81.2% – reporting a very positive

experience. More than 98% of respondents requested additional topics be included in the AIM Virtual Lab, and in the open feedback section of the survey, many suggested specific photonic components for future simulations, including Mach-Zehnder interferometers and modulators, y-branch splitters, ring resonators, photonic crystals, Bragg gratings, and grating couplers.

Table 1. Response to first week survey for the MITx course Photonic Integrated Circuits 1 (PIC1). At this point in the course, students had progressed through all three Virtual Lab simulations (waveguide fundamentals, radial bends, and directional couplers) and had answered assessment questions for the content in each simulation.

Survey Question	Response	#	%	Total
How was your overall experience with the Virtual Lab?	Very Positive	151	81.2	186
	Somewhat Positive	30	16.1	
	Neutral	5	2.7	
	Somewhat Negative	0	0	
	Very Negative	0	0	
How much do you agree with the following statement: The Virtual Lab tool contributed to my understanding of the course content.	Strongly Agree	126	68.1	185
	Somewhat Agree	54	29.2	
	Neither Agree nor Disagree	4	2.2	
	Somewhat Disagree	1	0.5	
	Strongly Disagree	0	0	
In future offerings of the course, should more components include Virtual Lab tools?	Yes	182	98.4	185
	No	3	1.6	

4. CONCLUSIONS AND FUTURE WORK

4.1 AIM Virtual Lab conclusions and outlook

The survey results and user feedback are an encouraging indication that there is a need for this content within the highly-skilled engineering audience. While more advanced content will continue to be developed for engineers, the 3D interactive simulations can easily be modified to meet the needs of technicians, and it is likely that the technician target audience will ultimately have the largest benefit from high-quality 3D simulations and animated visualizations. In addition, future light-weight versions of the AIM Virtual Lab content could be developed rapidly and at low cost by AIM Academy.

MOOC integration has greatly enhanced the reach of the first three simulations; however, stand-alone modules that include video lectures created specifically for use with the AIM Virtual Lab would greatly enhance future online courses, creating a seamless experience for the user. Well-designed modules could be reused by MOOC instructors who wish to use this content in future courses.

While the 3D graphics in this tool require specialized Unity development expertise, the data sharing process itself could be modified and scaled for the community at large. Through custom-built developer tools and an easy-to-use procedure for sharing photonic simulation results directly from commercial photonic design software, a platform could be deployed that would enable any user to rapidly assemble their own user-friendly simulation libraries. This might foster a community of content creators building rudimentary versions of these educational simulations, leveraging photonics research in industry and academia to create workforce training tools.

4.2 Full edX integration, including gradebook access from within the AIM Virtual Lab

In future AIM Academy MOOCs featuring interactive simulations, full communication with the edX gradebook will be a priority. This will enable learning science research studies focused on the efficacy of the AIM Virtual Lab. Splitting students into cohorts with modified versions of the interactive tools will allow further analysis of learning outcomes from the implicit scaffolding methodology^{12,13} for engineer and technician audiences.

4.3 Game-based learning and game-based assessment

An exciting direction for the AIM Virtual Lab is the exploration of gamification and game-based learning, building on the sandbox mode to create a more expansive platform for circuit design and peer-to-peer interactions. In addition, this would enable the implementation of game-based assessment,^{19,20} where information from Unity Analytics would lead to a wealth of information about learners based on their actions during gameplay. This novel approach to assess student interactions directly opens many doors for finer and more accurate measurements of student understanding, as the process by which students use a simulation to answer questions can expose misconceptions that would not appear in multiple choice assessment questions. In this model, every user interaction, from the path the student uses to solve a problem to timing between user input, can be analyzed using machine learning and used to illuminate student knowledge gaps. This would later allow the platform to deliver custom content for each user to achieve desired learning outcomes.

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